Performance Analysis of M-Ary PSK Modulation Schemes over Multiple Double Rayleigh Fading Channels with EGC in Cooperative Networks

Batool Talha
Faculty of Engineering and Science,
University of Agder, Servicebox 509,
NO-4898 Grimstad, Norway
Email: batool.talha@uia.no

Matthias Pätzold
Faculty of Engineering and Science,
University of Agder, Servicebox 509,
NO-4898 Grimstad, Norway
Email: matthias.paetzold@uia.no

Serguei Primak
Department of ECE,
University of Western Ontario,
London, ON, N6A 5B9, Canada
Email: primak@engga.uwo.ca

***Abstract*— This article studies the performance of M-ary phase shift keying (PSK) modulation schemes over mobile-to-mobile (M2M) fading channels with equal gain combining (EGC) in cooperative networks. The frequency-nonselective M2M fading channels are modeled assuming non-line-of-sight (NLOS) propagation conditions. Furthermore, a dual-hop amplify-and-forward relay type cooperative network is taken into consideration here. It is assumed that K diversity branches are present between the source mobile station and the destination mobile station via K mobile relays. The performance of M-ary PSK modulation schemes is analyzed by evaluating the average bit error probability (BEP). We have derived a simple analytical approximation for the average BEP of M-ary PSK modulation schemes over relay-based M2M fading channels with EGC. The validity and accuracy of the analytical approximation is confirmed by simulations. The presented results show that in a dual-hop relay system with EGC, there is a remarkable improvement in the diversity gain as the number of diversity branches K increases.**

I. Introduction

Recently, cooperative relaying has emerged as an attractive technology in the field of wireless communications. Since it is capable of fulfilling the ever-increasing demand of high data-rates with improved coverage that is imposed by the consumers [1], [2]. Such relaying makes it possible to achieve a spatial diversity gain by exploiting the existing resources (i.e., the mobile stations) of the network. So far several cooperative diversity schemes have been proposed [3]–[5]. However, in all these schemes, the network resources assist the source mobile station by relaying its information signal to the destination mobile station.

In this article, a dual-hop amplify-and-forward relay type cooperative network has been considered. It is assumed that K mobile relays are connected in parallel between the source mobile station and the destination mobile. Consequently, this kind of configuration gives rise to K diversity branches. The signals received from these K diversity branches can then be combined with each other at the destination mobile station, thus providing the desirable spatial diversity gain. Selection combining (SC) [6], EGC [6], and maximal ratio combining (MRC) [6] are those diversity combining techniques that have been studied since decades. Studies pertaining to the statistical and the performance analysis of EGC along with MRC in non-cooperative networks over Rayleigh, Rice as well as Nakagami fading channels are reported in [7]–[9] and [10]–[12], respectively. In addition, the authors of [13]–[15] have analyzed the performance of cooperative diversity using EGC and MRC over Rayleigh and Nakagami-m fading channels.

Like cooperative relaying, M2M communications is also an emerging technology that has demonstrated its potential application in cooperative networks, ad hoc networks, and vehicle-to-vehicle (V2V) communications. It is widely acknowledged now that M2M fading channels [16] are statistically quite different from conventional cellular and land mobile terrestrial channels like, e.g., Rayleigh, Rice, and Suzuki channels. Under NLOS propagation conditions, M2M fading channels in relay-based cooperative networks can effectively be modeled as double Rayleigh stochastic processes [17]. A straightforward extension of the double Rayeigh channel model to the double Rice channel model for relay-based M2M fading channels under line-of-sight (LOS) propagation conditions is presented in [18]. A study on the performance of digital modulation schemes over double Nakagami-m fading channels with MRC diversity is available in [19]. However, there is a lack of information in the literature regarding the performance of digital modulation schemes over double Rayleigh and/or double Nakagami-m fading channels with EGC. Thus, we aim to fill in this gap by studying the performance of M-ary PSK modulation schemes over double Rayleigh fading channels with EGC assuming K diversity branches (mobile relays).

