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Reconfigurable intelligent surface-aided double-hop optical links in fading channels for future 6G IoT applications

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ABSTRACT

In this paper, we investigate a reconfigurable intelligent surface (RIS)-aided double-hop optical communication system designed for future sixth generation (6G) internet of things (IoT) applications. The considered system consists of two cascaded RIS-assisted links forming a double-hop transmission the link between the source and destination. Each hop is modeled under Gamma-Gamma fading channels to characterize the impact of atmospheric turbulence in free-space optical (FSO) environments, particularly under weak-to-moderate turbulence conditions. We evaluate the system performance in terms of the average symbol error rate (ASER) and compare the results with those of conventional non-RIS configurations. Numerical results are presented for different link distances and subcarrier quadrature amplitude modulation (QAM) schemes. The results demonstrate that the proposed RIS-assisted double-hop system significantly improves link reliability and reduces error rates. These findings highlight the potential of RIS technology in enabling robust and efficient optical wireless links for next-generation 6G-enabled IoT networks.

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1. INTRODUCTION

Free-space optical (FSO) communication systems predominantly operate over line-of-sight (LOS) links, where an unobstructed propagation path between the optical transmitter and receiver is essential. However, in practical environments, physical obstructions, atmospheric conditions, and deployment constraints may prevent the establishment of a direct LOS link. To address these challenges, recent research has explored non-line-of-sight (NLOS) FSO communication, which enables optical signals to reach the receiver through indirect propagation paths, such as reflection or scattering from surrounding surfaces [1]–[8]. Although NLOS FSO links generally suffer from higher propagation losses and reduced performance compared with conventional LOS systems, recent advances in optical transceivers, signal processing, and intelligent propagation technologies have demonstrated their potential for applications where a direct optical path is unavailable or difficult to establish [9]–[16].

By dynamically controlling the propagation characteristics of optical signals, reconfigurable intelligent surface (RIS)-assisted FSO systems can provide greater flexibility, adaptability, and robustness compared with conventional FSO links [17]–[24]. In particular, the capability of RIS to intelligently

manipulate optical propagation paths offers an effective approach to mitigating link blockages and extending communication coverage in dynamic and obstructed environments, thereby expanding the applicability of FSO technology in next-generation wireless networks [25]–[31]. A RIS-assisted double-hop FSO system further extends this concept by incorporating two RIS-based reflection stages between the transmitter and receiver. The resulting architecture introduces an intermediate optical propagation path, enabling the transmitted signal to circumvent physical obstacles and reach destinations that may otherwise be inaccessible through a conventional direct LOS link.

Therefore, this study proposes a double-hop RIS-assisted FSO communication system operating over Gamma–Gamma fading channels. The system performance is theoretically investigated under different link-distance configurations. In particular, quadrature amplitude modulation (QAM) is employed to quantitatively evaluate the average symbol error rate (ASER) of the proposed system, with comparisons between conventional FSO transmission without RIS and the proposed double-hop RIS-assisted configuration. The numerical results provide valuable insights into the effects of link distance and RIS deployment on the overall system performance. Section 2 presents the system configuration and optical channel model. Section 3 discusses the analytical and numerical results. Finally, Section 4 concludes the paper.

2. MODELS MODELING OF NEAR-TERRESTRIAL FSO LINKS AND CHANNELS

2.1. Near terrestrial optical link

By incorporating a second RIS into the communication architecture, the system can provide enhanced NLOS coverage, improve signal reception, and extend the communication range, making it particularly attractive for applications in urban, industrial, and emergency communication scenarios. Nevertheless, the use of multiple RIS stages also introduces several practical challenges, including stringent alignment requirements, additional power consumption, and increased system complexity. With continued advances in RIS control strategies, optical signal processing, and intelligent beam-steering technologies, double-hop RIS-assisted FSO systems have significant potential for next-generation optical wireless communication networks. Figure 1 illustrates the system model of the proposed.

