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Hybrid FSO/RF-FSO Systems over Generalized Málaga Distributed Channels with Pointing Errors

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***Abstract*—The combined effect of Málaga distributed atmospheric turbulence and pointing errors on the performance of a hybrid free-space optical (FSO)/ radio-frequency (RF)-FSO communication system is presented and analyzed in this paper. We considered three performance metrics, namely, outage probability, average bit error rate (BER) and average capacity. For each of the performance metrics, closed-form expressions are derived in terms of the Meijer's G function, analytical results are validated by Monte Carlo simulations and numerical values of the metrics are plotted for different channel conditions. Compared to a single FSO link or a single RF-FSO link, the proposed adaptive hybrid system achieves reduced outage probability, reduced BER and enhanced channel capacity at the cost of extra hardware.**

***Index Terms*—Free-space optics, Málaga distribution, adaptive RF-FSO link, amplify-and-forward relay.**

I. INTRODUCTION

The number of connected devices are growing exponentially and it would reach 20-25 billion by 2020. The current cellular backhaul optical fiber infrastructure is not sufficient to fulfil the huge bandwidth demand for rich multimedia based mobile applications. To overcome this difficulty, free space optical (FSO) communication system is considered as an emerging technology and have gained interest of many researchers in the communication industry due to its advantages including large bandwidth and high data rate that would be sufficient to manage the recent and future demands for modern days wireless communication systems. Moreover FSO system offers license-free spectrum, immunity to interference, highly secured, possibility of rapid deployment with low-cost maintenance and this system is suitable for the last mile backup application of future fifth generation (5G) communication systems. However, apart from its many advantages the main drawback of this technology is that this technology is heavily dependent on the weather conditions and is highly influenced by the atmospheric turbulence. Besides, transmitter/ receiver misalignment due to weak to heavy earthquakes, tornados may lead to beam vibration which is known as pointing error impairment [1].

To solve the last-mile connectivity problem, the mixed RF/FSO architecture are gaining more interest where both RF and FSO links are incorporated in a hybrid way and that has reflected in some recent literatures. In this architecture the FSO link and RF link connected in a hybrid manner may provide a way of reliable data transmission that would be an important alternate way for designing the next-generation mobile backhaul networks infrastructure. In this context, in our proposed FSO/RF-FSO architecture there exist two distinct transmission paths, a primary FSO link (S-D) and a backup RF-FSO link (S-R-D). In presence of clear line-of-sight (LOS) path during good atmospheric conditions, S-D link is used for better data transmission rate and better capacity. Under primary FSO link failure RF-FSO backup link is activated to sustain the connectivity. This particular hybrid system uses an adaptive algorithm to choose either a primary FSO link or amplify-and-forward based asymmetric RF-FSO link. One of the main concerns of the next generation cellular backhaul networks is the link availability and its reliability, which can be fulfilled or increased at least upto some extent using this hybrid scheme.

This study represents a hybrid FSO/RF-FSO transmission scheme using a generalized distributed channels with pointing error. Rayleigh distribution is used to model the fading in RF link whereas the FSO link is assumed to be characterised by generalized Málaga distributed turbulence channels with pointing error impairments. Málaga distribution have been chosen as, most of the other proposed statistical models characterizing the turbulence effect in FSO links [2] can be modelled by this Málaga distribution. The unified analytical closed-form expressions are obtained for some common used performance metrics (outage probability, average BER and average capacity) of the said system in terms of Meijer-G function. Various numerical results of different performance metrics are presented along with their corresponding simulation results to validate the proposed mathematical analysis. The overall performance of the system is analyzed and it is observed that the performance of the said system improves rather than a single FSO link, but considering the pointing errors, the performance degrades severely as the pointing errors contribute with the turbulence, in a multiplicative manner.

A. Literature Survey

One of the new strategies for improving the link reliability is using a mixed architecture composed of both RF and FSO links [3], [4]. In [5]–[8], authors have addressed different performance metrics using serial RF-FSO combination, while the parallel RF/FSO combination are considered in [9]–[11]. Some authors [12], [13] considered the effect of pointing error impairments for FSO link along with this mixed architecture and proposed novel coding schemes for switching between RF and FSO paths. On the other hand, different statistical models have been adopted for RF and FSO links to commensurate different atmospheric condition [14]–[16]. Some authors prefer the generalized Málaga distribution to model the FSO link in all weather condition [2].

