Multihop RIS-Assisted FSO-RF System Over Double Generalized Gamma Fading

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Abstract—Reconfigurable intelligent surface (RIS) is a promising technology to avoid signal blockage by creating virtual line-of-sight (LOS) connectivity for free-space optical (FSO) and radio frequency (RF) wireless systems. This paper considers a mixed FSO-RF system by employing multiple RISs in both the links for multihop transmissions to extend the communication range. We develop probability density function (PDF) and cumulative density function (CDF) of the signal-to-noise ratio (SNR) for the cascaded channels by considering double generalized gamma (dGG) turbulence with pointing errors for the FSO link and the dGG distribution to model the signal fading for the RF. We derive exact closed-form expressions of the outage probability, average bit-error-rate (BER), and ergodic capacity using the decode-and-forward (DF) relaying for the mixed system. We also present asymptotic analysis on the performance in the high SNR regime depicting the impact of channel parameters on the diversity order of the system. We use computer simulations to demonstrate the effect of system and channel parameters on the RIS-aided multihop transmissions.

Index Terms—Bit error rate, ergodic rate, Fox-H function, outage probability, reconfigurable intelligent surface (RIS).

I. INTRODUCTION

Reconfigurable intelligent surface (RIS) is emerging as a disruptive technology for 6G wireless communications [1]. RISs are artificial planar structures of metasurfaces, intelligently programmed to control electromagnetic waves in the desired direction. A single RIS can contain hundreds of elements, each sub-wavelength size, to beamform the signal for enhanced performance without requiring expensive relaying procedures. In recent years, free-space optical (FSO) for backhaul/fronthaul and radio frequency (RF) for broadband access have been considered as a potential architecture for next generation wireless systems. The FSO is a line-of-sight (LOS) technology with a higher unlicensed optical spectrum, which can be employed for secured high data rate transmissions. The RIS can assist FSO and RF communications to resolve signal blockage for enhanced performance.

The use of RIS for wireless systems is gaining greater research interests. The literature contains results of RIS-assisted RF transmissions over Rayleigh, Rician, Nakagami-\textit{m}, and fluctuating two-ray (FTR) fading channels [2]–[11]. RIS-assisted FSO [12]–[13], and mixed systems of RIS-assisted RF and conventional FSO [19]–[21]. There is a limited research on RIS-assisted FSO system with different turbulence conditions. The authors in [12]–[18] considered the Gamma-Gamma atmospheric turbulence with pointing errors to analyze the RIS based FSO system. By employing the central limit theorem, [15] used Gaussian distribution approximation to analyze the RIS-assisted FSO system. In our previous paper [17], we presented a unified performance analysis on RIS-empowered FSO for Fisher–Snedecor, Gamma-Gamma, and Malága distributions for atmospheric turbulence with pointing errors over various weather conditions. On the other hand, the RIS has only been employed on the RF side for mixed FSO-RF systems [19]–[21]. In [19], the performance of dual-hop visible light communication (VLC)-RF system was analyzed. In [20], [21], the authors mixed an FSO link over Gamma-Gamma turbulence with RIS-assisted RF link over Rayleigh fading.

Multihop cooperative relaying techniques are generally employed to extend the communication range and quality of service for the line-of-sight FSO technology and avoid signal blockage in the RF connectivity [22], [23]. In [24], the authors proposed a deep reinforcement learning (DRL) based multi-hop RIS-empowered terahertz system with Rician fading. The authors in [18] analyzed the performance of a multi-hop RIS assisted FSO system by presenting probability density function (PDF) and cumulative distribution function (CDF) of the cascaded channel assuming Gamma-Gamma atmospheric turbulence with pointing errors. It should be mentioned that the double generalized Gamma (dGG) fading is more versatile that can be used to model accurately different propagation conditions [25], [26], and yet to be included for RIS based analysis for RF and FSO systems. It is noted that the existing Meijer’s-G representation of the PDF of the dGG requires ratio of shape parameters integer for an exact performance analysis for FSO systems [27], [28].

