IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 27, 2017, accepted March 20, 2017, date of publication June 13, 2017, date of current version June 27, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2705018

Effective Rate of MISO Systems Over κ-μ Shadowed Fading Channels

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This work was supported in part by the National Science and Technology Major Project under Grant 2015ZX03001034, in part by the National Natural Science Foundation of China under Grant 61501404, in part by the Doctoral Scientific Funds of Henan Polytechnic University under Grant B2016-34, in part by the Open Research Fund of the State Key Laboratory of Networking and Switching Technology of Beijing University of Posts and Telecommunications under Grant SKLNST-2016-1-02, and in part by the Henan Scientific and Technological Research Project under Grant 172102210023.

ABSTRACT In this paper, the effective rate of multiple-input single-output (MISO) systems over independent and identically (i. i. d.) distributed κ-μ shadowed fading channels is studied under delay constraints. We derive an analytical expression for the effective rate of MISO systems over κ-μ shadowed fading channels. The approximate analysis method is further invoked to solve the infinite series problem. Based on the moment matching method, a closed-form expression for the effective rate is obtained. In addition, to capture insights into the effects of the model and fading parameters on the effective rate of the systems, the asymptotic effective rates in the high- and low-signal-to-noise ratio (SNR) regimes are obtained. The analytical results are compared with Monte Carlo simulations, which validate the correctness of the theoretical analysis.

INDEX TERMS Delay-limited rate, effective rate, κ-μ shadowed fading, multiple-input single-output (MISO).

I. INTRODUCTION

Multiple antennas represent a promising technology for substantially improving spectral efficiency and enhancing link reliability compared with single-antenna systems [1], [2]. A myriad of works have focused their attention on Shannon's capacity limits of multiple-antenna systems [3]–[7]. However, the effects of the system delays are not considered. Emerging wireless applications (for instance, voice over IP (VoIP), interactive gaming, multimedia stream and mobile computing) are sensitive to system delays. In these applications, transmitted data will expire if not delivered in a fixed amount of time. In this case, the performance evaluation of these applications calls for quantifying the delay-limited capacity.

To solve this problem, the effective rate was proposed as a key metric to characterize the system performance under quality of service (QoS) limitations [8]. Since then, significant attention has been paid to effective rate (or effective capacity, effective throughput) analysis in the field of wireless communications [9]–[15]. The common characteristic of the aforementioned work is that such work only considers the effects of multipath fading on the effective rate of the system; shadowing fading effects have been ignored. However, in practice, the links between transmitters and receivers suffer from both multipath fading and shadowing fading simultaneously. As discussed in [16]–[18], shadowing fading is a crucial factor because it has a significant impact on system performance.

Considering this fact, the authors in [19] performed an effective rate analysis of generalized-$\mathcal{K}$ multiple-input single-output (MISO) fading channels, where Nakagami-m multipath fading and Gamma shadowing fading were considered. Later, this model was extensively used to characterize the fluctuations of homogeneous scattering environments [13], [20]. However, the model falls short in capturing the variations of inhomogeneous fading channels. For this case, the authors in [20] proposed a κ-μ shadowed fading channel. This is a generic model for encompassing Rician and

Gamma shadowing fading and one-side Gaussian, Rayleigh, Nakagami-m, Rician, and κ-μ multipath fading. The effective capacity of κ-μ shadowed fading was investigated in [21]. However, the study in [21] was limited to single-antenna systems. To the best of the authors' knowledge, there is no prior work investigating the effective rate of MISO systems over κ-μ shadowed fading channels. For multiple antenna systems, the instantaneous channel power gain at the receiver is characterized by multivariate random variables, which is different from single antenna conditions [15].

Motivated by the above discussion, in this study, we investigate the effective rate of MISO systems over independent and identically distributed (i.i.d.) κ-μ shadowed fading channels. The exact analytical expression for the effective rate is derived. The derived expression involves an infinite series, which hinders us in further analyzing the effects of the system parameters on MISO systems. To circumvent this problem, an approximate expression for the effective rate is derived using a moment matching method. To obtain insights into the effects of the system and fading parameters on the system effective rate, we further perform asymptotic analysis in high- and low- signal-to-noise ratio (SNR) regimes.