B. Contributions

- An adaptive hybrid (FSO/ RF-FSO) transmission scheme is presented to increase the availability and reliability of FSO links. Though the performance analysis of the said system using Gamma-Gamma distribution under strong turbulence has been reported in [17], where the performance of the same hybrid FSO/RF-FSO transmission scheme is presented considering a unified Málaga distribution with pointing errors. The Málaga distribution is more general which is preferred over other fading models as it can be used for modelling different atmospheric turbulence conditions.
- Moreover, in this study, the performance analysis of the proposed system is performed considering the pointing error effects for FSO links that makes the signal fluctuate at a very high rate. The analytical closed-form expressions for different performance metrics are presented in terms of Meijer's G-functions. Further, all the mathematical analysis are verified through extensive Monte Carlo simulations.

The rest of this paper is organized as follows. The basic system model and its performance analylsis is presented in Section II. Section III provides numerical and computer simulation results. Finally, Section IV summarises the paper.

II. PERFORMANCE ANALYSIS

A. System and channel model

We begin our analysis with an architectural description of our proposed hybrid FSO/RF-FSO system. The source (S) consist of an FSO transmitter for primary FSO link (PL) and there is an RF transmitter for S-R link for the secondary RF-FSO link to communicate with destination D via relay node (R). The incoming RF signal from S is received at the relay R goes through a RF-FSO converter which accomplishes the subsequent RF-FSO conversion. The destination (D) consists of two distinct optical receivers for receiving incoming data through S-D primary link (PL) and backup S-R-D links (SL), respectively. There exist a feedback path from D to S for sending the channel state information (CSI) about the primary FSO link. When the atmospheric turbulence block the primary FSO link, S alter its data transmission path from PL to SL and notify D accordingly to switch to the receiver telescope that is aligned with R. Also, S transmits a pilot signal through primary FSO link at regular intervals to check the link condition so that the primary FSO link can be reactivated by sensing a confirmation feedback from D if the link quality meets the desired service level.

B. Modeling the Primary FSO Link

The primary FSO link experiences generalised Málaga distributed turbulence and pointing errors. If an IM/DD detection technique is employed, the probability density function (PDF) of the received instantaneous electrical signal to noise ratio (SNR) of the PL can be expressed as [2],

$$f_{\gamma_{fso}}(\gamma_{fso}) = \frac{{\xi_p}^2 \mathcal{A}}{4\gamma_{fso}} \sum_{m=1}^{\beta} b_m G_{1\,3}^{3\,0}\left[\mathcal{B}\sqrt{\frac{\gamma_{fso}}{\overline{\gamma}_{fso}}}\middle|_{{\xi_p}^2,\alpha_t,m}^{{\xi_p}^2+1}\right] \tag{1}$$

where $\mathcal{A} \triangleq \frac{2(\alpha_t)^{\frac{\alpha_t}{2}}}{(g_t)^{1+\frac{\alpha_t}{2}}\Gamma(\alpha_t)}\left(\frac{g_t k_t}{g_t k_t+\bar{\Omega_t}}\right)^{k_t+\frac{\alpha_t}{2}}$,
$\mathcal{B} = {\xi_p}^2 \alpha_t k_t \left(g+\bar{\Omega_t}\right)\left[\left({\xi_p}^2+1\right)\left(g_t k_t+\bar{\Omega_t}\right)\right]$,
$b_m = a_m[\alpha_t k_t/\left(g k_t+\bar{\Omega_t}\right)]^{-(\alpha_t+m)/2}$,
$a_m \triangleq \binom{\beta-1}{k_t-1}\frac{\left(g_t k_t+\bar{\Omega_t}\right)^{1-\frac{k_t}{2}}}{(k_t-1)!}\left(\frac{\bar{\Omega_t}}{g_t}\right)^{k_t-1}\left(\frac{\alpha_t}{k_t}\right)^{\frac{k_t}{2}}$,

$\bar{\Omega_t} = \Omega_t + 2b_0\rho_t + 2\sqrt{2b_0\rho_t\Omega_t}\cos(\Phi_A - \Phi_B)$, $G[\cdot]$ is the Meijers G function, and β, α_t, k_t, g_t and Ω_t are the fading parameters related to the atmospheric turbulence conditions [2], α_t is a positive parameter related to the effective number of large-scale of the scattering process, k_t is the amount of fading parameter and is a natural number, g_t denotes the average power of the scattering component received by off-axis eddies which are related with both average powers of the total scatter components ($2b_0$) and amount of scattering (ρ_t), with the value of the amount of scattering typically lying between zero and one, Ω_t represents the amount of average power of the line of sight (LOS) components between channel, ξ_p is the pointing error or misalignment coefficient and $K_{\alpha_t-k_t}(\cdot)$ is the modified Bessel function of the second kind of order $(\alpha_t - k_t)$. The corresponding cumulative distribution function (CDF) with pointing error is as follows

