This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2018.2877136, IEEE Transactions on Vehicular Technology

Physical-Layer Security for Mixed η-μ and $\mathcal{M}$-Distribution Dual-Hop RF/FSO Systems

Liang Yang, Ting Liu, Jianchao Chen, and Mohamed-Slim Alouini, *Fellow, IEEE*

***Abstract*— In this correspondence, we investigate the physical-layer security of a mixed radio frequency/free space optical (RF/FSO) dual-hop communication system for both fixed and variable gain relaying schemes. More specifically, we only assume that the eavesdropping happens at the RF link because the optical link has high security. We assume that all RF channels suffer from η-μ fading, while the FSO link experiences $\mathcal{M}$-distributed fading. Then, we derive some analytical results for the average secrecy rate (ASR) and secrecy outage probability (SOP).**

***Index Terms*— Average secrecy rate, $\mathcal{M}$-distributed fading, physical-layer security, radio frequency-free space optical, secrecy outage probability, η-μ fading.**

I. Introduction

Free space optical (FSO) communication has the advantages of large transmission capacity, high frequency bandwidth, high speed, high security, fast deployment, etc. Compared with the conventional radio frequency (RF) wireless communication, FSO communication has a wide range of applications and attracts more and more attention in recent years [1]-[2].

Recently, a mixed RF/FSO (MRFFSO) cooperative communication system was first proposed in [3]. As discussed in [4], this system can be applied in an uplink scenario where multiple users with RF capability can be multiplexed into a single high-speed FSO link. Regarding motivation behind such a model, detailed description can be found in [4]. Until now, there are many literatures that have analyzed the performance of MRFFSO systems under various channel fading models [3]-[8], for instance, Rayleigh fading/Gamma-Gamma (GG) fading [3], Rayleigh fading/GG fading with pointing errors [4], Rayleigh fading/$\mathcal{M}$-distributed fading [5], κ-μ or η-μ distributions/GG [6], η-μ fading/$\mathcal{M}$-distribution with multiuser diversity [7], and multiuser MRFFSO systems with a decode-and-forward (DF) mode [8].

On the other hand, in RF wireless communication systems, physical layer security which can achieve perfect confidential communications by using the randomness and time-varying nature of the wireless channels has become a powerful tool to improve the security of information transmission [9][10]. By far, the secrecy performance analysis of different RF system structures over various channel models has been extensively analyzed in the literature. However, to the best of the authors' knowledge, there are few works related to the physical-layer security for FSO systems. In [11], the authors considered the physical layer security for a point-to-point FSO network. Recently, a single-input multiple-output (SIMO) MRFFSO system was investigated in [12], where both maximum ratio combining (MRC) and selection combining (RC) were considered. They also considered the security-reliability trade-off. More recently, in [13], the secrecy performance of MRFFSO systems for both fixed and variable-gain relay schemes was studied, where the RF and FSO links were assumed to be subject to Nakagami-m fading and GG fading, respectively.

In this work, similar to the setting in [13], we investigate the physical layer security of a MRFFSO system, where the RF link and the FSO link are subject to η-μ fading and $\mathcal{M}$-distribution fading, respectively. In particular, we assume that the eavesdropping only happens at the RF link since the FSO link is very safe. The reason is that optical beams have high directionality. The η-μ distribution is able to accurately simulate the small-scale variation of the signals related to non-line-of-sight scenario and includes Hoyt and Nakagami-m fading as special cases [14]. On the other hand, $\mathcal{M}$-distribution is appropriate to the entire range of turbulent conditions and is capable to be easily transformed to the GG and K distributions under certain conditions. Based on such a setup, average secrecy rate (ASR) and secrecy outage probability (SOP) for both fixed gain relaying and variable gain relaying modes are analyzed. Since both RF and FSO links are generalized fading, our results are more general.

II. System and Channel Models

Consider a MRFFSO system as shown in Fig. 1, which consists of a RF source (S), a relay (R) with laser transmitter and amplify-and-forward (AF) protocol, a destination (D), and an eavesdropper (E) that can receive signal from the source node. In this work, both fixed gain relaying and variable gain relaying modes are considered. The detailed information transmission procedure is presented as follows.

Manuscript received Aug 9, 2018; accepted Oct 18, 2018. This work was in part supported by the National Natural Science Foundation of China (NSFC) under Grant 61671160, the Department of Education of Guangdong Province (No. 2016KZDXM050), and the open research fund of National Mobile Communications Research Laboratory, Southeast University (No. 2018D01). The review of this paper was coordinated by Prof. Xianbin Wang.(Corresponding author: Liang Yang)

L. Yang is with the Department of Communication Engineering, Guangdong University of Technology, Guangzhou 510006, and with the College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China.(e-mail:liangyang.guangzhou@gmail.com).

T. Liu and J. Chen are with the Department of Communication Engineering, Guangdong University of Technology, Guangzhou 510006, China.(e-mail:tingliu1236@foxmail.com;chenjianchouchao@foxmail.com).

M.-S. Alouini is with the Computer, Electrical, and Mathematical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.(e-mail: slim.alouini@kaust.edu.sa)

A. Channel Models

1) RF Links: In the first time slot, S broadcasts a RF signal to R and E. The electrical signal received by R and E can be expressed as

$$y_x = g_{S,x}s(t) + n_x, \tag{1}$$

where $x \in (R, E)$, $s(t)$ is the unit signal transmitted from the source, $g_{S,x}$ denotes the channel gain from S to x, and $n_{R,x}$ is the additive white Gaussian noise (AWGN) with zero mean and N_0 variance.