In this paper, we consider a mixed FSO-RF system by employing multiple RISs in both the links for multihop transmissions to extend the communication range by assuming the dGG turbulence with pointing errors for the FSO link and the dGG distribution to model the signal fading for the RF. By deriving statistical results of the product of independent and non identical (i.i.d.) random variables with a general PDF structure, we develop PDF and CDF of the signal-to-noise ratio (SNR) for the cascaded FSO and RF channels. We derive exact closed-form expressions of outage probability, average bit-error-rate (BER), and ergodic capacity for the mixed system with the decode-and-forward (DF) relaying in terms of Fox-H function. We also present asymptotic analysis in the high SNR
regime for outage probability and average BER in terms of simpler Gamma functions, and derive diversity order depicting the impact of fading parameters on the performance of the considered system. We use computer simulations to demonstrate the performance of the multihop system and validate the accuracy of derived analytical expressions through Monte-Carlo simulations for various fading scenarios.

II. SYSTEM MODEL

We consider a hybrid multihop FSO/RF system assisted by multiple RISs in both transmission links. We use the DF relaying protocol to integrate the links. The source communicates data to the DF relay through $K-1$ O-RISs, which is relayed to the destination through $K-1$ O-RISs. The received signal $y_R$ at the relay is given by [18]

$$y_R = h_t h_{s,1} \prod_{j=1}^{K-2} h_{j,j+1} h_{K-1,D} s + w_R \quad (1)$$

where $h_t$ is the path gain of the cascaded FSO link, $s$ is the transmitted signal of source with power $P$, $w_R$ is the additive white Gaussian noise (AWGN) with variance $\sigma_w^2$, $h_{s,1}$ is the channel coefficient from the source to the first-optical RIS, $h_{j,j+1}$ is the channel from $j$th-optical RIS to $(j+1)$-optical RIS, and $h_{K-1,D}$ is the channel coefficient of last $(K-1)$-optical RIS to relay.

Assuming perfect decoding at the relay and transmitted with power $P$, the received signal at destination is given by

$$y = g_t g_{s,1} \prod_{j=1}^{K-2} g_{j,j+1} g_{K-1,D} s + w_D \quad (2)$$

where $g_t$ is the path gain of the cascaded RF link, $w_D$ is the additive white Gaussian noise (AWGN) with variance $\sigma_w^2$, $g_{s,1}$ is the channel coefficient from the relay to the first RIS, $g_{j,j+1}$ is the channel from $j$th-RIS to $(j+1)$-RIS, and $g_{K-1,D}$ is the channel coefficient of the last $(K-1)$-RIS to destination. We consider the dGG distribution to model the atmospheric turbulence in the FSO and multi-path fading for the RF link. As such, the dGG is the product of two generalized Gamma functions. The PDF of a generalized Gamma function is given as

$$f_X(x) = \frac{\alpha x^{\alpha-1}}{(\beta)^\alpha \Gamma(\beta)} \exp \left( -\frac{\beta}{\Omega} x^\alpha \right) \quad (3)$$

where $\alpha, \beta$ are Gamma distribution shaping parameters and $\Omega = \left( \frac{\Gamma(\beta)}{\Gamma(\beta/2)} \right)^{\alpha/2}$ is the $\alpha$-root mean value.

In addition to the atmospheric turbulence, we consider pointing errors in each hop of the FSO link such that the combined channel fading is $h_{i,j} = h_{i,j}^{(p)} h_{i,j}^{(t)}$, where subscripts $(t)$ and $(p)$ denote atmospheric turbulence and pointing error fading coefficients. To characterize the statistics of pointing errors $h_{i,j}^{(p)}$, we use the recently proposed model for optical RIS in [14], which is based on the zero-bases model [29]:

$$f_{h_{i,j}^{(p)}}(x) = \frac{\rho^2}{A_0} x^{2\alpha-1}, 0 \leq x \leq A_0, \quad (4)$$

where the term $A_0 = \text{erf}(v)^2$ denotes the fraction of collected power. Define $v = \sqrt{\pi/2} a_r/\omega_z$ with $a_r$ as the aperture radius and $\omega_z$ as the beam width. We define the term $\rho^2 = \frac{\omega_r^2}{\omega_{eq}^2}$ where $\omega_{eq}$ is the equivalent beam width at the receiver. The use of $\chi_x = 4\sigma_x^2 d_1^2 + 16\sigma_z^2 d_2^2$ models the pointing errors for the RIS-FSO system, where $\sigma_x$ and $\sigma_z$ represent pointing error and RIS jitter angle standard deviation defined in [19].