$$F_{\gamma_{fso}}(\gamma_{fso}) = \frac{{\xi_p}^2 \mathcal{A}}{2} \sum_{m=1}^{\beta} b_m G_{2\,4}^{3\,1}\left[\mathcal{A}\sqrt{\frac{\gamma_{fso}}{\overline{\gamma}_{fso}}}\middle|_{{\xi_p}^2,\alpha_t,m,0}^{1,\ {\xi_p}^2+1}\right] \tag{2}$$

C. Modeling the Backup RF-FSO Link

During primary link failure, S communicates with D via intermediate relay, R, using the backup S-R-D link (SL), reaized with an average power scaling (APS) based fixed-gain amplify-and-forward (AF) relay. The S-R link can be characterized with Rayleigh fading whereas the R-D FSO link irradiance is described by Málaga distribution with pointing errors impairments as expressed in (1). If the instantaneous received electrical SNR for S-R and R-D links are denoted with γ_{rf} and γ_{fso}^{SL}, respectively, the equivalent end-to-end instantaneous electrical SNR for an APS-AF relay is given by $\gamma_{mix} = \gamma_{rf}\gamma_{fso}^{SL}/(\mathcal{G}_r + \gamma_{fso}^{SL})$ [18, eq. (6)], where the relay gain is $\mathcal{G}_r = (1 + 1/N_0)$. As per our model, the S-R link experiences Rayleigh fading and the PDF of immediate SNR can be expressed as

$$f_{\gamma_{rf}}(\gamma_{rf}) = \frac{1}{\overline{\gamma}_{rf}}\exp\left(-\frac{\gamma_{rf}}{\overline{\gamma}_{rf}}\right) \quad ;\gamma_{rf} \geq 0, \tag{3}$$

where $\overline{\gamma}_{rf}$ is the average SNR. The CDF of the end-to-end SNR $F_{\gamma_{mix}}(\gamma_{mix})$ of this dual-hop RF-FSO backup link may be derived by integrating the conditional density over the whole range of γ_{fso}^{SL} and using [19, eq. (2.24.3.1)], resulting in a closed-form expression as

$$F_{\gamma_{mix}}(\gamma_{mix}) = 1 - \mathcal{A}\exp\left(-\frac{\gamma_{mix}}{\overline{\gamma}_{mix}}\right) G_{2\ 7}^{7\ 0}\left[\omega\middle|_{\mathcal{D}_1}^{\kappa_1,\kappa_2}\right] \tag{4}$$

where, $\mathcal{D}_1 \in \left\{\frac{\xi_p{}^2}{2}, \kappa_1, \frac{\alpha_t}{2}, \frac{\alpha_t+1}{2}, \frac{k_t}{2}, \frac{k_t+1}{2}\right\}, \kappa_1 = \left(\xi_p{}^2+1\right)/2, \kappa_2 = \left(\xi_p{}^2+2\right)/2$ and $\omega = \frac{\mathcal{B}^2\gamma_{mix}\mathcal{G}_r}{16\overline{\gamma}_{rf}\overline{\gamma}_{fso}^{SL}}$. Therefore, the corresponding PDF of the end-to-end SNR $F_{\gamma_{mix}}(\gamma_{mix})$ can be expressed as [19, 8.2.2.30]

$$\begin{aligned} f_{\gamma_{mix}}(\gamma_{mix}) &= \frac{\mathcal{A}}{\overline{\gamma}_{mix}}\exp\left(-\frac{\gamma_{mix}}{\overline{\gamma}_{mix}}\right) G_{2\ 7}^{7\ 0}\left[\omega\gamma_{mix}\middle|_{\mathcal{D}_1,0}^{\kappa_1,\kappa_2}\right] \\ &- \mathcal{A}\omega\exp\left(-\frac{\gamma_{mix}}{\overline{\gamma}_{mix}}\right) G_{3\ 8}^{7\ 1}\left[\omega\gamma_{mix}\middle|_{\mathcal{D}_1,-1,0}^{\kappa_1,\kappa_2}\right] \end{aligned} \tag{5}$$

D. Link Switching Operation

The high-speed FSO link is the primary link (PL) which remains active until the received signal level γ_{fso}^{PL} falls below a certain specified threshold γ_{th}^{fso}, and this is monitored at frequent intervals at D to maintain the quality of service (QoS) of the system. When the received signal level deteriorates, to maintain the QoS of the system, an adaptive algorithm at S determines the path for further data transmission depending on the feedback sent from D. In this algorithm, when the PL falls into outage, the SL is followed for further data transmission if the qualities of both links of the SL overshoot a certain predefined threshold γ_{th}^{mix}; otherwise, the whole system falls into outage [9].