The remainder of this paper is organized as follows: Section 2 presents the system model and the statistical characteristics of the κ-μ shadowed fading channels. In Section 3, we derive the analytical expression for the effective rate of MISO systems over the i.i.d. κ-μ shadowed fading channels. Section 4 provides the approximate expression of the effective rate with the moment matching method, followed by the asymptotic analysis in the high- and low-SNR regimes. The numerical results and key findings are summarized in Section 5. Finally, we conclude the paper in Section 6.

Notations: We use upper and lower case boldface to denote vectors and matrices. The notation $\mathbb{C}$ denotes the set of complex numbers, while $\mathbb{E}[\cdot]$ returns the expectation of a matrix or vector. The notations $(\cdot)^H$ and $(\cdot)^{-1}$ denote the conjugate transpose and inverse operator of a matrix or vector, respectively. $\mathcal{CN}\left(\mu, \sigma^2\right)$ denotes a Gaussian distribution with mean μ and variance σ^2.

II. SYSTEM MODEL AND κ-μ SHADOWED STATISTICAL

A. SYSTEM MODEL

We consider a typical MISO system with N_t antennas at the transmitter and one antenna at the receiver. Therefore, the received signal at the receiver can be expressed as

$$y = \mathbf{h}\mathbf{x} + n \tag{1}$$

where $\mathbf{h} \in \mathbb{C}^{1\times N_t}$ denotes the MISO channel fading vector between the multi-antenna transmitter and the single receiver, $\mathbf{x} \in \mathbb{C}^{N_t\times 1}$ represents the transmitted signal vector, and n is the complex additive white Gaussian noise (AWGN) with $n \sim \mathcal{CN}(0, N_0)$.

As a key metric of wireless link level, effective capacity was originally proposed by [8] for block fading channels, in which the channel varies from one block to another while remaining constant in each single block. According to the definition of [8], in wireless communications, the effective rate is the maximum constant arrival rate satisfying a statistical QoS requirement. By quantizing the QoS exponent as θ, it can be expressed as

$$a(\theta) = -\frac{1}{\theta T}\ln\left(\mathbb{E}\left[\exp(-\theta T C)\right]\right), \quad \theta \neq 0 \tag{2}$$

where T is the duration of the block. In addition, C is the transmit rate as a random variable (RV) with respect to $\mathbf{h}$. The parameter θ is the delay exponent, which is used to characterize the asymptotic decay rate of the buffer occupancy as

$$\theta = -\lim_{x\to\infty}\frac{\ln \Pr[L > x]}{x} \tag{3}$$

where L represents the equilibrium queue length of the buffer at the transmitter [8] and x is the threshold of the queue length.

In this paper, we assume that the transmitter has no channel state information. In this case, the transmitter sends identical power and an uncorrelated circularly symmetric zero-mean complex Gaussian signals [22]. Based on the definition of [8], the effective rate can be succinctly formulated as follows:

$$\mathcal{R}(\gamma, \theta) = -\frac{1}{A}\log_2\left(\mathbb{E}\left\{\left(1 + \frac{\gamma}{N_t}\mathbf{h}\mathbf{h}^H\right)^{-A}\right\}\right) \tag{4}$$

where $A = \theta T B \log_2(e)$, B represents the system bandwidth, and γ is the average transmit SNR. Here, the expectation is taken over the random channel matrix $\mathbf{h}$. For no delay constraints ($\theta = 0$), the effective rate reduces to the well-known Shannon's ergodic rate, which has been well studied by [1]–[7].

