Analysis of Differentially Modulated Cooperative Communications over Asymmetric Fading Channels

(Invited Paper)

Sara AlMaeeni[‡], Paschalis C. Sofotasios[*,§], Sami Muhaidat[*], and George K. Karagiannidis[¶]

[‡]Space Engineering Department, Mohammed Bin Rashid Space Centre, P. O. Box: 211833, Dubai, United Arab Emirates, (e-mail: sara.almaeeni@mbrsc.ae)

[*]Department of Electrical and Computer Engineering, Khalifa University of Science and Technology, P. O. Box 127788, Abu Dhabi, United Arab Emirates (e-mail: paschalis.sofotasios; sami.muhaidat@ku.ac.ae)

[§]Department of Electronics and Communications Engineering, Tampere University of Technology, FI-33101, Tampere, Finland (e-mail: {paschalis.sofotasios; mikko.e.valkama}@tut.fi)

[¶]Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, GR-51124, Thessaloniki, Greece (e-mail: geokarag@auth.gr)

***Abstract*—Differential modulation has largely re-attracted the attention of academia and industry due to its advantages relating to simple implementation and no need for knowledge of channel state information. The present work analyzes the average bit error rate performance of dual-hop cooperative systems over generalized multipath fading conditions. The considered system is differentially modulated and is assumed to operate based on the amplify-and-forward relaying protocol. Therefore, the main advantage of the considered set up is that it does not require any channel state information neither at the relay nor at the destination nodes. Novel closed-form expressions are derived for the end-to-end error rate under asymmetric generalized multipath fading conditions, which are encountered in realistic wireless communication scenarios. These expressions are subsequently employed in quantifying the effect of generalized fading conditions on the achieved bit error rate performance. It is shown that the impact of multipath fading and shadowing effects is detrimental at both high and low signal-to-noise ratio regimes as the corresponding deviations are often close to an order of magnitude. The incurred difference is also significantly different than the conventional Rayleigh fading conditions, which verifies that accurate channel characterization is of paramount importance in the effective design of conventional and emerging wireless technologies. In addition, it indicates that differential modulation can be a suitable modulation scheme for relay systems, under certain conditions, since it can provide adequate performance at a reduced implementation complexity.**

I. Introduction

Cooperative communications have received significant attention due to their capability to ensure increased reliability, network coverage and reduced power consumption in emerging wireless communication systems [1]. To this end, different relaying strategies have been proposed during the past years demonstrating a substantial improvement of the overall performance and robustness of communication systems. The most distinct and widely considered strategies have been the decode-and-forward (DF), or regenerative, relaying strategy and the amplify-and-forward (AF), or non-regenerative, relaying strategy. Particularly the latter has been considered extensively in the context of various communication scenarios thanks to its relatively simple structure that is based on the amplification of received signals in the involved relays, by certain amplification factor, and their subsequent forwarding to the destination [2].

However, it is recalled that fading phenomena create detrimental effects on the performance of conventional and emerging communication systems since they distort radio communication signals during wireless propagation. Based on this, the envelope of wireless channels experiences different fluctuations that have been attempted to be characterized accurately by various statistical models [3]–[11]. Motivated by this, the performance of AF relay systems was analyzed in numerous reported contributions taking into consideration the effects of small-scale and large-scale fading, as well as challenges relating to optimal power allocation strategies and criteria [2], [12] $-$ and the references therein.

However, it has been widely known that Rayleigh and even Nakagami$-m$ fading models provide poor characterization of multipath fading. As a consequence, the determined error rates typically correspond to largely deviated signal-to-noise ratio (SNR) levels, often over an order of magnitude, which corresponds to wasted energy resources and/or increased system complexity and cost. One effective solution to the accurate modeling of multipath fading in non-line of sight (NLOS) communication scenarios was the introduction of the $\eta - \mu$ distribution, which constitutes a rather flexible fading model, particularly in scenarios where the scatterers surfaces are spatially correlated [14]. The accuracy of this model has been verified by its capability to provide excellent fit to corresponding results from extensive field measurement results, while its remarkable flexibility is based on its named parameters, η and μ. Furthermore, it includes as special cases the widely used Rayleigh, Nakagami$-m$ and Hoyt fading

978-1-5386-4609-0/18/$31.00 ©2018 IEEE

distributions [13]. To this effect, the authors in [15] determined the average bit error rate (ABER) for a dual-hop AF system under non-identical fading conditions that are assumed to be mixed $\eta-\mu$ and $\kappa-\mu$ distributed. Likewise, the contribution in [16] analyzes the performance of AF systems over extended generalized-$\mathcal{K}$ (EGK) fading channels, that have been shown capable of accounting for both multipath fading and shadowing effects. In addition, the performance of non-regenerative half-duplex relay systems over mixed generalized multipath fading channels was analyzed in [18], whereas the effects of generalized asymmetric fading conditions on full-duplex regenerative cooperative systems was investigated in [19], along with a comprehensive energy efficiency analysis.

Nevertheless, the reported investigations were typically based on the usual theoretical assumption of full or partial knowledge of channel state information (CSI). However, in practical implementation and realization of wireless communication systems, correct and accurate estimation of CSI is a rather challenging and cumbersome task, particularly under the effect of multipath fading and shadowing. Furthermore, the estimation of the corresponding CSI requires sophisticated hardware requirements which ultimately increase the overall corresponding power consumption and transceiver complexity. This is, in fact, a critical issue in large scale emerging wireless systems, which are largely characterized by stringent requirements and particularly increased overheads. In this context, it is recalled that differential phase shift keying (DPSK) modulation is an effective solution to avoid the requirement of CSI, while it has been shown capable of providing robustness against phase ambiguities, particularly in fast-fading channels. Based on this, several analyses have been focused on investigating and improving the performance of differentially modulated relay systems [20]–[25]. Yet, all reported results are limited to either conventional symmetric fading scenarios and/or the simplistic cases of Rayleigh and Nakagami$-m$ multipath fading conditions, which have been shown to exhibit a rather poor modeling performance.

Motivated by the above, the present work is devoted to the error analysis of differentially modulated relay systems over asymmetric generalized fading conditions. To this end, the statistics of the end-to-end signal-to-noise ratio (SNR) are utilized in the derivation of a novel closed-form expression for the corresponding average bit-error-rate (BER) of DPSK based AF systems over $\eta-\mu$ fading channels in the source-to-relay and relay-to-destination links. On the contrary, the aforementioned fading asymmetry is realized by assuming that the source-to-destination path experiences K_G fading conditions. Given that the K_G distributed fading model is based on the composite Nakagami$-m$/gamma distribution, both the effects of multipath fading and shadowing are taken into account. In fact, such conditions are practically encountered in realistic communication scenarios since the presence of shadowing is standard and even dominant in the source-to-destination link due to the increased distance compared to the other two links. Moreover, the composite nature of the K_G model also includes the cases of only multipath fading or shadowing conditions and thus, it can lead to the development of useful insights on the impact of these effects on the overall system performance.