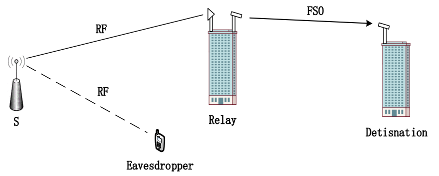

Fig. 1. System diagram of mixed RF/FSO dual-hop relay systems in the presence of eavesdropping.

In (1), $g_{S,x}$ suffers from the η-μ fading which can be presented in two formats (format 1 and format 2) [14]. According to [14], format 2 can be obtained by bilinear transformation of format 1. Without loss of generality, in our work we consider the format 1.To obtain tractable analysis, we only focus on the integer case of μ_i. According to [7], the PDF of the η-μ distribution for integer μ can be expressed as

$$f_{\gamma_i}(\gamma) = \sum_{l_i=0}^{\mu_i-1} \frac{\Gamma(\mu_i+l_i)\mu_i^{\mu_i-l_i} h_i^{\mu_i}\gamma^{\mu_i-l_i-1}}{\Gamma(\mu_i)l_i!\Gamma(\mu_i-l_i)4^{l_i}\bar{\gamma}_i^{\mu_i-l_i}H_i^{\mu_i+l_i}} \times \left[(-1)^{l_i} e^{-2\mu_i(h_i-H_i)\frac{\gamma}{\bar{\gamma}_i}} + (-1)^{\mu_i} e^{-2\mu_i(h_i+H_i)\frac{\gamma}{\bar{\gamma}_i}}\right], \tag{2}$$

where $i \in 1, 3$ correspond to the S-R and S-E links, respectively. In (2), $h_i = (2 + \eta_i^{-1} + \eta_i)/4$, $H_i = (\eta_i^{-1} - \eta_i)/4$, $\gamma_1 = |g_{S,R}|^2/N_0$ and $\gamma_3 = |g_{S,E}|^2/N_0$ denote the SNRs of the S-R link and the S-E link, respectively, $\bar{\gamma}_i$ denotes the average SNR of γ_i, and $\Gamma(x)$ is the gamma function. In (2), μ_i and η_i are the fading parameters with $\mu_i > 0$ and $\eta_i \in (0, \infty)$.

Accordingly, the cumulative distribution function (CDF) of the η-μ distribution for integer values of μ is [15, Eq. (3)]

$$F_{\gamma_i}(\gamma) = 1 - \frac{1}{\Gamma(\mu_i)}\left(\frac{h_i}{H_i}\right)^{\mu_i} \sum_{n_i=1}^{2} \times \sum_{k_i=0}^{\mu_i-1}\sum_{l_i=0}^{\mu_i-k_i-1} \frac{A_{i,n_i}^{l_i} a_{n_i,k_i}}{l_i!}\gamma^{l_i}\exp(-A_{i,n_i}\gamma), \tag{3}$$

where $A_{i,1} = 2\mu_i(h_i - H_i)/\bar{\gamma}_i$, $A_{i,2} = 2\mu_i(h_i + H_i)/\bar{\gamma}_i$, $a_{1_i,k_i} = \frac{(-1)^{k_i}\Gamma(\mu_i+k_i)H_i^{-k_i}}{2^{\mu_i+k_i}k_i!(h_i-H_i)^{\mu_i-k_i}}$, $a_{2_i,k_i} = \frac{(-1)^{\mu_i}\Gamma(\mu_i+k_i)H_i^{-k_i}}{2^{\mu_i+k_i}k_i!(h_i+H_i)^{\mu_i-k_i}}$.

2) FSO Link: In this work, we assume that subcarrier intensity modulation (SIM) scheme is applied at the relay [3]. Then, the received RF signal is converted to an optical signal and forwarded to D. Therefore, the transmitted optical signal at R can be expressed as

$$S_{opt}(\gamma) = G(1 + \eta' y_R), \tag{4}$$

where G is the amplifying gain including both fixed and variable gain modes and η' represents the electrical-to-optical conversion factor. Then, the received optical signal at D can be shown to be given by

$$y_D = \xi' IG(1 + \eta'(g_{S,R}s(t) + n_R)) + n_D, \tag{5}$$

where ξ' is the photoelectric conversion factor, and n_D is the AWGN at D with zero mean and N_1 variance. In (5), I is the channel coefficient following the $\mathcal{M}$-distribution fading [16] and [17]. From [16][17], the PDF of $\mathcal{M}$-distribution is given by

$$f_{\gamma_2}(\gamma) = A\sum_{b=1}^{\beta} B_b \frac{\gamma^{\frac{\alpha+b}{4}-1}}{2\bar{\gamma}_2^{\frac{\alpha+b}{4}}} K_{\alpha-b}\left(2\sqrt{\frac{\alpha\beta}{\omega\beta+\Omega'}\sqrt{\frac{\gamma}{\bar{\gamma}_2}}}\right), \tag{6}$$

where $\gamma_2 = \xi'^2\eta'^2I^2/N_1 = \bar{\gamma}_2 I^2$ denotes the SNR of the FSO link, $\bar{\gamma}_2$ denotes the average SNR of the FSO link, $K_v(.)$ is the Bessel function of the second kind and order v [18]. In (6), A and B_b are defined as $A = \frac{2\alpha^{\frac{\alpha}{2}}}{\omega^{1+\frac{\alpha}{2}}\Gamma(\alpha)}\left(\frac{\omega\beta}{\omega\beta+\Omega'}\right)^{\beta+\frac{\alpha}{2}}$ and $B_b = \binom{\beta-1}{b-1}\frac{(\omega\beta+\Omega')^{1-\frac{b}{2}}}{(b-1)!}\left(\frac{\Omega'}{\omega}\right)^{b-1}\left(\frac{\alpha}{\beta}\right)^{\frac{b}{2}}$, where α is the channel parameter and with $\alpha > 0$, $\omega = E[|U_S^G|^2] = 2b_0(1-\rho)$, U_S^G is a component due to off-axis vortex scatters energy to the receiver, ρ is a constant with $\rho \in [0, 1]$, $\Omega' = \Omega + 2\rho b_0 + 2\sqrt{2b_0\Omega\rho}\cos(\varphi_A - \varphi_B)$, φ_A and φ_B are the deterministic phases of the LOS propagation and the coupled-to-LOS component, respectively, Ω and $2b_0$ denote the average powers of the LOS term and the total scatter components, respectively, and β is a non-negative integer and denotes the amount of fading.