B. κ-μ SHADOWED FADING

The κ-μ shadowing model is a general fading model that can be used to simulate many types of classical wireless fading channels [20], e.g., one-side Gaussian ($\mu = 0.5, \kappa \to 0, m \to \infty$), Rayleigh ($\mu = 1$, $\kappa \to 0, m \to \infty$), Nakagami-$m$ ($\mu = m, \kappa \to 0, m \to \infty$, m is the Nakagami-m factor), Rician ($\mu = 1, \kappa = K, m \to \infty$, K is the Rician factor), κ-μ ($m \to \infty$), and Rician shadowed ($\mu = 1$, $\kappa = K$) models. In our case, it is assumed that the entries of $\mathbf{h}$ follow an i.i.d. κ-μ shadowed distribution. Additionally, the probability density function (PDF) of $X = |h_l|^2, l = 1, \cdots, N_t$ is given as

$$\begin{aligned} p_X(x) = &\frac{\mu m^m (1+\kappa)^\mu}{\Gamma(\mu)\,\Omega(\mu\kappa + m)^m}\left(\frac{x}{\Omega}\right)^{\mu-1} \\ &\times \exp\left(-\frac{\mu(1+\kappa)x}{\Omega}\right){}_1F_1\left(m, \mu; \frac{\mu^2\kappa(1+\kappa)}{(\mu\kappa+m)\,\Omega}x\right) \end{aligned} \tag{5}$$

where Ω is the signal average power, with $\Omega = \mathbb{E}[X]$, m is the shaping parameter of the Nakagami-m RV, κ is the ratio between the total power of the dominant components and the total power of the scattered waves, μ is the number of clusters, $\Gamma(\cdot)$ is the Gamma function as defined in

[23, Eq. (8.310.1)], and ${}_1F_1(\cdot)$ is the confluent hypergeometric function as defined in [23, Eq. (9.14.1)].

Let $Y = \sum_{l=1}^{N_t} X_l$. According to the result of [20, Corollary 1], the PDF of Y is provided as

$$p_Y(y) = \frac{1}{\Gamma(\mu N_t)} \frac{\mu^{\mu N_t} m^{m N_t} (1+\kappa)^{\mu N_t}}{\Omega^{\mu N_t} (\mu\kappa + m)^{m N_t}} y^{\mu N_t - 1} \times \Phi_2\left(\mu N_t - m N_t, m N_t, \mu N_t; \frac{-\mu(1+\kappa)}{\Omega} y, \frac{-\mu(1+\kappa) m}{\Omega(\mu\kappa + m)} y\right) \quad (6)$$

where $\Phi_2(\cdot)$ is the confluent multivariate hypergeometric function as defined in [23] and [24].

III. EFFECTIVE RATE

In this section, the analytical closed-form expression for the effective rate of κ-μ shadowed MISO fading channels is provided in the following theorem. It is noted that the entries of $\mathbf{h}$ are i.i.d. κ-μ shadowed RV.

Theorem 1: For i.i.d. κ-μ shadowed fading channels, the effective rate of MISO systems is given as

$$\mathcal{R}(\gamma, \theta) = \frac{\mu N_t}{A} \log_2\left(\frac{\gamma}{a N_t}\right) + \frac{m N_t}{A} \log_2(b) - \frac{1}{A} \log_2 \left[\sum_{p,q=0}^{\infty} \frac{(c)_p (m N_t)_q}{\Gamma(\mu N_t)(\mu N_t)_{p+q} p! q!} \left(-\frac{a N_t}{\gamma}\right)^{p+q} \times \left(\frac{1}{b}\right)^q \frac{\Gamma(\mu N_t + p + q)\Gamma(A - \mu N_t - p - q)}{\Gamma(A)}\right] \quad (7)$$

where $a = \frac{\mu(1+\kappa)}{\Omega}$, $b = \frac{\mu\kappa + m}{m}$, $c = \mu N_t - m N_t$, and $(\alpha)_n$ is the Pochammer symbol defined as $(\alpha)_n = \Gamma(\alpha + n)/\Gamma(\alpha)$ with $(\alpha)_0 = 1$ [25], $(\cdot)!$ is the factorial operation, and $\mathcal{B}(\cdot)$ is the Beta function as defined in [23, Eq. (8.380.1)].