The derived analytic expressions are given in terms of known elementary and special functions, which are included as built-in functions in popular software packages such as MATLAB, MAPLE and MATHEMATICA. Furthermore, the algebraic representation of the offered analytic results is long but tractable, which renders them convenient to handle both analytically and numerically. Capitalizing on this, the offered results are employed in quantifying the effect of generalized fading on the system performance. It is shown that generalized fading phenomena have detrimental effects on the considered AF systems at both low and high SNR regimes. Also, the shadowing effects are particularly detrimental and non-negligible as they differ from conventional Rayleigh fading cases by at least an order of magnitude across all SNR regimes. However, selecting a DPSK modulation scheme appears to provide adequate performance even at severe fading conditions. Based on this, it can be considered an effective modulation scheme particularly in cases of efficient and low complexity wireless communication systems, which will be encountered in numerous future wireless applications of interest.

The remainder of the paper is organized as follows: Section II describes the considered system and channel models. Then, Section III derives the novel analytic expressions for the corresponding average probability of error under asymmetric fading conditions, whereas the corresponding results and discussions are provided in Section IV. Finally, the paper is concluded with useful remarks in Section V.

II. System and Channel Models

A. System Model

We consider a dual-hop cooperative system, where the source node, S, broadcasts a sequence of symbols, $x(n)$, to the relay terminal R. The communication in the considered setup is realized in two time-slots; during the first time-slot, the information bits are differentially encoded as

$$x(n) = x(n-1)s(n), \quad n = 1, ..., N \tag{1}$$

where $s(n) \in \{\pm 1\}$ are the information bits, $x(0) = 1$ and N is the number of bits within the frame. Based on this, the received signals at the relay are represented as

$$y_R(n) = h_{S,R}x(n) + w_R(n) \tag{2}$$

where $h_{S,R}$ is the channel coefficient in the source-relay $(S-R)$ link and w_R denotes the corresponding additive white Gaussian noise (AWGN) with zero mean and variance equal to N_0. In the second time-slot, the received signal at the relay, $y_R(n)$, is amplified according to [24], namely

$$y_R^{'}(n) = \frac{y_R(n)}{\sqrt{N_0 + \sigma^2_{S,R}}}. \tag{3}$$

Finally, the signal received at the destination during the second time-slot is represented as

$$y(n) = h_{R,D}y_r^{'}(n) + w_D(n) \tag{4}$$

where $h_{R,D}$ denote the channel coefficient in the relay-destination $(R-D)$ link. To this effect, the received signal is detected as

$$\hat{y}(n)=\text{sign}\left\{\text{Re}\left\{y(n)\right\}\right\}. \tag{5}$$

B. Channel Model

It is recalled here that the SNR probability density function (PDF) of the $\eta-\mu$ fading distribution is expressed as [14]

$$p_\gamma(\gamma)=\alpha\gamma^{\mu-1/2}\text{exp}\left(-\frac{2\mu h\gamma}{\overline{\gamma}}\right)I_{\mu-\frac{1}{2}}\left(\frac{2\mu H\gamma}{\overline{\gamma}}\right) \tag{6}$$

where

$$\alpha=\frac{2\sqrt{\pi}\mu^{\mu+\frac{1}{2}}h^{\mu}}{\Gamma(\mu)H^{\mu-\frac{1}{2}}\overline{\gamma}^{\mu+\frac{1}{2}}} \tag{7}$$

with $\Gamma(\cdot)$ and $I_\nu(\cdot)$ denoting the Euler gamma function and the modified Bessel function of the first kind with order ν, respectively. Also, $\mu>0$ is related to the number of multipath clusters and $\overline{\gamma}$ denotes the corresponding average SNR. Furthermore, the parameters h and H are expressed according to the two formats[1] of the distribution, which are listed below [14]:

- Format I: $h=\frac{2+\eta^{-1}+\eta}{4}$ and $H=\frac{\eta^{-1}-\eta}{4}$, where $0<\eta<\infty$ represents the power ratio between the in-phase and quadrature scattered waves in each multi-path cluster.
- Format II: $h=\frac{1}{1-\eta^2}$ and $H=\frac{\eta}{1-\eta^2}$, where $-1<\eta<1$ represents the correlation coefficient between the in-phase and quadrature scattered waves in each multi-path cluster.

III. Average BER Analysis

A. End to end Statistics and $\overline{P}_{e1}$

As a already mentioned, the considered analysis assumes $\eta-\mu$ multipath fading in the $S-D$ and $R-D$ links. In this context, the equivalent instantaneous SNR of the relay link is given by [23]–[26]

$$\gamma_{\text{eq}}=\frac{\gamma_{sr}\gamma_{rd}}{\overline{\gamma}_{sr}+\gamma_{rd}+1} \tag{8}$$

where γ_{ij} and $\overline{\gamma}_{ij}$ denote the instantaneous and average SNRs in each respective link. Based on (8), the PDF of γ_{eq} in the considered scenario can be derived, namely [24]

$$\begin{aligned}p(\gamma_{\text{eq}})=&A\int_0^\infty\frac{\left(\bar{\gamma}_{\text{sr}}+\gamma_{\text{rd}}+1\right)^{\mu_{\text{sr}}+\frac{1}{2}}}{\gamma_{\text{rd}}^{-\mu_{\text{rd}}+\mu_{\text{sr}}+1}}e^{-\frac{\left(\bar{\gamma}_{\text{sr}}^{-1}+1\right)\left(2\gamma_{\text{eq}}h_{\text{sr}}\mu_{\text{sr}}\right)}{\gamma_{\text{rd}}}}\\&\times I_{\mu_{\text{sr}}-\frac{1}{2}}\left(\frac{\frac{2\gamma_{\text{eq}}H_{\text{sr}}\mu_{\text{sr}}}{\bar{\gamma}_{\text{sr}}}\left(\bar{\gamma}_{\text{sr}}+\gamma_{\text{rd}}+1\right)}{\gamma_{\text{rd}}}\right)e^{-\frac{2h_{\text{rd}}\gamma_{\text{rd}}\mu_{\text{rd}}}{\bar{\gamma}_{\text{rd}}}}\\&\times I_{\mu_{\text{rd}}-\frac{1}{2}}\left(\frac{2\mu_{\text{rd}}H_{\text{rd}}\gamma_{\text{rd}}}{\bar{\gamma}_{\text{rd}}}\right)d\gamma_{\text{rd}}.\end{aligned} \tag{9}$$

[1]Format I and Format II of the $\eta-\mu$ distribution are also known as $\eta-\mu$ and $\lambda-\mu$ fading models, respectively. However, the present analysis considers the two different cases in the standard unified manner, as commonly described by the two formats.