For notation simplicity, let $\varpi = \frac{\alpha\beta}{\omega\beta+\Omega'}$. From [18, eq.(9.34.3)], $K_{\alpha-b}\left(2\sqrt{\varpi\sqrt{\frac{\gamma}{\bar{\gamma}_2}}}\right) = \frac{1}{2}G_{0,2}^{2,0}\left[\varpi\sqrt{\frac{\gamma}{\bar{\gamma}_2}}\Big|_{0.5(\alpha-b),0.5(b-\alpha)}^{-}\right]$, where $G_{p,q}^{m,n}(\cdot)$ is the Meijer G-function [18, Eq. (9.301)]. Then, the PDF of γ_2 is

$$f_{\gamma_2}(\gamma) = \sum_{b=1}^{\beta}\frac{AB_b\gamma^{\frac{\alpha+b}{4}-1}}{4\bar{\gamma}_2^{\frac{\alpha+b}{4}}} G_{0,2}^{2,0}\left[\varpi\sqrt{\frac{\gamma}{\bar{\gamma}_2}}\Big|_{\frac{\alpha-b}{2},\frac{b-\alpha}{2}}^{-}\right]. \tag{7}$$

From (7) and by using [19, eq.(07.34.21.0084.01)], the CDF of γ_2 can be obtained as

$$F_{\gamma_2}(\gamma) = \sum_{b=1}^{\beta}\frac{B_bA}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}}\gamma^{\frac{\alpha+b}{4}} G_{1,5}^{4,1}\left[\frac{\varpi^2\gamma}{16\bar{\gamma}_2}\Big|_{\kappa_1}^{1-\frac{\alpha+b}{4}}\right]. \tag{8}$$

where $\kappa_1 = \frac{\alpha-b}{4}, \frac{\alpha-b+2}{4}, -\frac{\alpha-b}{4}, \frac{-\alpha+b+2}{4}, -\frac{\alpha+b}{4}$.

B. Channel Statistics

From (5), the resulting SNR at D can be written as

$$\gamma_D^Q = \frac{\xi'^2I^2G^2\eta'^2|g_{S,R}|^2}{\xi'^2I^2G^2N_0 + N_1} = \frac{\frac{|g_{S,R}|^2}{N_0}\frac{\xi'^2\eta'^2I^2}{N_1}}{\frac{\xi'^2\eta'^2I^2}{N_1} + \frac{1}{G^2N_0}} = \frac{\gamma_1\gamma_2}{\gamma_2 + \frac{1}{G^2N_0}}. \tag{9}$$

where $Q \in (FG, VG)$ and FG and VG denote the fixed-gain and variable-gain cases, respectively.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2018.2877136, IEEE Transactions on Vehicular Technology

1) Fixed Gain Relaying: For fixed gain relaying, the amplifying gain G is a constant regardless of the channel gain g_{SR}. Let $C = 1/(G^2 N_0)$, (9) can be rewritten as

$$\gamma_D^{FG} = \frac{\gamma_1 \gamma_2}{\gamma_2 + C}. \tag{10}$$

The CDF of γ_D^{FG} can be written as

$$F_{\gamma_D^{FG}}(\gamma) = \int_0^\infty P\left(\frac{\gamma_1\gamma_2}{\gamma_2 + C} < \gamma \middle| \gamma_2\right) f_{\gamma_2}(\gamma_2) d\gamma_2. \tag{11}$$

From (3), we have

$$P\left(\frac{\gamma_1\gamma_2}{\gamma_2+C} < \gamma \middle| \gamma_2\right) = 1 - \frac{1}{\Gamma(\mu_1)}\left(\frac{h_1}{H_1}\right)^{\mu_1} \sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1} \times \sum_{n_1=1}^{2} \frac{A_{1,n_1}^{l_1} a_{n_1,k_1}}{l_1!}\left[\gamma\left(1+\frac{C}{\gamma_2}\right)\right]^{l_1} \exp\left[-A_{1,n_1}\gamma\left(1+\frac{C}{\gamma_2}\right)\right]. \tag{12}$$

Expressing $\exp(-x)$ in terms of the Meijer's G-function [19, eq.(01.03.26.0004.01)] and using [19, eq.(07.34.21.0013.01)]), we can evaluate the integral in (11) as

$$F_{\gamma_D^{FG}}(\gamma) = 1 - \frac{1}{\Gamma(\mu_1)}\left(\frac{h_1}{H_1}\right)^{\mu_1} \sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1} \frac{a_{n_1,k_1}}{l_1!} \times \sum_{b=1}^{\beta} \frac{B_b A}{8\pi \bar{\gamma}_2^{\frac{\alpha+b}{4}}} \sum_{j=0}^{l_1} \binom{l_1}{j} A_{1,n_1}^{l_1+\frac{\alpha+b}{4}-j} C^{\frac{\alpha+b}{4}} \gamma^{l_1+\frac{\alpha+b}{4}-j} \times \exp(-A_{1,n_1}\gamma) G_{0,5}^{5,0}\left[\frac{\varpi^2 A_{1,n_1} C\gamma}{16\bar{\gamma}_2}\middle|_{\kappa_2}^{-}\right]. \tag{13}$$

where $\kappa_2 = \frac{\alpha-b}{4}, \frac{\alpha-b+2}{4}, -\frac{\alpha-b}{4}, \frac{-\alpha+b+2}{4}, j - \frac{\alpha+b}{4}$.