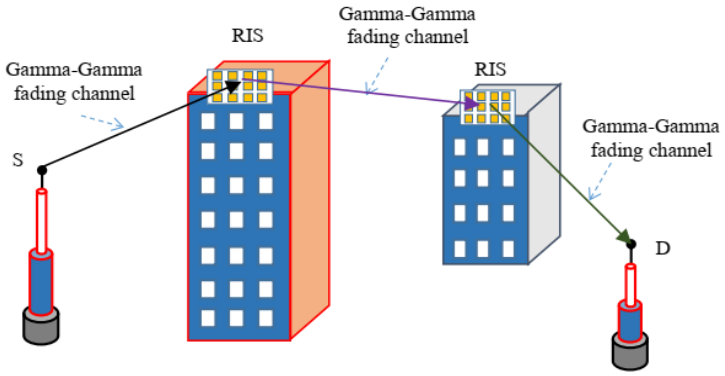


Figure 1. An overview of the system model

Figure 2 depicts the operating mechanism of the considered FSO link. During the first hop, the optical signal emitted by the source is incident on the first RIS, which adaptively controls and reflects the incoming signal toward the second RIS. Subsequently, in the second hop, the reflected signal impinges on the second RIS and is redirected toward the destination receiver. Through this cascaded reflection process, an alternative indirect transmission route is established, enabling the optical signal to circumvent obstacles that could otherwise block a conventional direct LOS or single-hop FSO link.

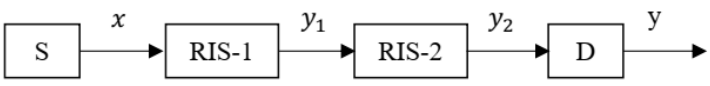


Figure 2. System overview of communication system

In the considered communication system, the signal travels from the source (S) to the destination (D) via two successive reflection stages provided by two RISs. This architecture extends the conventional single-hop RIS configuration, which employs only a single reflecting surface, by introducing a cascaded dual-RIS transmission path.

$$h = h_{S,RIS1} \times h_{RIS1,RIS2} \times h_{RIS2.D} \tag{1}$$

where h: channel matrix between hops. The signal received at the destination can be mathematically represented by y as:

$$y = h_{RIS2.D} y_2 \times h_{RIS1,RIS2} y_1 \times h_{S,RIS1} x + n \tag{2}$$

where x is the signal emitted by the source, n denotes the noise at the destination, y_1 and y_2 denote the diagonal matrices representing the phase shifts introduced by RIS-1 and RIS-2, respectively.

2.2. Statistical model of channel fading

The channel fading model characterizes the random variations in the received optical signal. In this study, the G–G distribution is adopted to model both small-scale and large-scale turbulence effects in the FSO link. This model provides an accurate representation of atmospheric turbulence and enables the analytical evaluation of system performance under different channel conditions. The probability density function (PDF) of signal-to-noise ratio (SNR)'s system, $f_\gamma(\gamma)$, is evaluated as [12].

$$f_\gamma(\gamma) = \int_0^\infty f_{\gamma_h}(t) f_{\gamma_g}\left(\frac{\gamma}{t}\right)\frac{1}{t} dt \tag{3}$$

where $f_{\gamma_h}(\cdot)$ and $f_{\gamma_g}(\cdot)$ represent the PDFs of the instantaneous SNRs for the links. Assuming identical weather conditions over both hops, the channel model incorporates the effects of atmospheric turbulence, pointing errors, and atmospheric attenuation. Accordingly, the PDF of the channel SNR is expressed as given in (4).

$$f_{\gamma_i}(\gamma_i) = \frac{\xi^2}{(A_0 X_l)^{\xi^2}\Gamma(\alpha)\Gamma(\beta)} \times G_{1,3}^{2,1}\left[\alpha\beta \frac{\gamma_i}{A_0 X_l \bar{\gamma}} \middle| \begin{matrix} 1+\xi^2 \\ \alpha,\ \beta,\ \xi^2 \end{matrix}\right] \tag{4}$$

Through successive substitutions γ_i by t and $\frac{\gamma}{t}$ in (4), and obtain $f_{\gamma_h}(t)$ and $f_{\gamma_g}(\frac{\gamma}{t})$ respectively as (5), (6).