The above representation is expressed in closed-form by [26, eq. (5)], namely

$$\begin{aligned}p(\gamma_{\text{eq}})=&A\sum_{j=0}^{\mu_{\text{sr}}-1}\sum_{l=0}^{\mu_{\text{sr}}-j}\sum_{i=0}^{\mu_{\text{rd}}-1}\\&\times\frac{\binom{\mu_{\text{sr}}-j}{l}\left(i+\mu_{\text{rd}}-1\right)!\left(j+b_2\right)!e^{b}\left(\frac{2H_{\text{rd}}\mu_{\text{rd}}}{\bar{\gamma}_{\text{rd}}}\right)^{-i-\frac{1}{2}}}{\pi i!j!b^{(j+\frac{1}{2})}2^{i+j}\left(-i+\mu_{\text{rd}}-1\right)!\binom{\mu_{\text{sr}}-j}{l}\left(-j+b_2\right)!}\\&\times\left\{\frac{(-1)^{i+j}K_{j+l+z-i}\left(4\sqrt{v_2\left(h_{\text{sr}}-H_{\text{sr}}\right)\left(h_{\text{rd}}-H_{\text{rd}}\right)}\right)}{e^{-w}\left(\frac{v_1\left(h_{\text{sr}}-H_{\text{sr}}\right)}{h_{\text{rd}}-H_{\text{rd}}}\right)^{\frac{i-j-l-z}{2}}}\right.\\&+\frac{(-1)^{j+\mu_{\text{rd}}}K_{j+l+z-i}\left(4\sqrt{v_2\left(h_{\text{sr}}-H_{\text{sr}}\right)\left(h_{\text{rd}}+H_{\text{rd}}\right)}\right)}{e^{-w}\left(\frac{v_1\left(h_{\text{sr}}-H_{\text{sr}}\right)}{h_{\text{rd}}+H_{\text{rd}}}\right)^{\frac{i-j-l-z}{2}}}\\&+\frac{(-1)^{\mu_{\text{sr}}+i}K_{j+l+z-i}\left(4\sqrt{v_2\left(h_{\text{sr}}+H_{\text{sr}}\right)\left(h_{\text{rd}}-H_{\text{rd}}\right)}\right)}{e^{w}\left(\frac{v_1\left(h_{\text{sr}}+H_{\text{sr}}\right)}{h_{\text{rd}}-H_{\text{rd}}}\right)^{\frac{i-j-l-z}{2}}}\\&\left.+\frac{(-1)^{\mu_{\text{rd}}+\mu_{\text{sr}}}K_{j+l+z-i}\left(4\sqrt{v_2\left(h_{\text{sr}}+H_{\text{sr}}\right)\left(h_{\text{rd}}+H_{\text{rd}}\right)}\right)}{e^{w}\left(\frac{v_1\left(h_{\text{sr}}+H_{\text{sr}}\right)}{h_{\text{rd}}+H_{\text{rd}}}\right)^{\frac{j+l+z-i}{2}}}\right\}\end{aligned} \tag{10}$$

where

$$A=\frac{4\pi\mu_{\text{rd}}^{\mu_{\text{rd}}+\frac{1}{2}}\mu_{\text{sr}}^{\mu_{\text{sr}}+\frac{1}{2}}h_{\text{rd}}^{\mu_{\text{rd}}}h_{\text{sr}}^{\mu_{\text{sr}}}\gamma_{\text{eq}}^{\mu_{\text{sr}}-\frac{1}{2}}e^{\left(-\frac{2\gamma_{\text{eq}}h_{\text{sr}}\mu_{\text{sr}}}{\bar{\gamma}_{\text{sr}}}\right)}}{H_{\text{rd}}^{\mu_{\text{rd}}-\frac{1}{2}}H_{\text{sr}}^{\mu_{\text{sr}}-\frac{1}{2}}\Gamma\left(\mu_{\text{rd}}\right)\Gamma\left(\mu_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}^{\mu_{\text{rd}}+\frac{1}{2}}\bar{\gamma}_{\text{sr}}^{\mu_{\text{sr}}+\frac{1}{2}}} \tag{11}$$

and

$$f=\frac{\mu_{\text{sr}}\bar{\gamma}_{\text{rd}}\left(\bar{\gamma}_{\text{sr}}+1\right)}{\mu_{\text{rd}}\bar{\gamma}_{\text{sr}}}, \tag{12}$$

$$w=\frac{2\gamma_{\text{eq}}H_{\text{sr}}\mu_{\text{sr}}}{\bar{\gamma}_{\text{sr}}}, \tag{13}$$

$$b=\frac{2\gamma_{\text{eq}}H_{\text{sr}}\mu_{\text{sr}}}{\bar{\gamma}_{\text{sr}}} \tag{14}$$

with $v_1=f\gamma_{\text{eq}}$, $v_2=n\gamma_{\text{eq}}$, $b_1=(\bar{\gamma}_{\text{sr}}+1)$, $b_2=\mu_{\text{sr}}-1$, and $z=\mu_{\text{rd}}-\mu_{\text{sr}}$. Furthermore $K_{.}(.)$ denotes the modified Bessel function of the second kind [27].

Capitalizing on the derivation of the PDF of $p(\gamma_{eq})$ in (10), the average BER was derived for the case of $\eta-\mu$ fading conditions in the $S-D$ and $R-D$ links[2], which is expressed by the closed-form representation in (15), at the top of the next page [26], where

$$f_2=\frac{2\mu_{\text{sr}}\left(h_{\text{sr}}-H_{\text{sr}}\right)}{\bar{\gamma}_{\text{sr}}}, \tag{16}$$

$$f_3=\frac{2\mu_{\text{sr}}\left(h_{\text{sr}}+H_{\text{sr}}\right)}{\bar{\gamma}_{\text{sr}}} \tag{17}$$

and

$$n=\frac{\mu_{\text{rd}}\mu_{\text{sr}}\left(\bar{\gamma}_{\text{sr}}+1\right)}{\bar{\gamma}_{\text{rd}}\bar{\gamma}_{\text{sr}}} \tag{18}$$

with ${}_1F_1\left(.;.;.\right)$ denoting the Kummer confluent hypergeometric function [27].

[2]This scenario assumes absence of a $S-D$ link.