Proof: Utilizing the PDF of (6), the effective rate of (4) can be formulated in integral form as

$$\mathcal{R}(\gamma, \theta) = -\frac{1}{A} \log_2\left(\frac{a^{\mu N_t}}{\Gamma(\mu N_t) b^{m N_t}} \int_0^{\infty} \left(1 + \frac{\gamma}{N_t} y\right)^{-A} y^{\mu N_t - 1} \times \Phi_2\left(c, m N_t, \mu N_t; -ay, -\frac{b}{a} y\right) dy\right) \quad (8)$$

To solve the integral, we focus on the following definition:

$$I = \int_0^{\infty} \left(1 + \frac{\gamma}{N_t} y\right)^{-A} y^{\mu N_t - 1} \Phi_2\left(c, m N_t, \mu N_t; -ay, -\frac{b}{a} y\right) dy \quad (9)$$

By substituting the following identity [23, Eq. (9.261.2)] into I,

$$\Phi_2(\alpha, \beta, \gamma, x, y) = \sum_{p,q=0}^{\infty} \frac{(\alpha)_p (\beta)_q}{(\gamma)_{p+q} p! q!} x^p y^q \quad (10)$$

formula (9) can be further simplified as

$$I = \sum_{p,q=0}^{\infty} \frac{(c)_p (m N_t)_q b^q}{(\mu N_t)_{p+q} p! q! a^{q-p}} \times \int_0^{\infty} \left(1 + \frac{\gamma}{N_t} y\right)^{-A} y^{\mu N_t + p + q - 1} dy \quad (11)$$

Moreover, by introducing the following result of [23, Eq. (3.251.11)],

$$\int_0^{\infty} (1 + \beta x^p)^{-\nu} x^{q-1} dx = \frac{1}{p} \beta^{-\frac{q}{p}} B\left(\frac{q}{p}, \nu - \frac{q}{p}\right) \quad (12)$$

the expression of (11) can be rewritten as

$$I = \sum_{p,q=0}^{\infty} \frac{(c)_p (m N_t)_q b^q}{(\mu N_t)_{p+q} p! q! a^{q-p}} \left(\frac{\gamma}{N_t}\right)^{-(p+q+1)} \times \mathcal{B}(\mu N_t p + q + 1, A - \mu N_t - p - q - 1) \quad (13)$$

where $\mathcal{B}(\cdot, \cdot)$ can be given by the following identity [23, Eq. (8.384.1)]:

$$\mathcal{B}(v, w) = \frac{\Gamma(v)\Gamma(w)}{\Gamma(v + w)} \quad (14)$$

After some simple manipulations, we can finally derive the desired result of (7). ■

Clearly, it can be seen that the effective rate of MISO systems over i.i.d. κ-μ shadowed fading channels can be expressed in closed-form and can be easily evaluated. However, the derived result involves an infinite series, which is adverse to the analysis. Therefore, we will further provide a tractable approximate expression for the effective rate of MISO systems with κ-μ shadowed fading channels with the moment matching method in the following section.

IV. APPROXIMATE EFFECTIVE RATE

A. APPROXIMATE ANALYSIS

Utilizing the similar methodology of [26]–[28], the squared κ-μ shadowed distribution can be approximated by a Gamma distribution. Recalling the property of the Gamma function, we can conclude that the sum of N_t i.i.d. squared κ-μ RVs with parameters κ, μ and m is approximated by a single Gamma RV, which is provided in the following proposition.

Proposition 1: Using the moment matching method, the distribution of the sum of N_t i.i.d. squared κ-μ shadowed RVs can be approximated by a single Gamma distribution, whose PDF is given as

$$p_Z(z) = \frac{1}{\Gamma(\Delta)} \left(\frac{\Omega N_t}{\Delta}\right)^{-\Delta} z^{\Delta - 1} \exp\left(-\frac{\Delta}{\Omega N_t} z\right) \quad (15)$$

where $\Delta = \frac{m\mu N_t (1+\kappa)^2}{m + \mu\kappa^2 + 2m\kappa}$.