III. STATISTICAL RESULTS FOR CASCADED CHANNELS

To facilitate the performance analysis, we require density and distribution functions of the cascaded FSO channels $h = \prod_{k=1}^{K} h_{i,k} = \prod_{k=1}^{K} h_{i,k}^{(p)}$ and cascaded RF channels $g = \prod_{j=1}^{K} g_{j,j+1}$ in the following two propositions, we express the PDF of dGG $g_t$ and product of dGG with pointing errors $h_i$ in terms of Fox-H function to remove the constraint of integer-valuing fading parameter expression of Meijer-G representation [25], [27].

Proposition 1. The PDF of double generalized-gamma $g_i = \chi_1 \chi_2$, where $\chi_1 \sim \mathcal{GG}G(\alpha_1, \beta_1, \Omega_1)$ and $\chi_2 \sim \mathcal{GG}G(\alpha_2, \beta_2, \Omega_2)$ is given by

$$f_{g_i}(x) = \frac{\rho^2 \chi_x^2}{(\alpha_1)^{\alpha_1} \beta_1^\alpha_1 \Gamma(\beta_1) \Gamma(\beta_2)} \int_0^\infty u^{\alpha_2 \beta_2 - 1} e^{-\chi_x} du \quad (5)$$

where $\psi = \left( \frac{\beta_1}{\beta_2} \right)^{\frac{\alpha_1}{\alpha_2}} \left( \frac{\beta_1}{\beta_2} \right)^{\frac{1}{\alpha_2}}$.

Proof: Using the PDF of the product of two random variables $f_{g_i}(x) = \int_0^\infty f_{\chi_1}(x, u) f_{\chi_2}(u) du$

$$f_{g_i}(x) = \frac{\rho^2 \chi_x^2}{(\alpha_1)^{\alpha_1} \beta_1^\alpha_1 \Gamma(\beta_1) \Gamma(\beta_2)} \int_0^\infty u^{\alpha_2 \beta_2 - 1} e^{-\chi_x} du \quad (6)$$

Using $u^{-\alpha_1} = t$, and representing the exponential function using Meijer-G, we get

$$f_{g_i}(x) = \frac{\rho^2 \chi_x^2}{(\alpha_1)^{\alpha_1} \beta_1^\alpha_1 \Gamma(\beta_1) \Gamma(\beta_2)} \int_0^\infty \frac{t^{\alpha_2 \beta_2 - 1}}{\alpha_1} C_{1,0}^{\alpha_2 \beta_2} \frac{\chi_x^2}{t^2} \ dt = G_{0.1}^{1,0} \left[ \frac{\chi_x^2}{\alpha_1}, t, 0 \right] C_{1,0}^{\alpha_2 \beta_2} \left[ \frac{\chi_x^2}{\alpha_1}, 1 \right] \quad (7)$$

Applying identity [30] 07.34.21.0012.01 in [7], we get (5). \hfill $\blacksquare$

Proposition 2. If the pointing error parameter $h_p$ is distributed according to [4], then the PDF of the single FSO link $h_{i,j} = g_i h_p$ with the combined effect of dGG and pointing errors is given by

$$f_{h_i}(x) = \frac{\rho^2 x^{2\alpha_i \beta_i - 1}}{A_0^{\alpha_i} \beta_i^{\alpha_i} \Gamma(\beta_1) \Gamma(\beta_2)} \left[ (\rho^2 - \alpha_2 \beta_2 + 1) \right] \Gamma(\beta_2)$$

$$H_{i,j}^{\theta_x} \left[ \left( \frac{\chi_x^2}{\alpha_1}, 0, \frac{1}{\alpha_1} \right), (\alpha_1 \beta_1 - \alpha_2 \beta_2, \frac{1}{\alpha_1}, (\rho^2 - \alpha_2 \beta_2, 1) \right] \quad (8)$$

where $\psi = \left( \frac{\beta_1}{\beta_2} \right)^{\frac{\alpha_1}{\alpha_2}} \left( \frac{\beta_1}{\beta_2} \right)^{\frac{1}{\alpha_2}}$.

Proof: The combined PDF of dGG and pointing error can be expressed as

$$f_{h_i}(x) = \int_0^\infty A_0 \rho^2 x^{\alpha - 1} f_{h_p}(u) du \quad (9)$$
Substituting (5) and (4) in (3) with the definition of Fox-H function and interchanging the integrals as per Fubinis theorem to get

\[ f_h(x) = \int_0^\infty \frac{x^{\alpha_2-1} e^{-\alpha_2 x}}{\Gamma(\alpha_2) \Gamma(\alpha_3)} \frac{e^{-\alpha_3 x}}{x^{\alpha_3}} \] 

Substituting (12) in (10) with the definition of Fox-H function and applying the definition of Fox-H function, we get (14).