$$
\begin{aligned}
\overline{P}_{e1}^{\eta-\mu|\eta-\mu} &= A \sum_{j=0}^{\mu_{\mathrm{sr}}-1} \sum_{l=0}^{\mu_{\mathrm{sr}}-j} \sum_{i=0}^{\mu_{\mathrm{rd}}-1} \frac{b_1^{-j-l+\mu_{\mathrm{sr}}} \binom{\mu_{\mathrm{sr}}-j}{l} (i+\mu_{\mathrm{rd}}-1)!\,(j+b_2)! e^{b} \left(\frac{2H_{\mathrm{rd}}\mu_{\mathrm{rd}}}{\bar{\gamma}_{\mathrm{rd}}}\right)^{-i-\frac{1}{2}}}{\pi i! j! b^{(j+\frac{1}{2})} 2^{i+j} (-i+\mu_{\mathrm{rd}}-1)! b_1^{-j-l+\mu_{\mathrm{sr}}} \binom{\mu_{\mathrm{sr}}-j}{l} (-j+b_2)!} \\
&\times \left\{ \frac{(-1)^{i+j}}{2} \frac{\Gamma(-i+j+l+z)\Gamma(\mu_{\mathrm{sr}}-j)\ {}_1F_1\left(\mu_{\mathrm{sr}}-j; 1-(i+j+l+z); \frac{4n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{f_2+1}\right)}{\left(\frac{f(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{h_{\mathrm{rd}}-H_{\mathrm{rd}}}\right)^{\frac{i-j-l-z}{2}} 2^{-(i-j-l-z-1)} (f_2+1)^{-j+\mu_{\mathrm{sr}}} \left(n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})\right)^{\frac{(-i+j+l+z)}{2}}} \right. \\
&\left. + \frac{\Gamma(i-j-l-z)\Gamma(i-j-l-z+l+\mu_{\mathrm{rd}})\ {}_1F_1\left(-i+l+\mu_{\mathrm{rd}}; -i+j+l+z+1; \frac{4n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{f_2+1}\right)}{2^{i-j-l-z+1}(f_2+1)^{-i+l+\mu_{\mathrm{rd}}} \left(n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})\right)^{\frac{-(-i+j+l+z)}{2}}} \right\} \\
&\times \left\{ \frac{(-1)^{j+\mu_{\mathrm{rd}}}}{2} \frac{\Gamma(-i+j+l+z)\Gamma(\mu_{\mathrm{sr}}-j)\ {}_1F_1\left(\mu_{\mathrm{sr}}-j; -i+j+l+z+1; \frac{4n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{f_2+1}\right)}{\left(\frac{f(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{h_{\mathrm{rd}}+H_{\mathrm{rd}}}\right)^{\frac{i-j-l-z}{2}} 2^{-(i-j-l-z-1)} (f_2+1)^{-j+\mu_{\mathrm{sr}}} \left(n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})\right)^{\frac{-i+j+l+z}{2}}} \right. \\
&\left. + \frac{\Gamma(i-j-l-z)\Gamma(i-j-l-z+l+\mu_{\mathrm{rd}})\ {}_1F_1\left(-i+l+\mu_{\mathrm{rd}}; -i+j+l+z+1; \frac{4\mu_{\mathrm{rd}}\mu_{\mathrm{sr}}(\bar{\gamma}_{\mathrm{sr}}+1)(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})}{2\mu_{\mathrm{sr}}\bar{\gamma}_{\mathrm{rd}}(h_{\mathrm{sr}}-H_{\mathrm{sr}})+\bar{\gamma}_{\mathrm{rd}}\bar{\gamma}_{\mathrm{sr}}}\right)}{2^{i-j-l-z+1}(f_2+1)^{-i+l+\mu_{\mathrm{rd}}} \left(n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}-H_{\mathrm{sr}})\right)^{\frac{-(-i+j+l+z)}{2}}} \right\} \\
&\times \left\{ \frac{(-1)^{i+\mu_{\mathrm{sr}}}}{2} \frac{\Gamma(-i+j+l+z)\Gamma(\mu_{\mathrm{sr}}-j)\ {}_1F_1\left(\mu_{\mathrm{sr}}-j; 1-(i+j+l+z); \frac{4n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{f_3+1}\right)}{\left(\frac{f(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{h_{\mathrm{rd}}-H_{\mathrm{rd}}}\right)^{\frac{i-j-l-z}{2}} 2^{-(i-j-l-z-1)} (f_3+1)^{-j+\mu_{\mathrm{sr}}} \left(n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})\right)^{\frac{-i+j+l+z}{2}}} \right. \\
&\left. + \frac{\Gamma(i-j-l-z)\Gamma(i-j-l-z+l+\mu_{\mathrm{rd}})\ {}_1F_1\left(-i+l+\mu_{\mathrm{rd}}; -i+j+l+z+1; \frac{4n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{4(f_3+1)}\right)}{2^{i-j-l-z+1}(f_3+1)^{-i+l+\mu_{\mathrm{rd}}} \left(n(h_{\mathrm{rd}}-H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})\right)^{\frac{-(-i+j+l+z)}{2}}} \right\} \\
&\times \left\{ \frac{(-1)^{\mu_{\mathrm{rd}}+\mu_{\mathrm{sr}}}}{2} \frac{\Gamma(-i+j+l+z)\Gamma(\mu_{\mathrm{sr}}-j)\ {}_1F_1\left(\mu_{\mathrm{sr}}-j; 1-(-i+j+l+z); \frac{4n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{f_3+1}\right)}{\left(\frac{f(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{h_{\mathrm{rd}}+H_{\mathrm{rd}}}\right)^{\frac{i-j-l-z}{2}} 2^{-(i-j-l-z-1)} (f_3+1)^{-j+\mu_{\mathrm{sr}}} \left(n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})\right)^{\frac{-i+j+l+z}{2}}} \right. \\
&\left. + \frac{\Gamma(i-j-l-z)\Gamma(i-j-l-z+l+\mu_{\mathrm{rd}})\ {}_1F_1\left(-i+l+\mu_{\mathrm{rd}}; -i+j+l+z+1; \frac{4n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})}{f_3+1}\right)}{2^{i-j-l-z+1}(f_3+1)^{-i+l+\mu_{\mathrm{rd}}} \left(n(h_{\mathrm{rd}}+H_{\mathrm{rd}})(h_{\mathrm{sr}}+H_{\mathrm{sr}})\right)^{\frac{-i+j+l+z}{2}}} \right\}
\end{aligned} \tag{15}
$$

B. End to end Average BER under Asymmetric Fading

Having derived P_{e1} assists in the derivation of the end-to-end average BER in the presence of a direct link. To this end, we consider the case of composite fading channels, which are encountered in practical communication scenarios and in the present investigation characterize the asymmetric fading in the considered set up. It is recalled that composite fading channels account for the simultaneous occurrence of multi-path fading and shadowing effects, that in this analysis are assumed to follow the K_G distribution. This model consists of Nakagami-m distribution, which accounts for multipath fading, and Gamma distribution, which accounts for shadowing [13]. Also, its algebraic representation is rather tractable, which renders it convenient to handle both analytically and numerically.

Based on the above, the end-to-end average BER, $\overline{P}_{e2}^{\eta-\mu|\eta-\mu|\mathrm{K_G}}$, is derived in the following theorem.