E. Outage Probability

To ensure QoS of the considered hybrid system, the instantaneous end-to-end SNR, γ must not fall below the predetermined threshold γ_{th}. Otherwise, the system encounters an outage and data transmission stops. Outage probability is important for checking outage situation and to ensure uninterrupted data transmission when the system operates under adverse weather conditions. In this considered hybrid system, an outage occurs when the instantaneous end-to-end SNR of both links (PL and SL) are not capable of meeting the respective threshold levels. Therefore the outage probability of the whole system can be mathematically expressed as

$$P_{out} = P_{out}^{fso(PL)}\left(\gamma_{th}^{fso}\right) P_{out}^{mix}\left(\gamma_{th}^{mix}\right) \tag{6}$$

where $P_{out}^{fso(PL)}$ and P_{out}^{mix} are the outage probability of the PL and the SL given in (2) and (4) respectively. The predetermined thresholds γ_{th}^{fso} and γ_{th}^{mix} act as the minimum SNR above which the links can guarantee a specific QoS.

F. Average Bit-Error Rate

In our considered hybrid FSO/ RF-FSO system at any given instance only one link (PL or SL) remain active during non-outage period. Therefore, considering three distinct scenarios as described in Section-II-D, the average BER for the entire system can be formulated as [17]

$$\begin{aligned} BER &= \frac{B^{fso}\left(\gamma_{th}^{fso}\right)}{1-P_{out}^{(1)}} + \frac{P_{out}^{rf}\left(\gamma_{th}^{mix}\right)\ B^{mix}\left(\gamma_{th}^{mix}\right)}{1-P_{out}^{fso(PL)}\left(\gamma_{th}^{fso}\right)} \\ &+ \frac{P_{out}^{fso(SL)}\left(\gamma_{th}^{mix}\right)\ B^{mix}\left(\gamma_{th}^{mix}\right)}{\left(1-P_{out}^{(1)}\right)\left(1-P_{out}^{rf}\left(\gamma_{th}^{mix}\right)\right)}, \end{aligned} \tag{7}$$

where $B^{fso}\left(\gamma_{th}^{fso}\right)$ and $B^{mix}\left(\gamma_{th}^{mix}\right)$ are the average BER when PL and SL links are active, respectively, while $P_{out}^{fso(PL)}\left(\gamma_{th}^{fso}\right)$ and $P_{out}^{fso(SL)}\left(\gamma_{th}^{fso}\right)$ are the outage probabilities of the FSO links at S-D and R-D links respectively. The outage probability of the S-R link $P_{out}^{rf}\left(\gamma_{th}^{mix}\right)$ is given in [17, eq. (22)]. During the active primary FSO link, the average BER considering OOK modulation scheme, can be expressed as

$$B^{fso}\left(\gamma_{th}^{fso}\right) = \int_{\gamma_{th}^{fso}}^{\infty} P\left(e\middle|\gamma_{fso}^{PL}\right) f_{\gamma_{fso}^{SL}}\left(\gamma_{fso}^{PL}\right) \mathrm{d}\gamma_{fso}^{PL}. \tag{8}$$

The average BER, when secondary RF-FSO link is active, is

$$B^{mix}\left(\gamma_{th}^{mix}\right) = \int_{\gamma_{th}^{mix}}^{\infty} P\left(e\middle|\gamma_{mix}\right) f_{\gamma_{mix}}\left(\gamma_{mix}\right) \mathrm{d}\gamma_{mix} \tag{9}$$

After some mathematical manipulation using [20, eq. (1.211.3)], [19, eq. (2.24.1.1), (8.4.14.2)] and [21, eq. (26)], the above integral can be expressed as a sum of individual integrals as

$$B^{mix}\left(\gamma_{th}^{mix}\right) = (\mathcal{B}_1+\mathcal{B}_2) - (\mathcal{P}_1+\mathcal{P}_2+\mathcal{P}_3+\mathcal{P}_4) \tag{10}$$