Here, the performance of M-ary PSK modulation schemes is analyzed by evaluating the average BEP. We have derived a simple analytical approximation for the average BEP of M-ary PSK modulation schemes over M2M fading channels with EGC. The derivation of the approximation requires the knowledge of the probability density function (PDF) of the received signal envelope at the output of the equal gain (EG) combiner. The output of the EG combiner is modeled as a sum of K statistically independent but not necessarily identical double Rayleigh fading channels. Furthermore, we approximate the PDF of this sum process with the help of

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an orthogonal series expansion. Depending upon the purpose of use of the approximated PDF and the amount of accuracy required, there are various orthogonal series to choose from. The Edgeworth series, the Gram-Charlier series, and the Laguerre series expansion [20] are just to name a few. To obtain a simple and closed-form approximate expression for the PDF of the sum process, we have employed the Laguerre series expansion. It turns out that the first term in the Laguerre series equals the gamma distribution, which provides a simple approximation of high accuracy. The average BEP computed by making use of the approximate PDF of the sum process is validated by simulations. A good fitting of the approximate theoretical results with those of the exact results obtained by simulations confirms the correctness of our approach. The presented results illustrate that in a dual-hop relay system with EGC, there is a significant improvement in the diversity gain as the number of diversity branches K increases.

The remaining part of the paper is organized as follows. Section II describes the system model for EGC over M2M fading channels in amplify-and-forward relay networks. The PDF of the received signal envelope at the output of the EG combiner is derived in Section III. Section IV deals with the derivation of the average BEP of M-ary PSK modulation schemes over relay-based M2M fading channels with EGC. Verification of the analytical expressions by simulations and a detailed discussion on the presented results are included in Section V. Finally, the article is concluded in Section VI.

II. EGC OVER M2M FADING CHANNELS

In this section, we describe the system model for EGC over M2M fading channels in a K-parallel dual-hop cooperative network. Here, the K mobile relays in the network are connected in parallel between the source mobile station and the destination mobile station, as illustrated in Fig. 1. We target to study frequency-nonselective M2M fading channels under NLOS propagation conditions. Furthermore, the system model has been developed assuming isotropic scattering conditions. The mode of operation of all the mobile stations in the network, i.e., the source mobile station, the destination mobile station, and the K mobile relays is considered to be half-duplex. This means that the mobile stations do not transmit and receive a signal at the same time in the same frequency band.

The time-division multiple-access (TDMA) based amplify-and-forward relay protocols proposed in [21], [22] are taken into account here. Thus, the signals from the K diversity branches in different time slots can be combined at the destination mobile station using EGC. Let $s(t)$ denote the signal transmitted by the source mobile station. Then, the signal $r^{(k)}(t)$ received from the kth diversity branch at the destination mobile station can be expressed as

$$r^{(k)}(t) = \varsigma^{(k)}(t)\, s(t) + n^{(k)}(t) \quad (1)$$

where $\varsigma^{(k)}(t)$ and $n^{(k)}(t)$ $(k = 1, 2, \ldots, K)$ describe the fading process from the source mobile station to the destination mobile station via the kth mobile relay and the additive white

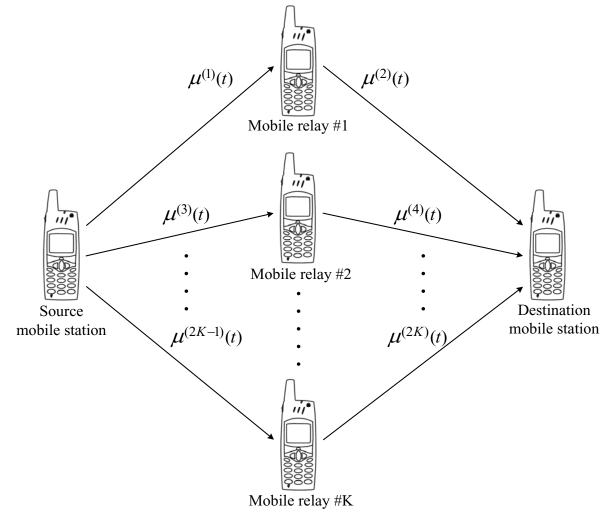

Fig. 1. The propagation scenario describing K-parallel dual-hop relay M2M fading channels.

Gaussian noise (AWGN) in the kth subchannel, respectively. The AWGN is a zero-mean stochastic process having variance $N_0/2$, where N_0 is the noise power spectral density.