2) Variable Gain Relaying: If the relay knows the full channel state information (CSI), the CSI-assisted relaying scheme can be applied at the relay. Then, the variable amplifying gain is chosen as $G^2 = 1/(|g_{S,R}|^2 + N_0)$. Hence, (9) can be rewritten as

$$\gamma_D^{VG} = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1} \cong \min(\gamma_1, \gamma_2). \tag{14}$$

where $\min(\gamma_1,\gamma_2)$ is the upper bound of $\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}$.

From (14), the CDF of γ_D^{VG} can be shown to be given by

$$F_{\gamma_D^{VG}}(\gamma) = F_{\gamma_1}(\gamma) + \frac{1}{\Gamma(\mu_1)}\left(\frac{h_1}{H_1}\right)^{\mu_1}\sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1} \times \frac{A_{1,n_1}^{l_1} a_{n_1,k_1}}{l_1!}\gamma^{l_1}\exp(-A_{1,n_1}\gamma) F_{\gamma_2}(\gamma). \tag{15}$$

III. Average Secrecy Rate Analysis

From [20][21], we know that the secrecy capacity is $C = \max_{pX} I(X;Y) - I(X;Z)$ and only optimal distribution of X can achieve the secrecy capacity. Thus, many works assume that X is complex Gaussian distribution and use secrecy rate as the performance metric. Similar to most of the works, we also consider ASR. From [22], the ASR can be written as

$$\bar{C}_s^Q = \int_0^\infty \frac{F_{\gamma_3}(\gamma)}{1+\gamma}\left(1 - F_{\gamma_D^Q}(\gamma)\right) d\gamma \tag{16}$$

A. ASR Analysis for Fixed Gain Relaying

Substituting (3) and (13) into (16) yields

$$\bar{C}_s^{FG} = \frac{1}{\Gamma(\mu_1)}\left(\frac{h_1}{H_1}\right)^{\mu_1}\sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1}\frac{A_{1,n_1}^{l_1}a_{n_1,k_1}}{l_1!} \times \sum_{j=0}^{l_1}\binom{l_1}{j}\sum_{b=1}^{\beta}\frac{B_b A}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}} A_{1,n_1}^{\frac{\alpha+b}{4}-j} C^{\frac{\alpha+b}{4}} [\times \underbrace{\int_0^\infty \frac{\gamma^{z_1}}{1+\gamma}\exp(-A_{1,n_1}\gamma) G_{0,5}^{5,0}\left[\frac{\varpi^2 A_{1,n_1}C\gamma}{16\bar{\gamma}_2}\middle|_{\kappa_2}^{-}\right] d\gamma}_{I_1} - \frac{1}{\Gamma(\mu_3)}\left(\frac{h_3}{H_3}\right)^{\mu_3}\sum_{n_3=1}^{2}\sum_{k_3=0}^{\mu_3-1}\sum_{l_3=0}^{\mu_3-k_3-1}\frac{A_{3,n_3}^{l_3}a_{n_3,k_3}}{l_3!} \times \underbrace{\int_0^\infty \frac{\gamma^{z_2}}{1+\gamma}\exp(-z_3\gamma) G_{0,5}^{5,0}\left[\frac{\varpi^2 A_{1,n_1}C\gamma}{16\bar{\gamma}_2}\middle|_{\kappa_2}^{-}\right] d\gamma}_{I_2}]. \tag{17}$$

where $z_1 = l_1 + \frac{\alpha+b}{4} - j$, $z_2 = \frac{\alpha+b}{4} + l_1 + l_3 - j$, and $z_3 = A_{1,n_1} + A_{3,n_3}$.

Using [18, eq. (9.31.5)][19, eq. (07.34.03.0271.01)], and[19, eq.(01.03.26.0004.01)], we obtain $\gamma^{z_1}/(1+\gamma) = G_{1,1}^{1,1}[\gamma|_{z_1}^{z_1}]$ and $\exp(-A_{1,n_1}\gamma) = G_{0,1}^{1,0}[A_{1,n_1}\gamma|_0^-]$. Then, using integral table [23]

$$\int_0^\infty G_{C,D}^{A,B}[ax|_{f_1,\ldots,f_D}^{e_1,\ldots,e_C}] G_{r,q}^{h,0}[bx|_{\beta_1,\ldots,\beta_r}^{\alpha_1,\ldots,\alpha_q}] G_{\gamma,\delta}^{\alpha,\beta}[cx|_{b_1,\ldots,b_D}^{a_1,\ldots,a_C}] dx = \frac{1}{b} G_{r,q:C,D:\gamma,\delta}^{h,0:A,B:\alpha,\beta}\left[\begin{matrix}\beta_1+1,\ldots,\beta_r+1\\ \alpha_1+1,\ldots,\alpha_q+1\end{matrix}\middle|_{f_1,\ldots,f_D}^{e_1,\ldots,e_C}\middle|_{b_1,\ldots,b_D}^{a_1,\ldots,a_C}\middle|\frac{a}{b},\frac{c}{b}\right] \tag{18}$$