Theorem 1. *For $\{\overline{\gamma}_{sr}, \overline{\gamma}_{rd}, \overline{\gamma}_{sd}\} \in \mathbb{R}^+$, $\{\mu_{sr}, \mu_{rd}, \mu_{sd}\} \in \mathbb{N}$ and $\{\eta_{sr}, \eta_{rd}, k, m\} \in \mathbb{R}^+$, the average end-to-end BER of the considered system AF system experiencing $\eta-\mu$ fading conditions in the S-R and R-D wireless links and K_G composite multipath/shadowing fading conditions in the S-D direct link is expressed as*

$$
\begin{aligned}
\overline{P}_{e2}^{\eta-\mu|\eta-\mu|\mathrm{K_G}} &= \overline{P}_{e1}^{\eta-\mu|\eta-\mu} \mathcal{I}_1^{K_G} + \frac{1}{4} \overline{P}_{e1}^{\eta-\mu|\eta-\mu} \mathcal{I}_2^{K_G} \\
&+ \frac{1}{8} \mathcal{I}_3^{\eta-\mu|\eta-\mu} \mathcal{I}_4^{K_G}
\end{aligned} \tag{19}
$$

where

$$
\begin{aligned}
\mathcal{I}_1^{\mathrm{K_G}} = \mathcal{I}_4^{\mathrm{K_G}} &= \frac{k^k m^k \Gamma(m-k)}{2\overline{\gamma}_{sd}^{k} \Gamma(m)}\ {}_1F_1\left(k; 1+k-m; \frac{k\,m}{\overline{\gamma}_{sd}}\right) \\
&+ \frac{k^m m^m \Gamma(k-m)}{2\overline{\gamma}_{sd}^{m} \Gamma(k)}\ {}_1F_1\left(m; 1+m-k; \frac{k\,m}{\overline{\gamma}_{sd}}\right)
\end{aligned} \tag{20}
$$

and

$$
\begin{aligned}
\mathcal{I}_2^{\mathrm{K_G}} &= \frac{k^{k+1} m^k \Gamma(m-k)}{2\overline{\gamma}_{sd}^{k} \Gamma(m)}\ {}_1F_1\left(k+1; k-m+1; \frac{k\,m}{\overline{\gamma}_{sd}}\right) \\
&+ \frac{k^m m^{m+1} \Gamma(m-k)}{2\overline{\gamma}_{sd}^{m} \Gamma(k)}\ {}_1F_1\left(m+1; m-k+1; \frac{k\,m}{\overline{\gamma}_{sd}}\right)
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
\mathcal{I}_3^{\eta-\mu|\eta-\mu} = & \sum_{j=0}^{\mu_{\rm sr}-1} \sum_{l=0}^{\mu_{\rm sr}-j} \sum_{i=0}^{\mu_{\rm rd}-1} \frac{\binom{\mu_{sr}-j}{l}\Gamma(\mu_{sr}+j)(\bar{\gamma}_{\rm sr}+1)^{\mu_{sr}-j-l}\Gamma(\mu_{rd}+i)\frac{\mu_{\rm sr}\bar{\gamma}_{\rm rd}(\bar{\gamma}_{\rm sr}+1)}{\mu_{\rm rd}\bar{\gamma}_{\rm sr}}^{\frac{z+l+j-i}{2}}}{i!j!\pi\Gamma(\mu_{rd}-i)\Gamma(\mu_{sr}-j)\left(\frac{\mu_{rd}H_{rd}}{\bar{\gamma}_{rd}}\right)^{i+\frac{1}{2}} 2^{2j+2i+1}\left(\frac{w}{2}\right)^{j+\frac{1}{2}}} \\
& \times \left\{ (-1)^{j+i}\left(\frac{h_{sr}-H_{sr}}{h_{rd}-H_{rd}}\right)^{\frac{z+l+j-i}{2}} \frac{2^{i-j}\Gamma(i-j-l-z)\Gamma\left(-i+l+b_1\right)}{2^{l+z_1}4\sqrt{m_1}^{i-j-l-z}(b-w+1)^{-i+l+b_1}} {}_1F_1\left(-i+l+b_1; -i+j+l+z_1; \frac{4\sqrt{m_1}^2}{c-4w}\right) \right. \\
& \left. + \quad \frac{\Gamma\left(-j+\mu_{\rm sr}+1\right)\Gamma(-i+j+l+z)}{2^{i-j-l-z_1}(1-wb)^{-j+\mu_{\rm sr}+1}4\sqrt{m_1}^{-i+j+l+z}} {}_1F_1\left(-j+\mu_{\rm sr}+1; i-j-l-z_1; \frac{4\sqrt{m_1}^2}{c-4w}\right) \right\} \\
& + \left\{ (-1)^{\mu_{rd}+i}\left(\frac{h_{sr}-H_{sr}}{h_{rd}+H_{rd}}\right)^{\frac{z+l+j-i}{2}} \frac{2^{i-j}\Gamma(i-j-l-z)\Gamma\left(-i+l+b_1\right)}{2^{l+z_1}4\sqrt{m_2}^{i-j-l-z}(b-w+1)^{-i+l+b_1}} {}_1F_1\left(-i+l+b_1; -i+j+l+z_1; \frac{4\sqrt{m_2}^2}{c-4w}\right) \right. \\
& \left. + \quad \frac{\Gamma\left(-j+\mu_{\rm sr}+1\right)\Gamma(-i+j+l+z)}{2^{i-j-l-z_1}4\sqrt{m_2}^{-i+j+l+z}(b-w+1)^{-j+\mu_{\rm sr}+1}} {}_1F_1\left(-j+\mu_{\rm sr}+1; i-j-l-z_1; \frac{4\sqrt{m_2}^2}{c-4w}\right) \right\} \\
& + \left\{ (-1)^{\mu_{sr}+i}\left(\frac{h_{sr}+H_{sr}}{h_{rd}-H_{rd}}\right)^{\frac{z+l+j-i}{2}} \frac{2^{i-j}\Gamma(i-j-l-z)\Gamma\left(-i+l+b_1\right)}{2^{l+z_1}4\sqrt{m_3}^{i-j-l-z}(wb+1)^{-i+l+b_1}} {}_1F_1\left(-i+l+b_1; -i+j+l+z_1; \frac{4\sqrt{m_3}^2}{c+4w}\right) \right. \\
& \left. + \quad \frac{\Gamma\left(-j+\mu_{\rm sr}+1\right)\Gamma(-i+j+l+z)}{2^{i-j-l-z_1}4\sqrt{m_3}^{-i+j+l+z}(b+w+1)^{-j+\mu_{\rm sr}+1}} {}_1F_1\left(-j+\mu_{\rm sr}+1; i-j-l-z_1; \frac{4\sqrt{m_3}^2}{c+4w}\right) \right\} \\
& + \left\{ (-1)^{\mu_{sr}+\mu_{rd}}\left(\frac{h_{sr}+H_{sr}}{h_{rd}+H_{rd}}\right)^{\frac{z+l+j-i}{2}} \frac{2^{i-j}\Gamma(i-j-l-z)\Gamma\left(-i+l+b_1\right)}{2^{l+z_1}4\sqrt{m_4}^{i-j-l-z}(b+w+1)^{-i+l+b_1}} {}_1F_1\left(-i+l+b_1; -i+j+l+z_1; \frac{4\sqrt{m_4}^2}{c+4w}\right) \right. \\
& \left. + \quad \frac{\Gamma\left(-j+\mu_{\rm sr}+1\right)\Gamma(-i+j+l+z)}{2^{i-j-l-z_1}4\sqrt{m_4}^{-i+j+l+z}(b+w+1)^{-j+\mu_{\rm sr}+1}} {}_1F_1\left(-j+\mu_{\rm sr}+1; i-j-l-z_1; \frac{4\sqrt{m_4}^2}{c+4w}\right) \right\}
\end{aligned} \tag{22}
$$

with k and m denoting the shape and fading parameters of the distribution respectively. In addition, the $\mathcal{I}_3^{\eta-\mu|\eta-\mu}$ term is given in (22)*, at the top of the page.*