In (1), we model the fading process $\varsigma^{(k)}(t)$ as a weighted zero-mean complex double Gaussian process, i.e.,

$$\varsigma^{(k)}(t) = \varsigma_1^{(k)}(t) + j\varsigma_2^{(k)}(t) = A_{\mathrm{R}^{(k)}}\, \mu^{(2k-1)}(t)\, \mu^{(2k)}(t) \quad (2)$$

for $k = 1, 2, \ldots, K$. In (2), $\mu^{(i)}(t)$ $(i = 1, 2, \ldots, 2K)$ represents a zero-mean complex circular Gaussian process having variance $2\sigma^2_{\mu^{(i)}}$. These Gaussian processes $\mu^{(i)}(t)$ are mutually independent, where each one is characterized by the classical Jakes Doppler power spectral density. The Gaussian process $\mu^{(i)}(t)$ for $i = 2k-1 = 1, 3, \ldots, (2K-1)$ corresponds to the scattered component of the subchannel between the source mobile station and the kth mobile relay. Likewise, the Gaussian process $\mu^{(i)}(t)$ for $i = 2k = 2, 4, \ldots, 2K$ describes the scattered component of the subchannel between the kth mobile relay and the destination mobile station. In (2), $A_{\mathrm{R}^{(k)}}$ is the relay gain of the kth relay. It is noteworthy that the relay gain $A_{\mathrm{R}^{(k)}}$ is only a scaling factor for the variance of the complex Gaussian process $\mu^{(i)}(t)$, i.e., $\mathrm{Var}\left\{A_{\mathrm{R}^{(k)}}\mu^{(i)}(t)\right\} = 2(A_{\mathrm{R}^{(k)}}\sigma_{\mu^{(i)}})^2$, where $i = 2, 4, \ldots, 2K$.

It is imperative to stress that in a real amplify-and-forward relay system, the total noise $n_{\mathrm{T}}^{(k)}(t)$ in the kth relay link is in fact given as follows

$$n_{\mathrm{T}}^{(k)}(t) = A_{\mathrm{R}^{(k)}}\, \mu^{(2k)}(t)\, n^{(2k-1)}(t) + n^{(2k)}(t) \quad (3)$$

for all $k = 1, 2, \ldots, K$. However, for reasons of simplicity, we have considered the total noise $n_{\mathrm{T}}^{(k)}(t)$ in the link from the source mobile station to the destination mobile station via the kth mobile relay to be AWGN, i.e., $n^{(k)}(t)$.

Finally, the total signal $r(t)$ at the destination mobile station, after combining the signals $r^{(k)}(t)$ received from the

kth diversity branch can be given as

$$r(t) \;=\; \sum_{k=1}^{K} r^{(k)}(t) = \Xi(t)\, s(t) + N(t) \tag{4}$$

under the assumption of perfect channel state information (CSI) at the destination mobile station. In (4), $\Xi(t)$ represents the fading envelope at the output of the EG combiner, which can be written as [6]

$$\Xi(t) = \sum_{k=1}^{K} \chi^{(k)}(t) \tag{5}$$

where $\chi^{(k)}(t)$ is the absolute value of $\varsigma^{(k)}(t)$. Thus, each $\chi^{(k)}(t)$ is a double Rayleigh process. In (4), $N(t)$ is the total received noise, i.e., $N(t) = \sum_{k=1}^{K} n^{(k)}(t)$.

III. PDF of a Sum of Double Rayleigh Processes

In this section, we approximate the PDF $p_{\Xi}(x)$ of a sum of double Rayleigh processes $\Xi(t)$ by making use of an orthogonal series expansion. Depending upon the purpose of use of the approximated PDF and the amount of accuracy required, one can choose from various options of such series, like, e.g., the Edgeworth series, the Gram-Charlier series, and the Laguerre series expansion [20]. In our study, we employ the Laguerre series since it provides a good enough statistical accuracy even when only the first term of this series is used [20].