, we have

$$I_1 = \frac{1}{A_{1,n_1}} G_{1,0:1,1:0,5}^{1,0:1,1:5,0}\left[\begin{matrix}1\\ -\end{matrix}\middle|_{z_1}^{z_1}\middle|_{\kappa_2}^{-}\middle|\frac{1}{A_{1,n_1}}, \frac{\varpi^2 C}{16\bar{\gamma}_2}\right], \tag{19}$$

where $G_{r,q:C,D:\gamma,\delta}^{h,0:A,B:\alpha,\beta}[\cdot]$ is the extended generalized bivariate Meijers G-function (EGBMGF) defined in [24]. Similar to (19), we can obtain

$$I_2 = \frac{1}{z_3} G_{1,0:1,1:0,5}^{1,0:1,1:5,0}\left[\begin{matrix}1\\ -\end{matrix}\middle|_{z_2}^{z_2}\middle|_{\kappa_2}^{-}\middle|\frac{1}{z_3}, \frac{\varpi^2 A_{1,n_1} C}{16\bar{\gamma}_2 z_3}\right]. \tag{20}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2018.2877136, IEEE Transactions on Vehicular Technology

B. ASR Analysis for Variable Gain Relaying

Similar to the analysis for Eq. (19), substituting (3) and (15) into (16) and using [24, eq. (2.3.6.9)], we have

$$\bar{C}_s^{VG}=\frac{1}{\Gamma(\mu_1)}\left(\frac{h_1}{H_1}\right)^{\mu_1}\sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1}\frac{A_{1,n_1}^{l_1}a_{n_1,k_1}}{l_1!}$$
$$\times\left[\Gamma(l_1+1)\psi(l_1+1,l_1+1;A_{1,n_1})-\sum_{b=1}^{\beta}\frac{B_bA}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}A_{1,n_1}}\right.$$
$$\times G_{1,0:1,1:1,5}^{1,0:1,1:4,1}\left[\begin{array}{c}1\\-\end{array}\middle|\begin{array}{c}\frac{\alpha+b}{4}+l_1\\\frac{\alpha+b}{4}+l_1\end{array}\middle|\begin{array}{c}1-\frac{\alpha+b}{4}\\\kappa_1\end{array}\middle|\frac{1}{A_{1,n_1}},\frac{\varpi^2A_{1,n_1}^{-1}}{16\bar{\gamma}_2}\right]$$
$$+\left(\frac{h_3}{H_3}\right)^{\mu_3}\sum_{n_3=1}^{2}\sum_{k_3=0}^{\mu_3-1}\sum_{l_3=0}^{\mu_3-k_3-1}\frac{A_{3,n_3}^{l_3}a_{n_3,k_3}}{l_3!\Gamma(\mu_3)}\left(\sum_{b=1}^{\beta}\frac{B_bA}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}z_3}\right.$$
$$\times G_{1,0:1,1:1,5}^{1,0:1,1:4,1}\left[\begin{array}{c}1\\-\end{array}\middle|\begin{array}{c}\frac{\alpha+b}{4}+l_1+l_3\\\frac{\alpha+b}{4}+l_1+l_3\end{array}\middle|\begin{array}{c}1-\frac{\alpha+b}{4}\\\kappa_1\end{array}\middle|\frac{1}{z_3},\frac{\varpi^2}{16\bar{\gamma}_2z_3}\right]$$
$$\left.\left.-\frac{\psi(l_1+l_3+1,l_1+l_3+1;z_3)}{(\Gamma(l_1+l_3+1))^{-1}}\right)\right].\tag{21}$$

where $\psi(a,b;c)$ is the confluent hypergeometric function defined in [18, eq. (9.211.4)].

IV. Secrecy Outage Probability Analysis

SOP is defined as the probability of the instantaneous secrecy rate falls below the target secrecy rate R_s [13] and is an important performance metric given by

$$SOP=\Pr\{C_s(\gamma_D^Q,\gamma_3)\le R_s\}=\Pr\{\gamma_D^Q\le\theta\gamma_3+\theta-1\}\tag{22}$$

where $\theta=e^{R_s}$ and the instantaneous secrecy rate can be written as [25]

$$C_s(\gamma_D^Q,\gamma_3)=\max\{\ln(1+\gamma_D^Q)-\ln(1+\gamma_3),0\}\tag{23}$$

where $\ln(1+\gamma_D^Q)$ and $\ln(1+\gamma_3)$ are the rates of the primary channels and eavesdropper channels, respectively. According to [26], (22) can be approximated as

$$SOP\ge SOP_L^Q=\Pr\{\gamma_D^Q\le\theta\gamma_3\}=\int_0^\infty F_{\gamma_D^Q}(\theta\gamma)f_{\gamma_3}(\gamma)d\gamma\tag{24}$$

A. SOP for Fixed Gain Relaying

Substituting (2) and (13) into (24), and using [18, eq. (7.813.1)] , we can obtain SOP_L^{FG} as