Finally, we capitalize Theorem 1 with Proposition 1, Proposition 2 to find the PDF and CDF of the cascaded FSO and RF channels.

**Corollary 1.** If \( h_i \) is distributed according to (8), the PDF and CDF of cascaded FSO channel \( h = \prod_{i=1}^K h_i \) are

\[ f_h(x) = \frac{1}{x} \psi H_{K,0}^{[K]} \left[ U_1 x \bigg| \left\{ (\rho^2_i + 1, 1) \right\}^K \right] \] 

and

\[ F_h(x) = \psi H_{K+1,3K+1}^{[K]} \left[ U_1 x \bigg| \left\{ (\rho^2_i + 1, 1) \right\}^K \right] \] 

where

\[ \psi_1 = \prod_{i=1}^K \frac{1}{\beta_i - 1 \left( \frac{\beta_i}{x} \right) \Gamma(\frac{\beta_i}{x} \rho^2_i + 1)} \] 

\[ V_1 = \prod_{i=1}^K \frac{1}{\beta_i - 1 \left( \frac{\beta_i}{x} \right) \Gamma(\frac{\beta_i}{x} \rho^2_i + 1)} \]

**Proof:** A straightforward application of Theorem 1 proves the Corollary 1.

To prove \( f_0^\infty f_h(x) dx = 1 \), we use the identity [21] 2.8

\[ f_0^\infty f_h(x) dx = \psi_1 f_0^\infty H_{K,0}^{[K]} \left[ U_1 x \bigg| \left\{ (\rho^2_i + 1, 1) \right\}^K \right] \] 

and

\[ \psi_2 = \prod_{i=1}^K \frac{1}{\beta_i - 1 \left( \frac{\beta_i}{x} \right) \Gamma(\frac{\beta_i}{x} \rho^2_i + 1)} \] 

\[ V_2 = \prod_{i=1}^K \frac{1}{\beta_i - 1 \left( \frac{\beta_i}{x} \right) \Gamma(\frac{\beta_i}{x} \rho^2_i + 1)} \]

**Proof:** A straightforward application of Theorem 1 completes the proof.

**IV. PERFORMANCE ANALYSIS**

In this section, we analyze the performance of the considered mixed FSO-RF system. Using the IM/DD detector, we denote SNR of the cascaded FSO link as \( \gamma_{FSO} = \frac{\gamma_{FSO}|h|^2}{\sigma_n^2} \) and the cascaded RF as \( \gamma_{RF} = \frac{\gamma_{RF}|g|^2}{\sigma_n^2} \), where \( \gamma_{FSO} = \frac{P_{FSO}|h|^2}{\sigma_n^2} \) and \( \gamma_{RF} = \frac{P_{RF}|g|^2}{\sigma_n^2} \) are the SNR terms without fading for the FSO and RF links, respectively.

Since \( \gamma_{FSO} \) and \( \gamma_{RF} \) are independent, end-to-end SNR of DF relaying system is given as \( \gamma = \min\{\gamma_{FSO}, \gamma_{RF}\} \). Hence, the CDF of the SNR is

\[ F_{\gamma}(\gamma) = F_{\gamma_{FSO}}(\gamma) + F_{\gamma_{RF}}(\gamma) - F_{\gamma_{FSO}}(\gamma)F_{\gamma_{RF}}(\gamma) \]

where

\[ F_{\gamma_{FSO}}(\gamma) = F_h\left(\sqrt{\frac{\gamma}{\gamma_{FSO}}}\right) \]

and

\[ F_{\gamma_{RF}}(\gamma) = F_g\left(\sqrt{\frac{\gamma}{\gamma_{RF}}}\right) \]
\[ P_{\text{out}} = \psi_1 \left[ \prod_{i=1}^{K} \frac{\Gamma(\beta_{i,1} - n_{1,i})}{\Gamma(\beta_{i,1})} \frac{1}{n_{1,i}} \right] \frac{1}{2 \pi \rho_2} \text{Erfc} \left( \frac{\beta_{i,2}}{\sqrt{2 \rho_2}} \right) \Gamma(\beta_{i,2} - n_{2,i}) \]
$$\eta_1 = \frac{\log_2(e)}{2} \psi_1 H_{K+2}^{3K+2,1} \left[ U_1 \sqrt{\frac{1}{\pi \sigma^2}} \right] \left\{ \left( \beta_{i,1}, \frac{1}{\alpha_{i,1}} \right), \left( \beta_{i,2}, \frac{1}{\alpha_{i,2}} \right), \left( \rho_2^2, 1 \right) \right\}_N$$