The PDF $p_{\Xi}(x)$ of $\Xi(t)$ can be expressed using the Laguerre series expansion as [20]

$$p_{\Xi}(x) = \sum_{n=0}^{\infty} b_n\, e^{-x} x^{\alpha_L} L_n^{(\alpha_L)}(x) \tag{6}$$

where

$$L_n^{(\alpha_L)}(x) = e^{x} \frac{x^{(-\alpha_L)} d^n}{x! dx^n} \left[e^{(-x)} x^{n+\alpha_L} \right],\ \alpha_L > -1 \tag{7}$$

denote the Laguerre polynomials. The coefficients b_n can be given as

$$b_n = \frac{n!}{\Gamma(n+\alpha_L+1)} \int_0^{\infty} L_n^{(\alpha_L)}(x)\; p_{\Xi}(x)\, dx \tag{8}$$

where $x = y/\beta_L$ and $\Gamma(\cdot)$ is the gamma function [23].

The parameters α_L and β_L can be computed by solving the system of equations in [20, p. 21] for $b_1 = 0$ and $b_2 = 0$, which yields

$$\alpha_L = \frac{\left(\kappa_1^{\Xi}\right)^2}{\kappa_2^{\Xi}} - 1, \qquad \beta_L = \frac{\kappa_2^{\Xi}}{\kappa_1^{\Xi}} \tag{9a,b}$$

where κ_1^{Ξ} is the first and κ_2^{Ξ} is the second cumulant of the stochastic process $\Xi(t)$. It is important to understand here that the first and second cumulant of $\Xi(t)$ are merely the mean value and the variance, respectively. Mathematically, κ_1^{Ξ} and κ_2^{Ξ} can be expressed as

$$\kappa_1^{\Xi} = \sum_{k=1}^{K} \kappa_1^{\chi^{(k)}}, \qquad \kappa_2^{\Xi} = \sum_{k=1}^{K} \kappa_2^{\chi^{(k)}} \tag{10a,b}$$

where $\kappa_n^{\chi^{(k)}}$ $(n = 1, 2)$ denotes the cumulants associated with the double Rayleigh process $\chi^{(k)}(t)$. The first two cumulants of $\chi^{(k)}(t)$ are [24]

$$\kappa_1^{\chi^{(k)}} = \frac{A_{\mathrm{R}^{(k)}} \sigma_{\mu^{(2k-1)}} \sigma_{\mu^{(2k)}} \pi}{2}, \tag{11a}$$

$$\kappa_2^{\chi^{(k)}} = \frac{1}{4} A_{\mathrm{R}^{(k)}}^2 \sigma_{\mu^{(2k-1)}}^2 \sigma_{\mu^{(2k)}}^2 \left(16 - \pi^2\right). \tag{11b}$$

Given $\kappa_n^{\chi^{(k)}}$ $(n = 1, 2)$ for all $\chi^{(k)}(t)$, leads to a straightforward evaluation of κ_n^{Ξ} using (10a,b). This in turn allows an easy computation of α_L and β_L in (9a,b). Substituting the obtained quantities α_L and β_L in the Laguerre series expansion provides an exact solution for the PDF $p_{\Xi}(x)$. The first term of the series can be identified as the gamma distribution, i.e.,

$$p_{\Gamma}(x) = \frac{x^{\alpha_L}}{\beta_L^{(\alpha_L+1)} \Gamma(\alpha_L+1)} e^{-\frac{x}{\beta_L}}. \tag{12}$$

The PDF $p_{\Xi}(x)$ of $\Xi(t)$ can thus be approximated as

$$p_{\Xi}(x) \approx p_{\Gamma}(x) = \frac{x^{\alpha_L}}{\beta_L^{(\alpha_L+1)} \Gamma(\alpha_L+1)} e^{-\frac{x}{\beta_L}}. \tag{13}$$

The approximation in (13) will be used in the following section for deriving the average BEP of M-ary PSK modulation schemes over double Rayleigh processes with EGC.

IV. Performance Analysis of M-ary PSK Modulation Schemes over Double Rayleigh Fading Channels with EGC

In Section II, we derived the total received signal envelope at the output of the EG combiner, $\Xi(t)$, and the total received noise, $N(t)$. This makes it possible to define the instantaneous signal-to-noise ratio per bit $\gamma_{\mathrm{EGC}}(t)$ at the output of the EG combiner as [25], [26]

$$\gamma_{\mathrm{EGC}}(t) = \frac{\Xi^2(t)}{E\{N^2(t)\}} E_b = \frac{\Xi^2(t)}{K\, N_0} E_b \tag{14}$$

where E_b is the energy (in joules) per bit and $E\{\cdot\}$ is the expectation operator..