$$SOP_L^{FG}=1-\left(\frac{h_1}{H_1}\right)^{\mu_1}\sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1}\frac{a_{n_1,k_1}}{\Gamma(\mu_1)l_1!}$$
$$\times\sum_{b=1}^{\beta}\frac{B_bA}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}}\sum_{l_3=0}^{\mu_3-1}\frac{\Gamma(\mu_3+l_3)\mu_3^{\mu_3-l_3}h_3^{\mu_3}H_3^{-\mu_3-l_3}}{\Gamma(\mu_3)l_3!\Gamma(\mu_3-l_3)4^{l_3}\bar{\gamma}_3^{\mu_3-l_3}}\sum_{j=0}^{l_1}\binom{l_1}{j}$$
$$\times C^{\frac{\alpha+b}{4}}(A_{1,n_1}\theta)^{l_1+\frac{\alpha+b}{4}-j}\left[(-1)^{l_3}(A_{1,n_1}\theta+A_{3,1})^{z_4}\right.$$
$$\times G_{1,5}^{5,1}\left[\frac{\varpi^2A_{1,n_1}C\theta}{16\bar{\gamma}_2[A_{1,n_1}\theta+A_{3,1}]}\middle|\begin{array}{c}1+z_4\\\kappa_2\end{array}\right]+(A_{1,n_1}\theta+A_{3,2})^{z_4}$$
$$\left.\times(-1)^{\mu_3}G_{1,5}^{5,1}\left[\frac{\varpi^2A_{1,n_1}C\theta}{16\bar{\gamma}_2[A_{1,n_1}\theta+A_{3,2}]}\middle|\begin{array}{c}1+z_4\\\kappa_2\end{array}\right]\right].\tag{25}$$

where $z_4=l_3+j-\frac{\alpha+b}{4}-l_1-\mu_3$.

B. SOP for Variable Gain Relaying

Similarly, substituting (2) and (15) into (24) and using [18, eq. (3.351.3)][18, eq. (7.813.1)], we have

$$SOP_L^{VG}=1+\sum_{n_1=1}^{2}\sum_{k_1=0}^{\mu_1-1}\sum_{l_1=0}^{\mu_1-k_1-1}\frac{A_{1,n_1}^{l_1}a_{n_1,k_1}}{h_1^{-\mu_1}\Gamma(\mu_1)l_1!}\sum_{l_3=0}^{\mu_3-1}\frac{\Gamma(\mu_3+l_3)}{\Gamma(\mu_3-l_3)}$$
$$\times\frac{\mu_3^{\mu_3-l_3}h_3^{\mu_3}\theta^{l_1}H_3^{-\mu_3-l_3}}{H_1^{\mu_1}\Gamma(\mu_3)l_3!4^{l_3}\bar{\gamma}_3^{\mu_3-l_3}}\left[\sum_{b=1}^{\beta}\frac{B_bA\theta^{\frac{\alpha+b}{4}}}{8\pi\bar{\gamma}_2^{\frac{\alpha+b}{4}}}\left((A_{1,n_1}\theta+A_{3,1})^{-z_5}\right.\right.$$
$$\times(-1)^{l_3}G_{2,5}^{4,2}\left[\frac{\varpi^2\theta}{16\bar{\gamma}_2(A_{1,n_1}\theta+A_{3,1})}\middle|\begin{array}{c}\kappa_3\\\kappa_1\end{array}\right]+(A_{1,n_1}\theta+A_{3,2})^{-z_5}$$
$$\left.\times(-1)^{\mu_3}G_{2,5}^{4,2}\left[\frac{\varpi^2\theta}{16\bar{\gamma}_2(A_{1,n_1}\theta+A_{3,2})}\middle|\begin{array}{c}\kappa_3\\\kappa_1\end{array}\right]\right)-(z_6-1)!$$
$$\left.\times\left((-1)^{l_3}(A_{1,n_1}\theta+A_{3,1})^{-z_6}+(-1)^{u_3}(A_{1,n_1}\theta+A_{3,2})^{-z_6}\right)\right].\tag{26}$$

where $z_5=l_1+u_3-l_3+\frac{\alpha+b}{4}$, $z_6=l_1+u_3-l_3$, and $\kappa_3=1+l_3-u_3-l_1-\frac{\alpha+b}{4},1-\frac{\alpha+b}{4}$.

V. Numerical Results

In this section, the numerical results are provided to demonstrate the secrecy performance of the mixed RF/FSO systems with fixed amplifying gain and variable-gain. The parameters are set to $\rho=1$, $\Omega^{'}=1$, $C=1$, R_s = 0.01 nat/s, $\eta_1=\eta_3$ and $\mu_1=\mu_3$.

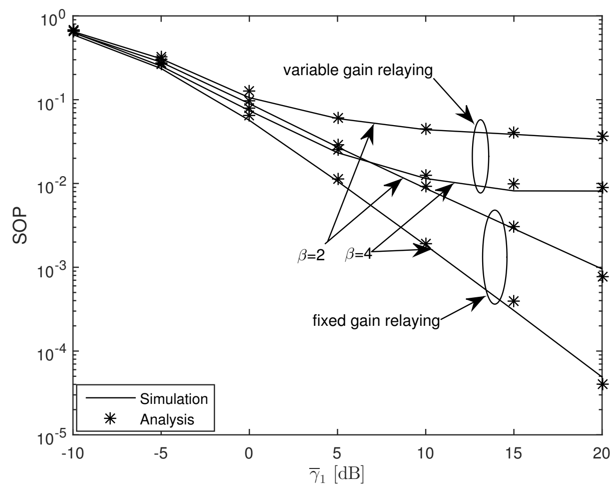

Fig. 2. SOP versus $\bar{\gamma}_1$ with $\eta=0.5,\mu=1,\alpha=4.2,\bar{\gamma}_2=10\ dB$, and $\bar{\gamma}_3=-10\ dB$.