where,

$$\begin{aligned} \mathcal{B}_1 &= \frac{\mathcal{A}}{2\sqrt{\pi}\overline{\gamma}_{mix}}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^q\left(\frac{1}{2}\right)^{-q-1} \\ &G_{4\ 8}^{7\ 2}\left[2\omega\middle|_{\mathcal{D}_1,0,-q-1}^{-q,1/2-q-1,\kappa_1,\kappa_2}\right] \end{aligned} \tag{11}$$

$$\begin{aligned} \mathcal{B}_2 &= \frac{\omega\mathcal{A}}{2\sqrt{\pi}\overline{\gamma}_{mix}}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^q\left(\frac{1}{2}\right)^{-q-1} \\ &G_{4\ 5}^{7\ 3}9\left[2\omega\middle|_{\mathcal{D}_2,-1,0,-q-1}^{-1,-q,1/2-q-1,\frac{\xi_p{}^2-1}{2},\frac{\xi_p{}^2}{2}}\right] \end{aligned} \tag{12}$$

$$\begin{aligned} \mathcal{P}_1 &= \frac{\mathcal{A}}{12\overline{\gamma}_{mix}}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{1}{2}+\frac{1}{\overline{\gamma}_{mix}}\right)^q \\ &(\gamma_{th}^{mix})^{(q+1)}G_{3\ 8}^{7\ 1}\left[\omega\gamma_{th}^{mix}\middle|_{\mathcal{D}_1,0,-q-1}^{-q,\kappa_1,\kappa_2}\right] \end{aligned} \tag{13}$$

$$\begin{aligned} \mathcal{P}_2 &= \frac{\mathcal{A}}{4\overline{\gamma}_{mix}}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{2}{3}+\frac{1}{\overline{\gamma}_{mix}}\right)^q \\ &(\gamma_{th}^{mix})^{(q+1)}G_{3\ 8}^{7\ 1}\left[\omega\gamma_{th}^{mix}\middle|_{\mathcal{D}_1,0,-q-1}^{-q,\kappa_1,\kappa_2}\right] \end{aligned} \tag{14}$$

$$\mathcal{P}_3 = \frac{\mathcal{A}\omega}{12}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{1}{2}+\frac{1}{\overline{\gamma}_{mix}}\right)^q \left(\gamma_{th}^{mix}\right)^{(q+1)} G^{7\;2}_{4\;9}\left[\omega\gamma_{th}^{mix}\middle|{}^{-1,-q,\frac{\xi_p{}^2-1}{2},\frac{\xi_p{}^2}{2}}_{\mathcal{D}_2,-1,-q-1,0}\right] \tag{15}$$

$$\mathcal{P}_4 = \frac{\mathcal{A}\omega}{4}\sum_{q=0}^{\infty}\frac{(-1)^q}{q!}\left(\frac{2}{3}+\frac{1}{\overline{\gamma}_{mix}}\right)^q \left(\gamma_{th}^{mix}\right)^{(q+1)} G^{7\;2}_{4\;9}\left[\omega\gamma_{th}^{mix}\middle|{}^{-1,-q,\frac{\xi_p{}^2-1}{2},\frac{\xi_p{}^2}{2}}_{\mathcal{D}_2,-1,-q-1,0}\right] \tag{16}$$

G. *Average Capacity*

Considering at least any one link remain active in this hybrid system, the average capacity of this considered hybrid system can be formulated as [17]

$$C = C_{fso}^{PL}\left(\gamma_{th}^{fso}\right) + P_{out}^{fso(PL)}\left(\gamma_{th}^{fso}\right)\ C_{mix}\left(\gamma_{th}^{mix}\right) + P_{out}^{rf}\left(\gamma_{th}^{mix}\right)\left[1-P_{out}^{fso(SL)}\left(\gamma_{th}^{mix}\right)\right]\ C_{fso}^{SL}\left(\gamma_{th}^{mix}\right), \tag{17}$$

where $P_{out}^{fso(PL)}\left(\gamma_{th}^{fso}\right)$ and $P_{out}^{rf}\left(\gamma_{th}^{mix}\right)$ are the outage probability of PL and the S-R link of S-R-D link (SL) respectively. $C_{fso}^{PL}\left(\gamma_{th}^{fso}\right)$ is the average capacity of the system, during PL is active. Whereas, during the outage at PL, when both S-R and R-D links are above cut-off threshold, $C_{mix}\left(\gamma_{th}^{mix}\right)$ is the average capacity of the SL. Again, during this situation when the PL is suffering from outage and $\gamma_{rf} < \gamma_{th}^{mix}$ i.e, S-R (RF) link also falls under outage P_{out}^{rf}, the R-D FSO link may remains active and busy in transmitting some stored data in relay node with a capacity $C_{fso}^{SL}\left(\gamma_{th}^{mix}\right)$.