The average BEP P_b over the fading channel statistics at the output of the EG combiner can be given as [25]

$$P_b = \int_0^{\infty} p_{\Xi}(x)\, P_{b|\Xi}(x)\, dx \tag{15}$$

where $P_{b|\Xi}(x)$ is the BEP of M-ary PSK modulation schemes conditioned on the fading amplitudes $\{x_k\}_{k=1}^{K}$, and $x = \sum_{k=1}^{K} x_k$. It is important to keep in mind that the fading amplitudes $\{x_k\}_{k=1}^{K}$ follow the double Rayleigh distribution.

The conditional BEP $P_{b|\Xi}(x)$ of M-ary PSK modulation schemes is known to be equal to [27]

$$\begin{aligned} P_{b|\Xi}(x) &\approx \frac{a}{\log_2 M}\, Q\left(\sqrt{2g \log_2 M \gamma_{\mathrm{EGC}}(x)}\right) \\ &\approx \frac{a}{\log_2 M}\, Q\left(\sqrt{\frac{2g \log_2 M\, E_b}{K\, N_0} x^2}\right) \end{aligned} \tag{16}$$

where $M = 2^b$ with b as the number of bits per symbol and $Q(\cdot)$ is the error function [28]. The parameter a equals 1 or 2 for M-ary PSK modulation schemes when $M = 2$ or $M > 2$, respectively, whereas for all M-ary PSK modulation schemes $g = \sin^2(\pi/M)$ [19].

Substituting (13) and (16) in (15) allows us to approximate the required average BEP P_b as

$$P_b \approx \frac{a}{\log_2 M} \frac{1}{\beta_L^{(\alpha_L+1)} \Gamma(\alpha_L + 1)} \int_0^\infty x^{\alpha_L} e^{-\frac{x}{\beta_L}} \times Q\left(\sqrt{\frac{2g \log_2 M \, E_b}{K \, N_0} x^2}\right) dx \, . \quad (17)$$

V. Numerical Results

This section deals with the evaluation of the derived theoretical results and their verification. The correctness and accuracy of the approximations in (13) and (17) are validated with the help of simulations. In order to obtain the simulation results, which are the true results, the sum-of-sinusoids (SOS) concept [29] has been exploited. Meaning thereby, the SOS concept has been applied on the uncorrelated Gaussian noise processes making up the received signal envelope at the output of the EG combiner. The generalized method of exact Doppler spread (GMEDS_1) [30] has been employed for the computation of the model parameters of the channel simulator. Each Gaussian process $\mu^{(i)}(t)$ was simulated using $\text{N}_l^{(i)} = 14$ for $i = 1, 2, \ldots, 2K$ and $l = 1, 2$, where $\text{N}_l^{(i)}$ is the number of sinusoids chosen to simulate the inphase $(l = 1)$ and quadrature components $(l = 2)$ of $\mu^{(i)}(t)$. The selection of $\text{N}_l^{(i)}$ is based on the fact that the simulated distribution of $\left|\mu^{(i)}(t)\right|$ closely approximates the Rayleigh distribution when $\text{N}_l^{(i)} \geq 7$ $(l = 1, 2)$ [29]. The maximum Doppler frequencies caused by the motion of the source mobile station and the destination mobile station were set to 91 Hz. However, the maximum Doppler frequencies caused by the motion of K mobile relays were chosen to be 125 Hz. The variances $\sigma^2_{\mu^{(i)}}$ were selected from the set $\{0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75\}$ $\forall\, i = 1, 2, \ldots, 2K$. The relay gains $A_{\text{R}^{(k)}}$ were set to be unity, i.e., $A_{\text{R}^{(k)}} = A_{\text{R}} = 1$ $\forall\, k = 1, 2, \ldots, K$ unless stated otherwise. The total number of symbols used for a reliable generation of the BEP curves was 10^6.