In Fig. 2, we plot the SOP versus $\bar{\gamma}_1$ for both the fixed gain and variable gain relaying schemes with different values of β. At high SNR regions, it can be observed that increasing β can result in a good SOP performance. The reason is that the parameter β has the definition $\beta=(E[X])^2/Var[X]$, where X is a variable following a gamma distribution and $Var[X]$ is the variance operator, and $1/\beta$ is the amount of fading and is used to quantify the severity of fading experienced for a particular channel model. Thus, increasing β in turn results in good system performance. At high $\bar{\gamma}_1$, we can see that the variable gain scheme is independent of $\bar{\gamma}_1$ and zero floors

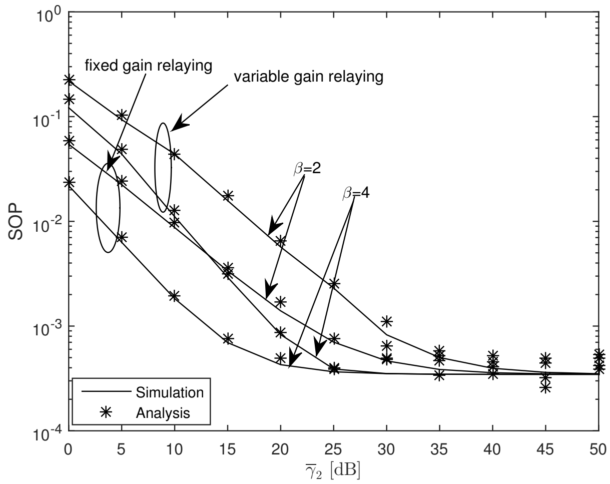

Fig. 3. SOP versus $\bar{\gamma}_2$ with $\eta = 0.5, \mu = 1, \alpha = 4.2$, $\bar{\gamma}_1 = 10\ dB$ and $\bar{\gamma}_3 = -10\ dB$.

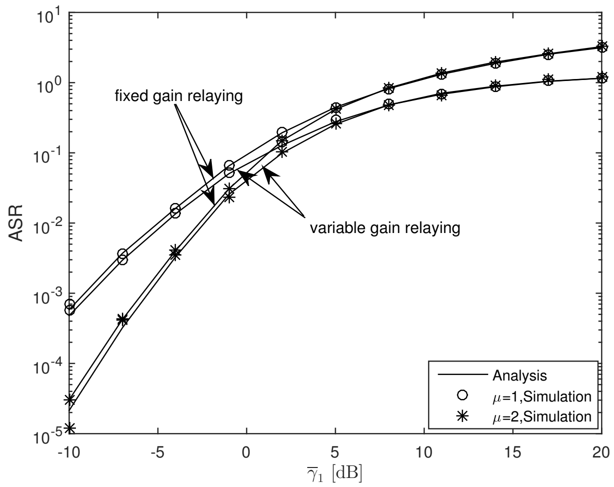

Fig. 4. ASR versus $\bar{\gamma}_1$ with $\eta = 0.5, \alpha = 4.2, \beta = 2$, $\bar{\gamma}_2 = 10\ dB$, and $\bar{\gamma}_3 = 1\ dB$.

appear. Using the same parameters as Fig. 2, in Fig. 3 we plot the SOP versus $\bar{\gamma}_2$ for both the fixed gain and variable gain relaying schemes with different values of β. Unlike the observations in Fig. 2, we can observe that zero floors happen for both schemes at high $\bar{\gamma}_2$.

In Fig. 4, we plot the ASR versus $\bar{\gamma}_1$ for the fixed gain and variable gain relaying schemes with different values of μ. It is clearly shown that a small μ can obtain a high ASR at low $\bar{\gamma}_1$. However, at high $\bar{\gamma}_1$, the difference can be ignored. Using the same parameters as Fig. 4, in Fig. 5 we plot the ASR versus $\bar{\gamma}_2$ for the fixed gain and variable gain relaying schemes with different values of μ. Similar observations can be obtained.

VI. Conclusions

In this correspondence, we have studied the secrecy performance of MRFFSO communication systems for both fixed gain and variable gain schemes over generalized fading channels. Result show that increasing the value of β can obtain better secrecy performance. In the future, we will consider the secrecy performance of Unmanned Aerial Vehicle (UAV)-based RF/FSO communication systems.

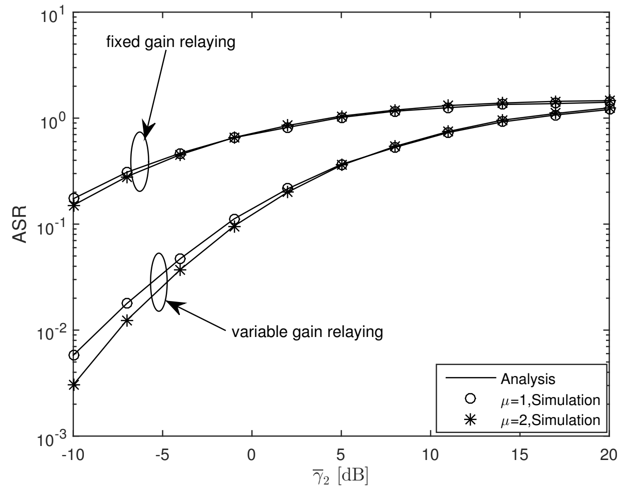

Fig. 5. ASR versus $\bar{\gamma}_2$ with $\eta = 0.5, \alpha = 4.2, \beta = 2$, $\bar{\gamma}_1 = 10\ dB$ and $\bar{\gamma}_3 = 1\ dB$.

References

[1] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commmun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231-2258, Jun. 2014.

[2] A. A. Farid and S. Hranilovic, "Outage capacity optimization for free-space optical links with pointing error," *J. Lightw. Technol.*, vol. 25, no. 7, pp. 1702-1710, Jul. 2007.

[3] E. Lee, J. Park, D. Han, and G. Yoon, "Performance analysis of the asymmetric dual-hop relay transmission with mixed RF/FSO links," *IEEE Photon. Technol. Lett.*, vol. 23, no. 21, pp. 1642-1644, Nov. 2011.