Proof: We define RV $z \sim \mathcal{G}(\omega, \eta)$ as a Gamma RV with shape parameter ω and scale parameter η, which is used to approximate the PDF of (5). The PDF is given as

$$p_z(z) = \frac{\eta^{-\omega}}{\Gamma(\omega)} z^{\omega - 1} \exp\left(-\frac{z}{\eta}\right) \quad (16)$$

Using the similar methodology of [26], [27], ω and η of (16) can be expressed as

$$\omega = \frac{m\mu(1+\kappa)^2}{m+\mu\kappa^2+2m\kappa} \tag{17}$$

$$\eta = \frac{\Omega\left(m+\mu\kappa^2+2m\kappa\right)}{m\mu(1+\kappa)^2} \tag{18}$$

Finally, by letting $Z = \sum_{l=1}^{N_t} z_l$ and employing the property of the Gamma function [27], [29], we can complete the proof of the above proposition after some algebraic manipulations. ■

Utilizing the above proposition, we provide the approximate expression for the effective rate of MISO systems over κ-μ shadowed fading channels in the following theorem.

Theorem 2: For i.i.d. κ-μ shadowed fading channels, the approximate expression for the effective rate of MISO systems is given as

$$\mathcal{R}_A(\gamma,\theta) = \log_2\left(\frac{\Omega\gamma}{\Delta}\right) - \frac{1}{A}\log_2\left(U\left(A, A-\Delta+1, \frac{\Delta}{\Omega\gamma}\right)\right) \tag{19}$$

where $U(\cdot)$ is the Tricomi hypergeometric function as defined in [30, Eq. (13.1.3)], and Δ is defined in Proposition 1.

Proof: The proof starts by substituting (15) into (4). The approximate effective rate thus can be expressed in integral form:

$$\mathcal{R}_A(\gamma,\theta) = -\frac{1}{A}\log_2\left(\frac{1}{\Gamma(\Delta)}\left(\frac{\Omega N_t}{\Delta}\right)^{-\Delta}\int_0^\infty\left(1+\frac{\gamma}{N_t}z\right)^{-A} \times z^{\Delta-1}\exp\left(-\frac{\Delta}{\Omega N_t}z\right)dz\right) \tag{20}$$

Applying the following integral identity [31, Eq. (39)],

$$\int_0^\infty (1+ax)^{-\nu}x^{q-1}\exp(-px)\,dx = \times a^{-q}\Gamma(q)\,U\left(q, q+1-\nu, \frac{p}{a}\right) \tag{21}$$

(20) can then be further simplified as

$$\mathcal{R}_A(\gamma,\theta) = -\frac{1}{A}\log_2\left(\left(\frac{\Omega\gamma}{\Delta}\right)^{-\Delta} \times U\left(\Delta, \Delta+A-1, \frac{\Delta}{\Omega\gamma}\right)\right) \tag{22}$$

Recalling the following Kummer's transformation as defined in [25, Eq. (07.33.17.0007.01)],

$$U(a,b,x) = x^{1-b}U(a-b+1, 2-b, x) \tag{23}$$

we can further re-write the result of (22) as

$$\mathcal{R}_A(\gamma,\theta) = \log_2\left(\frac{\Omega\gamma}{\Delta}\right) - \frac{1}{A}\log_2\left(U\left(A, A+1-\Delta, \frac{\Delta}{\Omega\gamma}\right)\right) \tag{24}$$

We can finally arrive at the desired result of this theorem. ■

The above expression can be expressed in closed form and effectively evaluated by standard software packages, e.g., Matlab, Maple, or Mathematica. Unfortunately, this form lacks physical insights into the system and the fading parameter effects on the effective rate of MISO systems. We henceforth perform the asymptotic analysis in the high- and low-SNR regimes in the following corollaries.

B. HIGH-SNR ANALYSIS

Although (19) presents the approximate effective rate of MISO systems over κ-μ shadowed fading channels, the expression does not provide intuitive insights into the impact of system and fading parameters on the effective rate performance. To this end, we pursue a detailed analysis in the high-SNR regime in the following corollary.