$$C_{fso}^{PL}\left(\gamma_{th}^{fso}\right) = \int_{\gamma_{th}^{fso}}^{\infty}\log_2\left(1+\gamma_{fso}^{PL}\right) f_{\gamma_{fso}^{SL}}\left(\gamma_{fso}^{PL}\right)\mathrm{d}\gamma_{fso}^{PL} \tag{18}$$

Furthermore, the average capacity when PL is under outage and SL become active,

$$C_{mix}\left(\gamma_{th}^{mix}\right) = \int_{\gamma_{th}^{mix}}^{\infty}\log_2\left(1+\gamma_{mix}\right) f_{\gamma_{mix}}(\gamma_{mix})\mathrm{d}\gamma_{mix} \tag{19}$$

can be expressed as a combination of four individual integrals, $C_{mix}\left(\gamma_{th}^{mix}\right) = (\mathcal{C}_1+\mathcal{C}_2)-(\mathcal{C}_3+\mathcal{C}_4)$, where the closed-form of each term using [20, eq. (1.211.3)], [19, eq. (2.24.1.1), (8.4.6.5)] and [21, eq. (26)] can be expressed as follows

$$\mathcal{C}_1 = \frac{\mathcal{A}}{\ln(2)\overline{\gamma}_{mix}}\sum_{q=1}^{\infty}\frac{(-1)^{q+1}}{q!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^{-q-1} G^{7\;1}_{3\;7}\left[\omega\overline{\gamma}_{mix}\middle|{}^{-q,\kappa_1,\kappa_2}_{\mathcal{D}_1,0}\right] \tag{20}$$

$$\mathcal{C}_2 = \frac{\mathcal{A}}{\ln(2)\overline{\gamma}_{mix}}\sum_{q=1}^{\infty}\frac{(-1)^{q+1}}{q!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^{-q-1} G^{7\;2}_{4\;8}\left[\omega\overline{\gamma}_{mix}\middle|{}^{-q,-1,\frac{\xi_p{}^2-1}{2},\frac{\xi_p{}^2}{2}}_{\mathcal{D}_2,-1,0}\right] \tag{21}$$

$$\mathcal{C}_3 = \frac{1}{\ln(2)}\sum_{q=0}^{\infty}\frac{(-1)^{q+1}}{q!}\sum_{p=0}^{\infty}\frac{(-1)^p}{p!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^p \frac{\mathcal{A}}{\overline{\gamma}_{mix}}\left(\gamma_{th}^{mix}\right)^{p+q+1} G^{7\;1}_{3\;8}\left[\omega\gamma_{th}^{mix}\middle|{}^{-p-q,\kappa_1,\kappa_2}_{\mathcal{D}_1,0,-p-q-1}\right] \tag{22}$$

$$\mathcal{C}_4 = \frac{1}{\ln(2)}\sum_{q=0}^{\infty}\frac{(-1)^{q+1}}{q!}\sum_{p=0}^{\infty}\frac{(-1)^p}{p!}\left(\frac{1}{\overline{\gamma}_{mix}}\right)^p \mathcal{A}\omega\left(\gamma_{th}^{mix}\right)^{p+q+1} G^{7\;2}_{4\;9}\left[\omega\gamma_{th}^{mix}\middle|{}^{-1,-p-q,\kappa_1,\kappa_2}_{\mathcal{D}_2,-1,0,-p-q-1}\right] \tag{23}$$

where, $\mathcal{D}_2 = \frac{\xi_p{}^2-2}{2}, \frac{\xi_p{}^2-1}{2}, \frac{\alpha_t-2}{2}, \frac{\alpha_t-1}{2}, \frac{k_t-2}{2}, \frac{k_t-1}{2}$

III. NUMERICAL RESULTS AND DISCUSSION

In this section, the performance of our proposed hybrid FSO/RF-FSO system is presented in terms of different performance metrics. All the performance metrics are measured in presence of pointing error effects (ξ_p) for each FSO links and compared with the single RF-FSO link.