$$\eta_2 = \frac{\log_2(e)}{2} \psi_2 H_{2K+2}^{2K+2,1} \left[ U_2 \sqrt{\frac{1}{\pi \sigma^2}} \right] \left\{ \left( \beta_{i,3}, \frac{1}{\alpha_{i,3}} \right), \left( \beta_{i,4}, \frac{1}{\alpha_{i,4}} \right), \left( \rho_2^2, 1 \right) \right\}_N$$

$$\eta_{12} = \frac{\log_2(e)\psi_1 \psi_2 H_{3N}^{2N,1} 2K+1,2} {U_1 U_2 \sqrt{\frac{1}{\pi \sigma^2}}} \left\{ \left( \beta_{i,3}, \frac{1}{\alpha_{i,3}} \right), \left( \beta_{i,4}, \frac{1}{\alpha_{i,4}} \right), \left( \rho_2^2, 1 \right) \right\}_N$$

$$\eta_{21} = \frac{\log_2(e)\psi_1 \psi_2 H_{2N}^{2N,1} 3N,1} {U_1 U_2 \sqrt{\frac{1}{\pi \sigma^2}}} \left\{ \left( \beta_{i,1}, \frac{1}{\alpha_{i,1}} \right), \left( \beta_{i,2}, \frac{1}{\alpha_{i,2}} \right), \left( \rho_2^2, 1 \right) \right\}_N$$

$$\eta_{2} = \frac{\log_2(e)\psi_1 \psi_2 H_{2K+2}^{2K+2,1} 3K+2} {U_2 \sqrt{\frac{1}{\pi \sigma^2}}} \left\{ \left( \beta_{i,3}, \frac{1}{\alpha_{i,3}} \right), \left( \beta_{i,4}, \frac{1}{\alpha_{i,4}} \right), \left( \rho_2^2, 1 \right) \right\}_N$$

where $\psi_1 = \prod_{i=1}^K \left( \frac{1}{\alpha_{i,1}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}}$, $\psi_2 = \prod_{i=1}^K \left( \frac{1}{\alpha_{i,2}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}}$, $U_1 = \prod_{i=1}^K \left( \frac{1}{\alpha_{i,1}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}}$, $U_2 = \prod_{i=1}^K \left( \frac{1}{\alpha_{i,2}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}}$, $W_1 = \left\{ \left( 1 - \beta_{i,1}, \frac{1}{\alpha_{i,1}} \right), \left( 1 - \beta_{i,2}, \frac{1}{\alpha_{i,2}} \right), \left( 1 - \rho_2^2, 2, 1 \right) \right\}_N$, and $W_2 = \left\{ \left( 1 - \beta_{i,3}, \frac{1}{\alpha_{i,3}} \right), \left( 1 - \beta_{i,4}, \frac{1}{\alpha_{i,4}} \right), \left( 1 - \rho_2^2, 2, 1 \right) \right\}_N$.

**Proof:** To derive $\eta_1$, we use [20] to express

$$\eta_1 = \frac{1}{2} \prod_{i=1}^K \left( \frac{1}{\alpha_{i,1}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}} \int_{\mathbb{R}^+} \Gamma(\beta_{i,1} + \frac{n_1}{\alpha_{i,1}}) \Gamma(\beta_{i,2} + \frac{n_1}{\alpha_{i,1}})$$

$$\prod_{i=1}^K \left( \frac{1}{\alpha_{i,2}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}} \left( \int_0^\infty \gamma^{-1 - \frac{n_1}{\alpha_{i,2}}} \log(1 + \gamma) \right)$$

To solve the inner integral, we express $\ln(1 + \gamma)$ in terms of Meijer-G function and use the identity [21] [07.34.21.0009.01], $I = \prod_{i=1}^K \left( \frac{1}{\alpha_{i,2}} \right)^{-\frac{\rho_2^2}{\pi \sigma^2}} \Gamma(1 + \frac{\rho_2^2}{\pi \sigma^2})$, with the definition of Fox-H function to get [22]. We follow the similar approach to derive $\eta_2$ in [23].