The results presented in Figs. 2–5 show a good fitting of the approximated analytical and the exact (simulation) results. Figures 2 and 3 demonstrate the theoretical results of the PDF $p_\Xi(x)$ of $\Xi(t)$ described by (13). As an evidence of the correctness of the approximated analytical results, the simulation results obtained by evaluating the statistics of the waveforms generated by using the SOS-based channel simulator are included in Figs. 2 and 3. Keeping the relay gain A_{R} constant, the PDF $p_\Xi(x)$ of $\Xi(t)$ for a different number of diversity branches K, having the same and different variances is shown in Fig. 2 and Fig. 3, respectively. For $K = 1$ and $A_{\text{R}} = 1$, the PDF $p_\Xi(x)$ of $\Xi(t)$ reduces to the double Rayleigh distribution validating that our approximation in (13) is very accurate.

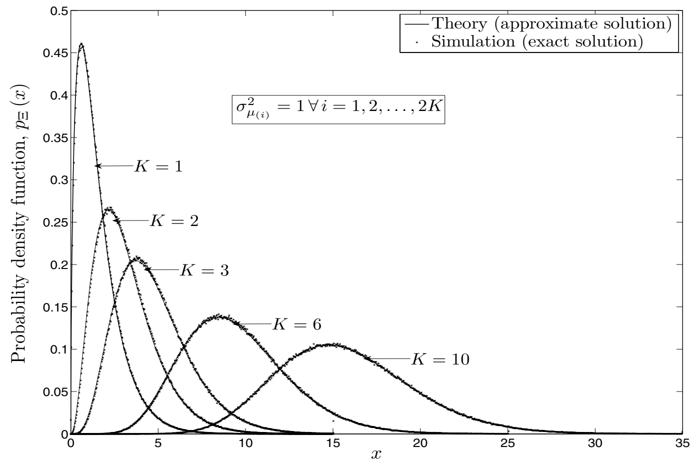

Fig. 2. The PDF $p_\Xi(x)$ of the received signal envelope $\Xi(t)$ at the output of the EG combiner for a different number of diversity branches K having the same variance.

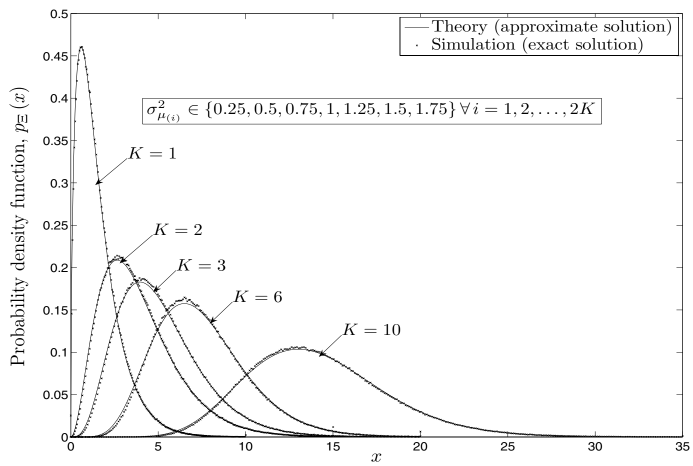

Fig. 3. The PDF $p_\Xi(x)$ of the received signal envelope $\Xi(t)$ at the output of the EG combiner for a different number of diversity branches K having different variances.

The average BEP P_b of M-ary PSK modulation schemes over double Rayleigh processes with EGC described by (15) is presented in Fig. 4. In this figure, a comparison of the average BEP P_b of quadrature PSK (QPSK), 8-PSK, and 16-PSK modulation schemes is shown and a different number diversity branches K is considered for each modulation scheme. Here, the average BEP P_b is evaluated while keeping the variances $\sigma^2_{\mu^{(i)}}$ equal to unity. For all modulation schemes, a remarkable improvement in the diversity gain can be observed when the number of diversity branches increases from $K = 1$ to $K = 6$. See, e.g., at $P_b = 10^{-3}$, a diversity gain of ≈ 26 dB can be achieved when K increases from $K = 1$ to $K = 6$. It can also be seen in Fig. 4 that the average BEP P_b curve associated with QPSK modulation shifts to the right when 8-PSK or 16-PSK modulation schemes are employed in the system. This shift that higher-order modulation schemes are more prone to errors. However, they have a higher data rate.