Corollary 1: For the high-SNR regime, the asymptotic effective rate of MISO systems over κ-μ shadowed fading channels tends to

$$\mathcal{R}_A^\infty = \log_2\left(\frac{\gamma\Omega}{\Delta}\right) - \frac{1}{A}\log_2\left(\frac{\Gamma(\Delta-A)}{\Gamma(\Delta)}\right) \tag{25}$$

Proof: The proof starts by taking the average transmit SNR γ of (20) as large ($\gamma\to\infty$)

$$\mathcal{R}_A(\gamma,\theta) = \log_2\left(\frac{1}{\Gamma(\Delta)}\left(\frac{\Omega N_t}{\Delta}\right)^{-\Delta}\left(\frac{\gamma}{N_t}\right)^{-A} \times \int_0^\infty z^{\Delta-A-1}\exp\left(-\frac{\Delta}{\Omega N_t}z\right)dz\right) \tag{26}$$

Then, employing the following integral identity [23, Eq. (3.381.4)],

$$\int_0^\infty x^{\nu-1}\exp(-\mu x)\,dx = \frac{\Gamma(\nu)}{\mu^\nu} \tag{27}$$

and after some algebraic manipulations, we can reap the result of the above corollary. ■

From the above corollary, we can observe that the effective rate increases logarithmically with the average SNR γ and the average power Ω in the high-SNR regime. The following subsection will examine the asymptotic behavior of MISO systems in the low-SNR regime.

C. LOW-SNR ANALYSIS

For the low-SNR regime, we adopt the similar methodology of [19] by using the second-order Taylor expansion of the SNR, $\gamma\to 0^+$:

$$\mathcal{R}(\gamma,\theta) = \dot{\mathcal{R}}(0,\theta)\gamma + \ddot{\mathcal{R}}(0,\theta)\frac{\gamma^2}{2} + o\left(\gamma^2\right) \tag{28}$$

where $\dot{\mathcal{R}}(0,\theta)$ and $\ddot{\mathcal{R}}(0,\theta)$ are the first- and second-order derivatives of the approximate effective rate with respect to the SNR $\gamma = 0$, respectively. Note that the above derivatives are related to the two key metrics of the minimum normalized energy per information bit to reliably convey any positive rate and the wideband slope, which was originally proposed in [32]. The two metrics are defined as

$$\frac{E_b}{N_0}_{\min} \triangleq \lim_{\gamma\to 0}\frac{\gamma}{\mathcal{R}(\gamma,\theta)} = \frac{1}{\dot{\mathcal{R}}(0,\theta)} \tag{29}$$

$$\mathcal{S}_0 \triangleq -\frac{2\ln 2\left[\dot{\mathcal{R}}(0,\theta)\right]^2}{\ddot{\mathcal{R}}(0,\theta)} \tag{30}$$

Proposition 2: For the low-SNR regime, the asymptotic effective rate of the MISO system over κ-μ shadowed fading channels is provided as

$$\mathcal{R}\left(\frac{E_b}{N_0}\right) \approx \mathcal{S}_0 \log_2\left(\frac{E_b}{N_0}\Big/\frac{E_b}{N_0}_{\min}\right) \tag{31}$$

where $E_b/N_{0\min}$ and $\mathcal{S}_0$ are given as

$$\frac{E_b}{N_0}_{\min} = \frac{\ln 2}{\Omega} \tag{32}$$

$$\mathcal{S}_0 = \frac{2N_t m\mu(1+\kappa)^2}{(A+1)\left(m+\mu\kappa^2+2m\kappa\right)+(2A+1)\,m\mu N_t\,(1+\kappa)^2} \tag{33}$$

Proof: Using the similar methodology of [33] and the PDF of Z in Proposition 1, the first and second derivatives of $\mathcal{R}(\gamma,\theta)$ in (4) with respect $\gamma \to 0$ are given as

$$\begin{aligned}\dot{\mathcal{R}}(0,\theta) &= -\frac{1}{A\ln 2}\left.\frac{\mathbb{E}\left[\frac{-AZ}{N_t}\left(1+\frac{\gamma Z}{N_t}\right)^{-A-1}\right]}{\mathbb{E}\left[\left(1+\frac{\gamma Z}{N_t}\right)^{-A}\right]}\right|_{\gamma=0}\\ &= \frac{\mathbb{E}[Z]}{N_t\ln 2}\end{aligned} \tag{34}$$