To derive $\eta_{12}$ and $\eta_{21}$, we use the PDF and CDF functions of the FSO and RF links, expand the definitions of Meijer-G function and Fox-H functions, use the identity [21] [2,8] to solve the resultant inner integrals, and apply the definition of Bi-variate Fox-H function to get [23].

**V. SIMULATION AND NUMERICAL RESULTS**

In this section, we demonstrate the performance of multihop FSO-RF system and validate the derived analytical expressions through numerical and Monte-Carlo simulations (averaged over $10^7$ realizations). We assume the link length as 10m for each hop and consider the same distance from source to relay and from relay to destination. Thus an increase in the number of hops increases the communication range by a factor of 10m. We consider varying fading parameters to demonstrate the effect of diversity order on system performance. We use dGG parameters corresponding to strong turbulence (ST) ($\alpha_1 = 1.8621, \alpha_2 = 1, \beta_1 = 0.5, \beta_2 = 1.8, \Omega_1 = 1.5074, \Omega_2 = 0.928$) and moderate turbulence (MT) ($\alpha_1 = 2.169, \alpha_2 = 1, \beta_1 = 0.55, \beta_2 = 2.35, \Omega_1 = 1.5793, \Omega_2 = 0.9671$) scenarios as in [27] for all the FSO links. For RF links, we use dGG parameters ($\alpha_3 = 1.5, \alpha_4 = 1, \beta_3 = 1.5, \beta_4 = 1.5, \Omega_3 = 1.5793, \Omega_4 = 0.9671$) from [26]. Considering a large RIS with such a short links, we assume the path gain of both the cascaded links unity to illustrate the impact of fading and fading on the multihop transmissions. A noise floor of $-104.4dBm$ is considered for RF links for a $20MHz$ channel bandwidth. We use pointing error parameters $A_0 = 0.02$ and $\rho_0^2 = 6$ in the first hop from source to first optical RIS and last hop (i.e., from K-1-RIS to the DF relay) using the recently proposed model [14]. However, pointing errors involving RIS-to-RIS are considered to be less with $\rho_0^2 = 25$.

Fig. 1(a) demonstrates the impact of number of hops on the outage performance of considered multihop RIS-assisted...
FSO-RF system. It can be easily seen that the performance degrades with the increase in $K$ due to an increase in the communication range. As such, for an outage probability of $10^{-3}$, an additional transmit power of $20\text{dBm}$ is required when the number of hops are increased from $K = 2$ to $K = 3$. Comparing the plots of outage probability for different sets of fading parameters (ST and MT on FSO links and fixed RF fading parameters), the impact of fading parameters on the diversity order can be confirmed. For example, the two sets of parameters have outage diversity orders $C_{\text{out}} = 0.46$ and $C_{\text{out}} = 0.59$, with the latter having a gain of $10\text{dB}$.

Next, Fig. 1(c) shows the average BER performance of the considered system for DBPSK modulation ($p = 1$, $q = 1$). Similar to outage probability, BER performance degrades with the increase in $K$. The diversity order using the average BER of the system can also be inferred from the plots similar to the outage probability. The impact of atmospheric turbulence on system behavior can also be seen, where the performance degrades by about $10\text{dBm}$ for the ST when compared with the MT scenario. Finally, we demonstrate the ergodic capacity in Fig. 1(c) for different fading parameters. There is a loss of about $10\text{bits/sec/Hz}$ in the ergodic capacity with an increase of $K = 2$ to $K = 3$ with strong turbulence. It can also be seen from the figure that an increase in the parameter $\beta$ improves the performance due to a decrease in the fading severity. In all the plots, we also validate our derived analytical results by numerically evaluating the Fox-H function with Monte-Carlo simulations.

VI. CONCLUSION

In this paper, we investigated the performance of a multihop RIS-assisted mixed FSO-RF system over DGG fading model with pointing errors for the FSO link. We developed closed-form expressions for the outage probability, average BER, and ergodic capacity of the considered system using the derived statistical results of the cascaded FSO and RF channels. To provide insights on the system performance, we also presented asymptotic analysis in the high SNR regime for the outage probability and demonstrated the impact of channel parameters on the diversity of the system. Simulation results show that the multihop system allows a higher communication range at the expense of performance degradation and may improve the performance for a fixed link distance. The impact of individual RIS elements with optimal phase compensation on the performance of RIS-assisted multihop system can be a promising future scope of the proposed work.

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