[4] I. S. Ansari, F. Yilmaz, and M. S. Alouini, "Impact of pointing errors on the performance of mixed RF/FSO dual-hop transmission systems," *IEEE Wireless Commun. Lett.*, vol. 2, no. 3, pp. 351-354, June 2013.

[5] H. Samimi, and M. Uysal , "End-to-end performance of mixed RF/FSO transmission systems," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1139-1144, Nov. 2013.

[6] J. Zhang, L. Dai, Y. Zhang, and Z. Wang, "Unified performance analysis of mixed radio frequency/free-space optical dual-hop transmission systems," *J. Lightw. Technol.*, vol. 33, no. 11, pp. 2286C2293, Jun. 2015.

[7] L. Yang, M. O. Hasna, and I. S. Ansari, "Unified performance analysis for multiuser mixed η-μ and $\mathcal{M}$-distribution dual-hop RF/FSO systems," *IEEE Trans. Commun.*, vol. 65, no. 8, pp. 3601-3613, Aug. 2017.

[8] N. I. Miridakis, M. Matthaiou, and G. K. Karagiannidis, "Multiuser relaying over mixed RF/FSO links," *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1634-1645, May 2014.

[9] J. Chen, L. Yang, and M.-S. Alouini, "Physical layer security for cooperative NOMA systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4645-4649, May 2018.

[10] L. Yang, M. O. Hasna, and I. S. Ansari, "Physical layer security for TAS/MRC systems with and without co-channel interference over η-μ fading channels," *IEEE Trans. Veh. Technol.*, DOI:10.1109/TVT.2018.2876915.

[11] F. J. Lopez-Martinez, G. Gomez, and J. M. Garrido-Balsells, "Physicallayer security in free-space optical communications," *IEEE Photon. J.*, vol. 7, no. 2, pp. 1-14, Apr. 2015.

[12] A. H. Abd El-Malek, A. M. Salhab, S. A. Zummo, and M. Alouini, "Security-reliability trade-off analysis for multiuser SIMO mixed RF/FSO relay networks with opportunistic user scheduling," *IEEE Trans Wireless Commun.*, vol. 15, no. 9, pp. 5904-5918, Sep. 2016 .

[13] H. Lei, Z. Dai, I. S. Ansari, K. Park, G. Pan, and M. Alouini, "On secrecy performance of mixed RF-FSO systems," *IEEE Photon. J.*, vol. 9, no. 4, Aug. 2017.

[14] M. D. Yacoub, "The κ-μ distribution and the η-μ distribution," *IEEE Antennas and Propag. Mag.*, vol. 49, no. 1, pp. 68-81, Feb. 2007.

[15] K. P. Peppas, "Dual-hop relaying communications with cochannel interference over η-μ fading channels," *IEEE Trans. Veh. Technol.*, vol. 62, no.8, pp. 4110-4116, Oct. 2013.

[16] A. Jurado-Navas, J. M. Garrido-Balsells, J. F. Paris, and A. Puerta-Notario, "A unifying statistical model for atmospheric optical scintillation," *in Numerical Simulations of Physical and Engineering Processes,* J. Awrejcewicz, Ed. Rijeka, Croatia: Intech, Sep. 2011, ch. 8.

[17] A. Jurado-Navas, J. M. Garrido-Balsells, J. F. Paris, M. Castillo-Vzquez, and A. Puerta-Notario, "Impact of pointing errors on the performance of generalized atmospheric optical channels," *Opt. Exp.*, vol. 20, no. 11, pp. 12550-12562, 2012.

[18] I. S. Gradshteyn, I. M. Ryzhic, and J. Alan, *Table of Integrals, Series and Products*, New York, NY, USA: Academia, 2000.

[19] (2001). Wolfram, Champaign, IL, USA. *The Wolfram Functions Site.* [Online]. Available: Available: http://functions.wolfram.com

[20] O. Ozel, E. Ekrem, and S. Ulukus, "Gaussian wiretap channel with amplitude and variance constraints," *IEEE Trans. Inf. Theory.*,vol. 61, no. 10, pp.5553-5563, Oct. 2015.

[21] A. Mostafa and L. Lampe, "Physical-layer security for MISO visible light communication channels," *IEEE J. Sel. Area Commun.*,vol. 33, no. 9, pp. 1806-1818, Sep. 2015.

[22] L. Wang, M. Elkashlan, J. Huang, R. Schober, and R. Mallik, "Secure transmission with antenna selection in MIMO Nakagami-m fading channels," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6054-6067, Nov. 2014.

[23] I. S. Ansari, S. Al-Ahmadi, F. Yilmaz, M. S. Alouini, and H. Yanikomeroglu, "A new formula for the BER of binary modulations with dual-branch selection over generalized-K composite fading channels," *IEEE Trans. Commun.*, vol. 59, no. 10, pp. 2654-2658, Oct. 2011.

[24] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marichev,*Integrals and Series*, vol. 1: Elementary Functions. New York, NY, USA: Gordon and Breach, 1992.

[25] M. Bloch, J. Barros, M. R. Rodrigues, and S. W. McLaughlin, "Wireless information-theoretic security ," *IEEE Trans. Inf. Theory.*,vol. 54, no. 6, pp. 2515-2534, Jun. 2008.

[26] H. Lei, C. Gao, Y. Guo, and G. Pan, "On physical layer security over generalized Gamma fading channels," *IEEE Commun. Lett.*,vol. 19, no. 7, pp. 1257C1260, Jul. 2015.