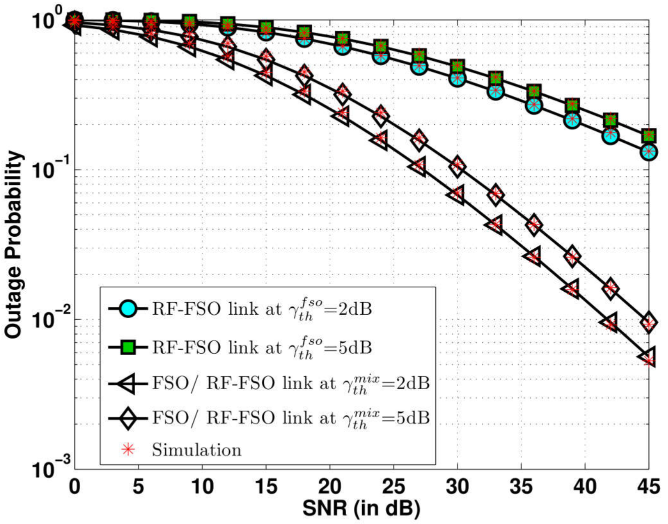

Fig. 1. Outage probability with threshold $\gamma_{th}^{mix} = 2, 5$ dB in presence of pointing error [$\xi_p = 0.9129$].

The outage probability of the hybrid FSO system is presented along with the Monte-Carlo simulations in Fig. 1 which clearly indicates that this scheme provides much better outage probability than any single RF-FSO link under same environments.

Fig. 2 demonstrates the average BER performance of the proposed scheme and depicts the improvements achieved over single RF-FSO link.

Finally, the average capacity of the system at threshold 2 dB is presented in Fig. 3 for three different depths of pointing error parameter ($\xi_p = 0.9129$, $\xi_p = 0.6890$ and $\xi_p = 0.5422$). Here, the increasing numeric value of pointing error indicates lowering the effects of pointing error. The average capacity of overall system of this hybrid scheme increases, but the pointing error effect restrict the average capacity of the system.

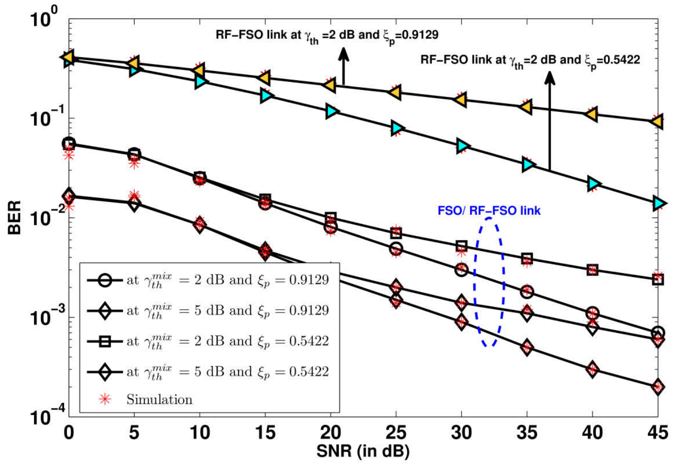

Fig. 2. Average BER with threshold $\gamma_{th}^{mix} = 2, 5$ dB in presence of pointing error [$\xi_p = 0.9129$ and $\xi_p = 0.5422$].

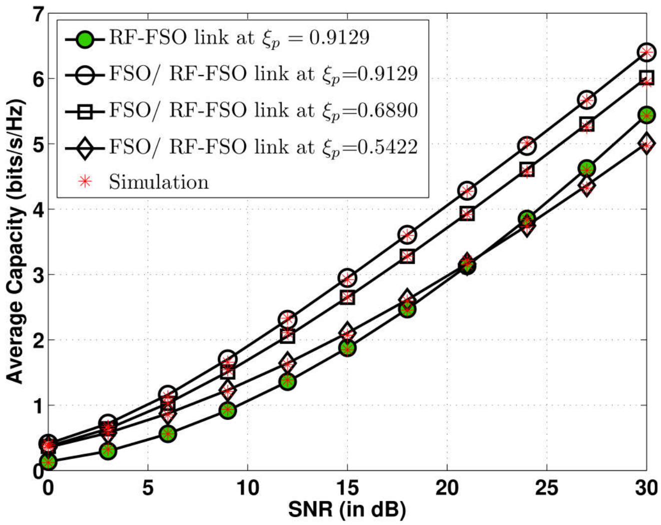

Fig. 3. Average capacity with threshold $\gamma_{th}^{mix} = 2$dB in presence of pointing error [$\xi_p = 0.9129$, $\xi_p = 0.6890$ and $\xi_p = 0.5422$].

IV. CONCLUSION

In this paper, we present a hybrid FSO system which operates on the principle of link adaptation through switching between primary FSO link and backup RF-FSO link. Generalized Málaga distribution is used to model the turbulence effects and it is assumed that pointing errors are also present in the FSO links. We have derived expressions for different performance metrics and presented numerical results along with Monte Carlo simulation results to validate those expressions. Further, the impact on the link performance has been studied for different values of pointing error. When compared to the conventional serial RF-FSO link this hybrid FSO system achieves improvement in outage and BER performances.