For the sake of completeness of our performance analysis, we have included in Fig. 5 the average BEP P_b curves when MRC is deployed at the destination mobile station. Keeping the number of diversity branches K constant, i.e., $K = 3$, the average BEP P_b of QPSK, 8-PSK, and 16-PSK modulation schemes is evaluated. By studying the curves in Fig. 5, a diversity gain of ≈ 1 dB can be observed when MRC is used instead of EGC. This gain however comes at the cost of increased complexity of the receiver.

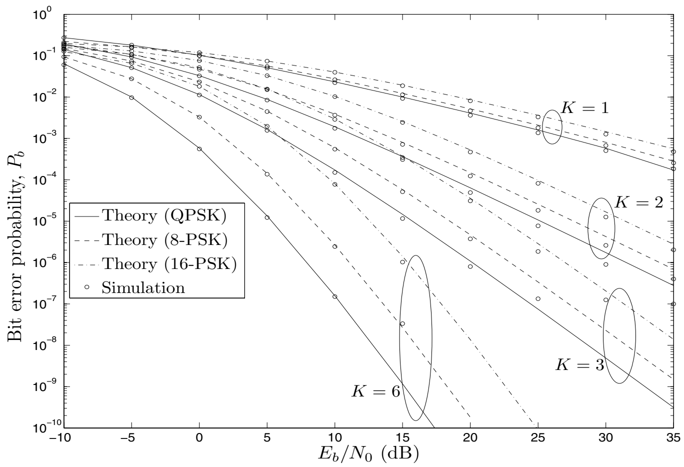

Fig. 4. The average BEP P_b of M-ary PSK modulation schemes over double Rayleigh processes with EGC.

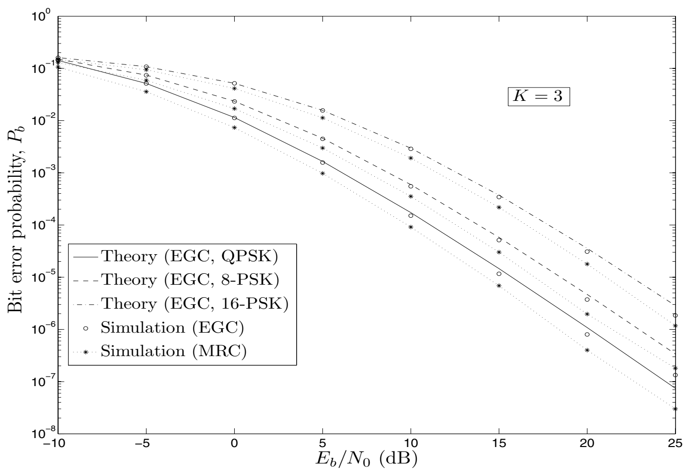

Fig. 5. A comparison of the average BEP P_b of M-ary PSK modulation schemes over double Rayleigh processes with EGC and MRC.

VI. Conclusion

In this article, we have analyzed the performance of M-ary PSK modulation schemes over M2M fading channels with EGC in a dual-hop amplify-and-forward relay network. The narrowband M2M fading channels are modeled assuming NLOS propagation conditions. It is further assumed that there exist K diversity branches between the source mobile station and the destination mobile station. The performance of M-ary PSK modulation schemes is studied by computing the average BEP. A simple analytical expression for the average BEP of M-ary PSK modulation schemes over double Rayleigh fading channels with EGC is derived. The derivation of this expression however, requires the knowledge of the PDF of the received signal envelope at the output of the EG combiner. Here, the output of the EG combiner is modeled as a sum of K independent, but not necessarily identical double Rayleigh fading channels. Furthermore, exploiting the properties of the Laguerre series expansion made it possible to approximate the PDF of the sum of double Rayleigh processes by a gamma distribution. Utilizing this approximation of the target PDF allowed us to evaluate with ease the required average BEP. The validity of all the obtained analytical expressions is confirmed by simulations. Note that the simulation results are the true results here. We have included in our discussion the results demonstrating the influence of the number of diversity branches K on the average BEP of different M-ary PSK modulation schemes. These results illustrate a remarkable improvement in the diversity gain as the number of diversity branches K increases.

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