Proof. It is recalled that the end-to-end average BER in the considered cooperative set-up is generically expressed as [24]

$$
\overline{P}_{e2}^{\,\rm gen} = \int_0^\infty \int_0^\infty \frac{4+\gamma_{eq}+\gamma_{sd}}{8\,e^{\gamma_{sd}}e^{\gamma_{eq}}} p(\gamma_{eq})p(\gamma_{sd})d\gamma_{eq}d\gamma_{sd} \tag{23}
$$

which can be equivalently re-written as

$$
\begin{aligned}
\overline{P}_{e2}^{\,\rm gen} = & \frac{1}{2}\int_0^\infty e^{-\gamma_{eq}}p(\gamma_{eq})d\gamma_{eq} \times \int_0^\infty e^{-\gamma_{sd}}p(\gamma_{sd})d\gamma_{sd} \\
& + \frac{1}{8}\int_0^\infty \gamma_{eq}e^{-\gamma_{eq}}p(\gamma_{eq})d\gamma_{eq} \times \int_0^\infty e^{-\gamma_{sd}}p(\gamma_{sd})d\gamma_{sd} \\
& + \frac{1}{8}\int_0^\infty e^{-\gamma_{eq}}p(\gamma_{eq})d\gamma_{eq} \times \int_0^\infty \gamma_{sd}e^{-\gamma_{sd}}p(\gamma_{sd})d\gamma_{sd}.
\end{aligned} \tag{24}
$$

By also recalling that the average BER of differentially modulated AF systems in the case of no direct link is generically expressed as [24]

$$
\overline{P}_{e1}^{\,\rm gen} = \frac{1}{2}\int_0^\infty e^{-\gamma_{eq}}p(\gamma_{eq})d\gamma_{eq} \tag{25}
$$

it follows that

$$
\begin{aligned}
\overline{P}_{e2}^{\,\rm gen} = & \overline{P}_{e1}^{\,\rm gen} \overbrace{\int_0^\infty \frac{p(\gamma_{sd})}{e^{\gamma_{sd}}}d\gamma_{sd}}^{\mathcal{I}_1^{\rm gen}} + \frac{\overline{P}_{e1}^{\,\rm gen}}{4} \overbrace{\int_0^\infty \frac{\gamma_{sd}}{e^{\gamma_{sd}}}p(\gamma_{sd})d\gamma_{sd}}^{\mathcal{I}_2^{\rm gen}} \\
& + \frac{1}{8} \underbrace{\int_0^\infty \frac{\gamma_{eq}}{e^{\gamma_{eq}}}p(\gamma_{eq})d\gamma_{eq}}_{\mathcal{I}_3^{\rm gen}} \underbrace{\int_0^\infty \frac{p(\gamma_{sd})}{e^{\gamma_{sd}}}d\gamma_{sd}}_{\mathcal{I}_4^{\rm gen}=\mathcal{I}_3^{\rm gen}}.
\end{aligned} \tag{26}
$$

For the case of K_G composite multipath/shadowing fading effects in the direct link, equation (26) becomes

$$
\begin{aligned}
\overline{P}_{e2}^{\,\eta-\mu|\eta-\mu|{\rm K_G}} = & \overline{P}_{e1}^{\,\eta-\mu|\eta-\mu} \overbrace{\int_0^\infty e^{-\gamma_{sd}}p(\gamma_{sd})d\gamma_{sd}}^{\mathcal{I}_1^{\rm K_G}} \\
& + \frac{\overline{P}_{e1}^{\,\eta-\mu|\eta-\mu}}{4} \overbrace{\int_0^\infty \frac{\gamma_{sd}p(\gamma_{sd})}{e^{\gamma_{sd}}}d\gamma_{sd}}^{\mathcal{I}_2^{\rm K_G}} \\
& + \frac{1}{8} \underbrace{\int_0^\infty \frac{\gamma_{eq}p(\gamma_{eq})}{e^{\gamma_{eq}}}d\gamma_{eq}}_{\mathcal{I}_3^{\eta-\mu|\eta-\mu}} \underbrace{\int_0^\infty \frac{p(\gamma_{sd})}{e^{\gamma_{sd}}}d\gamma_{sd}}_{\mathcal{I}_4^{\rm K_G}=\mathcal{I}_1^{\rm K_G}}.
\end{aligned} \tag{27}
$$

Given that $\mathcal{I}_1^{\rm K_G} = \mathcal{I}_4^{\rm K_G}$, and recalling the respective SNR PDF of the K_G fading model in [13], it immediately follows that

$$\mathcal{I}_1^{\mathrm{K_G}} = \frac{2k^{\frac{k+m}{2}} m^{\frac{k+m}{2}}}{\overline{\gamma}_{sd}^{\frac{k+m}{2}}\Gamma(m)\Gamma(k)} \times \int_0^\infty \gamma_{sd}^{\frac{k+m}{2}-1} e^{-\gamma_{sd}} K_{k-m}\left(2\sqrt{\frac{km}{\overline{\gamma}_{sd}}\gamma_{sd}}\right) d\gamma_{sd}. \tag{28}$$

It is noticed that the above integral can be expressed in closed-form in terms of the confluent hypergeometric function [27]. Based on this, we perform the necessary change of variables, we then substitute in (28) and after carrying out long but basic algebraic manipulations, equation (20) is deduced. It is observed that the algebraic representation of $\mathcal{I}_2^{\mathrm{K_G}}$ is similar to the one in $\mathcal{I}_1^{\mathrm{K_G}}$; therefore, by making the necessary variable transformation and after long but basic algebraic manipulations, equation (21) is deduced.

Next, we need to evaluate the $\mathcal{I}_3^{\eta-\mu|\eta-\mu}$ integral. To this end, by substituting $p(\gamma_{\rm eq})$ in (10) into (26) and by making the necessary variable transformation in [27, eq. (6.621.3)] as well as carrying out some long but basic algebraic manipulations, equation (22) is deduced. Based on the above, having derived $\mathcal{I}_1^{\mathrm{K_G}}, \mathcal{I}_2^{\mathrm{K_G}}, \mathcal{I}_3^{\eta-\mu|\eta-\mu}$ and recalling $\overline{P}_{e1}^{\eta-\mu|\eta-\mu}$ in (15), we substitute these equations in (27) and after some basic algebraic manipulations, equation (19) is deduced, which completes the proof. □

To the best of the authors' knowledge, the offered results in Theorem 1 have not been previously reported in the open literature.