$$\begin{aligned}\ddot{\mathcal{R}}(0,\theta) &= -\left.\frac{\mathbb{E}\left[\frac{-AZ}{N_t}\left(1+\frac{\gamma Z}{N_t}\right)^{-A-1}\right]^2}{A\ln 2\left\{\mathbb{E}\left[\left(1+\frac{\gamma Z}{N_t}\right)^{-A}\right]\right\}^2}\right|_{\gamma=0}\\ &\quad+\left.\frac{\mathbb{E}\left[\frac{-A(A+1)Z^2}{N_t^2}\left(1+\frac{\gamma Z}{N_t}\right)^{-A-2}\right]\mathbb{E}\left[\left(1+\frac{\gamma Z}{N_t}\right)^{-A}\right]}{A\ln 2\left\{\mathbb{E}\left[\left(1+\frac{\gamma Z}{N_t}\right)^{-A}\right]\right\}^2}\right|_{\gamma=0}\\ &= -\frac{(A+1)\,\mathbb{E}\left[Z^2\right]}{N_t^2\ln 2}-\frac{A\mathbb{E}^2[Z]}{N_t^2\ln 2}\end{aligned} \tag{35}$$

Combining (15) with (27), the first and second moments of Z can be addressed as

$$\mathbb{E}[Z] = N_t\Omega \tag{36}$$

$$\mathbb{E}\left[Z^2\right] = \frac{N_t^2\Omega^2(\Delta+1)}{\Delta} \tag{37}$$

By applying (36) and (37), the first and second derivatives of $\mathcal{R}(0,\theta)$ in (4) are given as

$$\dot{\mathcal{R}}(0,\theta) = \frac{\Omega}{\ln 2} \tag{38}$$

$$\ddot{\mathcal{R}}(0,\theta) = -\frac{\Omega^2(2A\Delta+\Delta+A+1)}{\Delta\ln 2} \tag{39}$$

Substituting (38) and (39) into (29) and (30), the desired result of Proposition 2 can be obtained after some simplifications. ■

From Proposition 2, we can observe that $\frac{E_b}{N_0}_{\min}$ is independent of the parameters m, κ, μ, A, and N_t. In other words, the delay constraint, fading parameter and number of transmit antennas have no effect on $\frac{E_b}{N_0}_{\min}$. It is only determined by the average power Ω. In addition, it indicates that $\mathcal{S}_0$ is independent of the average power Ω and increases linearly with the number of transmit antennas N_t. Furthermore, it monotonically decreases with increasing delay parameter A. Finally, when delay constrained, A reduces to zero, and the wideslope, $\mathcal{S}_0$, tends to the result of [33].

V. NUMERICAL RESULTS

In this section, numerical results are provided to validate the accuracy of our analysis. For a random channel, we generate the κ-μ shadowed RVs in 10^5 realizations, which are used to obtain the Monte Carlo result of the effective rate via (4).

In Fig. 1, the approximate effective rate in (18) is compared with the Monte Carlo result in (4) versus SNR for different N_t and A. In this simulation, we have the following sets: $N_t = \{4, 6, 10\}$, $\Omega = 1$, $m = 1$, $\kappa = 2$, $\mu = 2$, and $A = \{0.1, 5\}$. It is clearly shown that the approximate effective rate is applicable for arbitrary N_t and A, and the tightness between the proposed approximation and exact expressions improves with increasing N_t, which is consistent with [27]. Finally, the graph also indicates that the effective rate is systematically strengthened with loosening delay constraints.

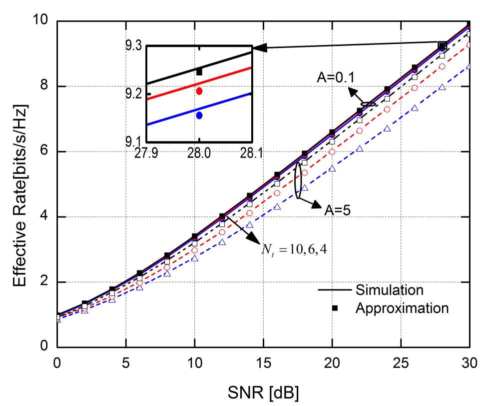

FIGURE 1. **Simulated and approximate effective rate versus the SNR of κ-μ fading channels with different values of N_t and A.**