REFERENCES

[1] H. G. Sandalidis, T. A. Tsiftsis, G. K. Karagiannidis, and M. Uysal, "BER Performance of FSO Links over Strong Atmospheric Turbulence Channels with Pointing Errors," *IEEE Commun. Lett.*, vol. 12, no. 1, pp. 44–46, Jan 2008.

[2] I. S. Ansari, F. Yilmaz, and M. Alouini, "Performance analysis of free-space optical links over malaga ($\mathcal{M}$) turbulence channels with pointing errors," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 1, pp. 91–102, 2016.

[3] A. Douik, H. Dahrouj, T. Y. Al-Naffouri, and M. S. Alouini, "Hybrid radio/free-space optical design for next generation backhaul systems," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2563–2577, Jun. 2016.

[4] H. Dahrouj, A. Douik, F. Rayal, T. Y. Al-Naffouri, and M. S. Alouini, "Cost-effective hybrid RF/FSO backhaul solution for next generation wireless systems," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 98–104, Oct. 2015.

[5] I. S. Ansari, F. Yilmaz, and M. S. Alouini, "On the performance of mixed RF/FSO dual-hop transmission systems," in *Proc. IEEE VTC*, Jun. 2013, pp. 1–5.

[6] E. Zedini, H. Soury, and M. S. Alouini, "On the performance analysis of dual-hop mixed FSO/RF systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3679–3689, May 2016.

[7] B. Bag, A. Das, A. Chandra, and C. Bose, "Capacity analysis for Rayleigh/Gamma-Gamma mixed RF/FSO link with fixed-gain AF relay," *IEICE Trans. Commun.*, vol. E100-B, no. 10, pp. 1747–1757, Oct. 2017.

[8] J. Park, E. Lee, G. Park, B. Roh, and G. Yoon, "Performance analysis of asymmetric RF/FSO dual-hop relaying systems for UAV applications," in *Proc. IEEE Military Communications Conference*, San Diego, CA, Nov. 2013, pp. 1651–1656.

[9] Usman, M. and Yang, H. C. and Alouini, M. -S., "Practical switching-based hybrid FSO/RF transmission and its performance analysis," *IEEE Photon. J.*, vol. 6, no. 5, pp. 1–13, Oct. 2014.

[10] Abdulhussein, A. and Oka, A. and Nguyen, T. T. and Lampe, L., "Rateless coding for hybrid free-space optical and radio-frequency communication," *IEEE Trans. Wireless Commun.*, vol. 9, no. 3, pp. 907–913, Mar. 2010.

[11] Zhang, W. and Hranilovic, S. and Shi, C., "Soft-switching hybrid FSO/RF links using short-length Raptor codes: Design and implementation," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1698–1708, Dec. 2009.

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

[13] 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, Jun. 2013.

[14] L. Kong, W. Xu, L. Hanzo, H. Zhang, and C. Zhao, "Performance of a free-space-optical relay-assisted hybrid RF/FSO system in generalized-distributed channels," *IEEE Photon. J.*, vol. 7, no. 5, pp. 1–19, Oct. 2015.

[15] E. Zedini, I. S. Ansari, and M. S. Alouini, "Performance analysis of mixed Nakagami-m and gamma-gamma dual-hop FSO transmission systems," *IEEE Photon. J.*, vol. 7, no. 1, pp. 1–20, Feb. 2015.

[16] 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. 2286–2293, Jun. 2015.

[17] B. Bag, A. Das, I. S. Ansari, A. Proke, C. Bose, and A. Chandra, "Performance analysis of hybrid fso systems using fso/rf-fso link adaptation," *IEEE Photonics Journal*, vol. 10, no. 3, pp. 1–17, June 2018.

[18] M. O. Hasna and M. S. Alouini, "A performance study of dual-hop transmissions with fixed gain relays," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1963–1968, Nov. 2004.

[19] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marichev, *Integrals and Series: More Special Functions*. Amsterdam, The Netherlands: Gordon and Breech Science, 1990, vol. 3.

[20] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. San Diego: Academic Press, 2000.

[21] V. S. Adamchik and O. I. Marichev, "The algorithm for calculating integrals of hypergeometric type functions and its realization in REDUCE system," in *Proc. ACM ISSAC*, Jul. 1990, pp. 212–224.