IV. Numerical Results

In this section, we utilize the derived analytic results in analyzing the average BER of the considered system and quantifying the effects of generalized multipath fading and shadowing on differentially modulated AF systems. To this end, we first assume differential BPSK, equal power allocation between source and relay and symmetric fading conditions in the *S-R* and *R-D* links. Based on this, Fig. 1 illustrates the ABER versus the average SNR for the following cases of Format I, of the $\eta-\mu$ fading:

- Case I: η_{sr}= 0.2, μ_{sr}= 1.0, η_{rd}= 0.4, μ_{rd}= 1.0.
- Case II: η_{sr}= 0.8, μ_{sr}= 1.0, η_{rd}= 0.4, μ_{rd}= 1.0.
- Case III: η_{sr}= 0.8, μ_{sr}= 2.0, η_{rd}= 0.4, μ_{rd}= 1.0.
- Case IV: η_{sr}= 0.8, μ_{sr}= 1.0, η_{rd}= 0.4, μ_{rd}= 2.0.

It is observed that the effect of generalized multipath fading affects the system performance since the average BER varies even at small variations of η and particularly of μ. This occurs at both low and high SNR regimes. Furthermore, it is shown that when $\mu_{S,R}$ is greater than $\mu_{R,D}$, the average BER differs by nearly 1 dB in the low SNR regime and 2 dB in the high SNR regime, when compared to the respective case that $\mu_{R,D}$ is greater than $\mu_{S,R}$.

The offered results were also used to quantify the fading effect in the context of Format II of the $\eta-\mu$ fading model

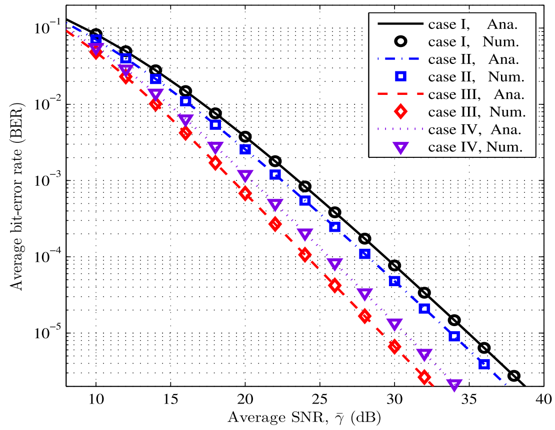

Fig. 1: ABER performance of dual-hop system in η-μ fading channel using Format I.

as shown in Fig. 2. To this end, the analysis considered the following realistic scenarios:

- Case I: η_{sr}= -0.5, μ_{sr}= 1, η_{rd}= -0.2, μ_{rd}= 2.
- Case II: η_{sr}= -0.5, μ_{sr}= 2, η_{rd}= -0.2, μ_{rd}= 1.
- Case III: η_{sr}= 0.8, μ_{sr}= 2, η_{rd}= 0.9, μ_{rd}= 1.
- Case IV: η_{sr}= -0.2, μ_{sr}= 2, η_{rd}= -0.5, μ_{rd}= 4.

As expected from the principles of Format II, the spatial correlation effects have a non-negligible impact on the average BER performance as the difference between light, moderate and severe fading conditions is generally about an order of magnitude at both high and low SNR regimes. The effect of unbalanced fading conditions is also demonstrated for different fading and average SNR conditions and is overall observed that Rayleigh distribution provides a poor characterization of multipath fading conditions. Therefore, the effects of multipath fading must be taken into detailed account in the design of future cooperative systems. In addition, it is shown that DPSK performs adequately at moderate and high SNR regimes even under severe fading conditions. Thus, it can be considered an effective and robust modulation scheme in cases of low complexity systems, including amplify and forward based cooperative communications.

For the case of asymmetric fading conditions, a non-linear environment with correlated scatterers and NLOS component is assumed at the relaying links using η-μ distribution model, while in the direct link, the K_G distribution is assumed with different fading severities. To this end and without loss of generality, it is assumed that $\eta_{sr} = \eta_{rd}$, $\mu_{sr} = \mu_{rd}$, and the performance of the proposed system is examined using Format I in Figure 3. It is evident that the result of end-to-end average BER for this scenario is exact and coincides with the analytical results. Also, the average BER is indicatively improved when μ_{sr} is increased. This verifies the substantial performance gain provided by the the number of multipath cluster across all SNR

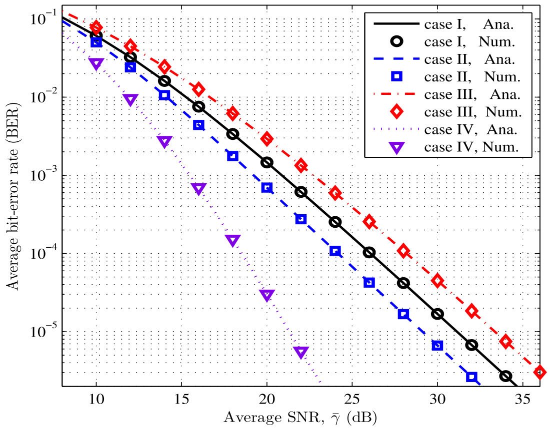

Fig. 2: ABER performance of dual-hop system in η-μ fading channel using Format II.

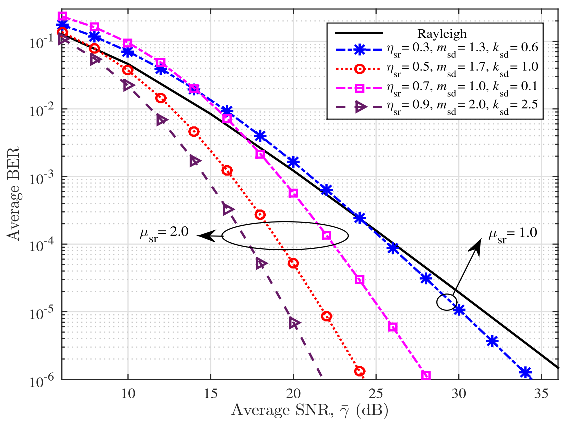

Fig. 3: Average BER for DPSK modulated AF systems over asymmetric fading channels: $\eta-\mu$ distributed $S-D$ and $R-D$ links and K_G distributed $S-D$ link.

regimes. Also, the K distribution is evaluated as a special case of the considered scenario. As shown in the figure, the average BER is improved by an order of magnitude between $k_{sd} = 0.1$ and $k_{sd} = 1.0$ at 20dB. Moreover, it is evident that deviation from the conventional Rayleigh case is considerable, which verifies the need for accurate channel characterization and modeling in conventional and emerging communication systems. It is evident that the resulting deviation is at least one order of magnitude in most cases. This indicates that the same performance can be practically achieved with reduced power, which can potentially reduce the complexity of transceivers and in turn increase the battery lifetime of hand-held devices. Conversely, the extra power can be potentially used for wireless power transfer applications, which is a topic of extensive interest in the context of emerging wireless technologies.

V. Conclusion

This work analyzed the effect of asymmetric fading conditions on the performance of differentially modulated amplify-and-forward relay systems. This assumed the presence of non-homogeneous generalized fading in the relay links and of composite multipath/shadowing fading conditions in the direct link. Novel closed-form expressions were derived for the corresponding average bit-error-rate which were then employed in analyzing the corresponding performance and quantify the detrimental effects of multipath fading and shadowing on the overall system performance. It was shown that differential modulation exhibits adequate performance at both moderate and high signal-to-noise ratio under severe multipath fading conditions. Also, the variation compared to the conventional Rayleigh fading conditions is at least an order of magnitude across all signal-to-noise ratio techniques. Thus, it is evident that accurate characterization and modeling of realistic fading conditions is of paramount importance in both conventional and emerging communication systems. Finally, it was shown that differential modulation can be potentially employed in low-complexity applications, including scenarios that do not necessary require prior knowledge of channel state information.