In Fig. 2, the tightness of the approximate expression in (18) and the high-SNR approximation in (24) are verified against SNR for different κ and μ. We have the following sets: $N_t = 6$, $\Omega = 1$, $m = 1$, $A = 1$, $\{\kappa$, and $\mu\} = \{\{1, 0.1\}$, $\{2, 0.5\}$, $\{2, 2\}$, $\{2, 10\}\}$. It is clearly shown that large κ and μ yield higher effective rates, which means that κ and μ are beneficial to the effective rate. The performance increases slightly for large κ and μ ($\kappa = 2, \mu = 10$). In addition, this graph indicates that the high-SNR approximation more quickly approaches its tight value under large κ and μ values. Finally, we can observe that the approximate effective rate and high-SNR approximation closely match the Monte-Carlo simulation results for all considered cases.

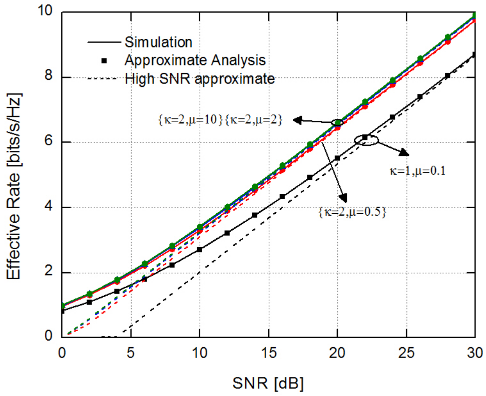

FIGURE 2. Simulated, approximate, and high-SNR approximate effective rate versus the SNR of κ-μ fading channels ($\{\kappa, \mu\} = \{ \{1, 0.1\}, \{2, 0.5\}, \{2,2\}, \{2, 10\} \}$).

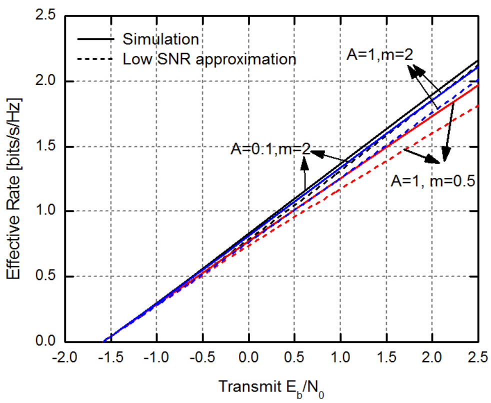

FIGURE 3. Low-SNR approximate and effective rate and versus the SNR for κ-μ fading channels ($m = \{0.5, 2\}$, A = $\{0.1, 1\}$).

Fig. 3 compares the low-SNR asymptotic result of Proposition 2 in (30) with the approximate effective rate in (18) for different parameters A and m. The parameter sets are given as follows: $N_t = 6$, $\Omega = 1$, $\kappa = 2$, $\mu = 2$, and $m = \{0.5, 2\}$, $A = \{0.1, 1\}$. Fig. 3 indicates that, at low SNR, the asymptotic result sufficiently matches the approximate effective rate for arbitrary A and m. In addition, the result demonstrates that the accuracy of our analytical result and the range for a good asymptotic expression improves if m increases, and the effective rate increases with decreasing A. The result demonstrates that the low-SNR asymptotic result with the lower A sufficiently matches the effective rate with loose delay constraints.

VI. CONCLUSION

In this paper, we investigate the effective rate of MISO systems over i.i.d. κ-μ shadowed fading channels. First, the exact analytical expression for the effective rate of MISO systems is derived. Unfortunately, the derived expression involves an infinite series, which makes system implementation and analysis challenging. Therefore, an approximate expression for the effective rate is derived using a Gamma distribution to approximate a κ-μ shadowed distribution wit the moment matching method. In addition, the closed-form asymptotic expressions for the effective rate in the high- and low-SNR regimes are also presented. It is demonstrated that the distribution of κ-μ shadowed fading channels can be sufficiently approximated by a Gamma distribution.

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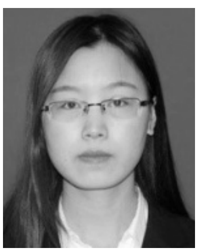

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