References

[1] J. N. Laneman, D.N.C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062−3080, Dec. 2004.

[2] L. J. Rodriguez, N.H. Tran, and L. Tho, "Achievable rate and power allocation for single-relay AF systems over Rayleigh fading channels at high and low SNRs," *IEEE Trans. Veh. Technol.*, vol. 63, no. 4, pp. 1726−1739, May 2014.

[3] J. F. Paris, P. C. Sofotasios, and T. A. Tsiftsis, "Guest editorial: advances in statistical channel modeling for wireless communications," *Hindawi International Journal of Antennas and Propagation*,Article ID 541619, 2 pages, 2015.

[4] J. F. Paris, "Advances in the statistical characterization of fading: from 2005 to present," *Hindawi International Journal on Antennas and Propagation*, pp. 1−5, July 2014.

[5] S. Ki Yoo, S. L. Cotton, P. C. Sofotasios, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The $\kappa-\mu$ / Inverse gamma fading model," *in IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015.

[6] S. Ki Yoo, P. C. Sofotasios, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The $\eta-\mu$ / Inverse gamma composite fading model," *in IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015.

[7] P. C. Sofotasios, T. A. Tsiftsis, K. Ho-Van, S. Freear, L. R. Wilhelmsson, and M. Valkama, "The $\kappa-\mu$/inverse-Gaussian composite statistical distribution in RF and FSO wireless channels," *in IEEE VTC '13 - Fall*, Las Vegas, USA, Sep. 2013.

[8] P. C. Sofotasios, T. A. Tsiftsis, M. Ghogho, L. R. Wilhelmsson, and M.Valkama, "The $\eta-\mu$/inverse Gaussian distribution: A novel physical multipath/shadowing fading model," *in IEEE ICC' 13*, Budapest, Hungary, June 2013.

[9] P. C. Sofotasios, and S. Freear, "The $\alpha-\kappa-\mu$/gamma composite distribution: A generalized non-linear multipath/shadowing fading model," *in IEEE INDICON '11*, Hyderabad, India, Dec. 2011.

[10] P. C. Sofotasios, and S. Freear, "The $\eta-\mu$/gamma and the $\lambda-\mu$/gamma multipath/shadowing distributions," *in ATNAC '11*, Melbourne, Australia, Nov. 2011.

[11] S. Harput, P. C. Sofotasios, and S. Freear, "A novel composite statistical model for ultrasound applications," *in IEEE IUS '11*, Orlando, FL, USA, Oct. 2011.

[12] A. Zafar, R.M. Radaydeh, Yunfei Chen, and M. S. Alouini, "Enhancing the efficiency of constrained dual-hop variable-gain AF relaying under Nakagami-*m* fading," *IEEE Trans. Signal Proc.*, vol. 62, no. 14, pp. 3616−3630, Jul. 2014.

[13] M. K. Simon and M. S. Alouni, *Digital Communication over Fading Channels*, $2^{\rm nd}$ edn., Wiley, New York, 2005.

[14] M. D. Yacoub, "The $\eta-\mu$ distribution and the $\kappa-\mu$ distribution," *IEEE Trans. Ant. and Propag. Mag.*, vol. 49, no. 1, 68-81, June 2007.

[15] K. P. Peppas, G.C Alexandropoulos, and P.T. Mathiopoulos, "erformance analysis of dual-hop AF relaying systems over mixed $\eta-\mu$ and $\kappa-\mu$ fading channels," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3149−3163, Sep. 2013.

[16] K. P. Peppas, "A new formula for the average bit error probability of dual-hop amplify-and-forward relaying systems over generalized shadowed fading channels," *IEEE in Wireless Commun. Lett.*, vol. 1, no. 2, pp. 85−88, April 2012.

[17] W. Cheng, "Ergodic capacity of dual-hop fixed gain relaying systems over mixed multipath/shadowing channels," *in Proc. Wireless Commun. and Signal Proc. (WCSP)*, pp.1-6, 23-25 Oct. 2014.

[18] K. P. Peppas, G. C. Alexandropoulos, and P. T. Mathiopoulos, "Performance analysis of dual-hop AF relaying systems over mixed $\eta-\mu$ and $\kappa-\mu$ fading channels," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3149−3163, September 2013.

[19] P. C. Sofotasios, M. K. Fikadu, S. Muhaidat, Q. Cui, G. K. Karagiannidis, and M. Valkama, "Full-duplex regenerative relaying and energy-efficiency optimization over generalized asymmetric fading channels," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 3232−3351, May 2017.

[20] L. Peng, S. Gazor, and K. Il-Min, "A Practical differential receiver for amplify-and-forward relaying," *IEEE Wireless Commun. Lett.*, vol. 3, no. 4, pp. 349−352, Aug. 2014.

[21] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, McGraw-Hill, 1991.

[22] P. Liu, S. Gazor, Il-Min Kim, and Dong In Kim, "Noncoherent Amplify-and-Forward Cooperative Networks: Robust Detection and Performance Analysis," *IEEE Transactions on in Communications*, vol.61, no.9, pp.3644−3659, September 2013.

[23] Q. Zhao and H. Li, "Performance analysis of an amplify-based differential modulation for wireless relay networks under Nakagami-m fading channels," in *Signal Processing Advances in Wireless Communications,* June 2005, pp. 211−215.

[24] Q. Zhao and H. Li, " Performance of differential modulation with wireless relays in Rayleigh fading channels," *IEEE Commun. Lett*., vol. 9, , no. 4, pp. 343−345, Apr. 2005.

[25] S. Al Maeeni, P. C. Sofotasios, S. Muhaidat, G. K. Karagiannidis, and M. Valkama, "Distributed differential modulation over asymmetric fading channels," *IEEE Signal Proc. Lett*, vol. 23, no. 12, pp. 1712−1716, Dec. 2016.

[26] S. Al Maeeni, P. C. Sofotasios, S. Muhaidat, G. K. Karagiannidis, and M. Valkama, "Error analysis of differentially modulated cooperative systems under generalized fading," *IEEE ICT '16*, Thessaloniki, Greece, May 2016.

[27] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*, in 7^{th} ed. Academic, New York, 2007.

[28] M. K. Simon and M. S. Alouni, " A unified approch to the performance analysis of digital communication over generalized fading channels," in*Proceedings of the IEEE.*, vol. 86, , no. 9, pp. 1860−1877, Sep. 1998.

[29] J. G. Proaks, *Digital Communications*, New York: McGraw-hill, 4th edition, 2000.

[30] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions with formulas, graphs, and mathematical tables.*, New York: Dover, 1974.