$$f_{\gamma_h}(t) = \frac{\xi^2}{(A_0 X_l)^{\xi^2}\Gamma(\alpha)\Gamma(\beta)} \times G_{1,3}^{2,1}\left[\alpha\beta \frac{t}{A_0 X_l \bar{\gamma}_h} \middle| \begin{matrix} 1+\xi^2 \\ \alpha,\ \beta,\ \xi^2 \end{matrix}\right] \tag{5}$$

$$f_{\gamma_g}(\tfrac{\gamma}{t}) = \frac{\xi^2}{(A_0 X_l)^{\xi^2}\Gamma(\alpha)\Gamma(\beta)} \times G_{1,3}^{2,1}\left[\alpha\beta \frac{\gamma}{A_0 X_l \bar{\gamma}_g t} \middle| \begin{matrix} 1+\xi^2 \\ \alpha,\ \beta,\ \xi^2 \end{matrix}\right] \tag{6}$$

In (5) and (6), $\bar{\gamma}_h$ and $\bar{\gamma}_g$ represent the average values of the SNRs, γ_h and γ_g, respectively. We substitute (5) and (6) in to (3), the pdf of SNR, $f_\gamma(\gamma)$, can be evaluated according to (7).

$$f_\gamma(\gamma) = \frac{\xi^4}{(X_l A_0)^{\xi^4}(\Gamma(\alpha)\Gamma(\beta))^2} \times H_{2,6}^{4,2}\left(\frac{(\alpha\beta)^2\gamma}{(A_0 X_l)^2 \bar{\gamma}_h \bar{\gamma}_g} \middle| \begin{matrix} (1+\xi^2,1),(1-\alpha,-1),(1-\beta,-1),(1-\xi^2,-1) \\ (\alpha,1),\ (\beta,1),(-\xi^2,-1),(\xi^2,1) \end{matrix}\right) \tag{7}$$

2.3. Average symbol error rate analysis

Single-carrier QAM is an effective modulation scheme for wireless communication systems, offering high spectral efficiency and reliable data transmission under challenging channel conditions. It combines the advantages of single-carrier transmission with the amplitude and phase modulation characteristics of QAM. The ASER represents the average probability of incorrectly detecting a transmitted symbol at the receiver and is therefore an important metric for evaluating the reliability of the communication system [18].

$$P_{se} = \int_0^{+\infty} P_e(\gamma) f_\gamma(\gamma) d\gamma \tag{8}$$

where $P_e(\gamma)$ denotes the conditional error probability (CEP), which is given by (9).

$$P_e(\gamma) = 1 - [1 - 2q(M_I)Q(A_I\sqrt{\gamma}][1 - 2q(M_Q)Q(A_Q\sqrt{\gamma})] \quad (9)$$

Assuming that the turbulence processes of the single-input single-output (SISO) sub-channels are independent, uncorrelated, and identically distributed, the overall PDF can be represented as the product of the first-order PDFs of the individual channel elements. The ASER is an important metric for assessing the performance and reliability of the proposed system, particularly in high-data-rate communication scenarios. A lower ASER indicates improved transmission reliability, fewer detection errors, and consequently better data integrity.

$$\bar{P}_{se}(\gamma) = 2\int_0^\infty q(M_Q)Q(A_Q\sqrt{\gamma})f(\gamma)d\gamma + 2\int_0^\infty q(M_I)Q(A_I\sqrt{\gamma})f(\gamma)d\gamma - 4\int_0^\infty q(M_Q)Q(A_Q\sqrt{\gamma})q(M_I)Q(A_I\sqrt{\gamma})f(\gamma)d\gamma \quad (10)$$

3. NUMERICAL RESULTS AND DISCUSSIONS

Based on (7) and (10), the ASER performance of the double-hop RIS-assisted FSO system is numerically evaluated. We consider an FSO link under atmospheric turbulence, where the source (S) and destination (D) are assumed to be located at equal distances, as illustrated in Figure 3, while different QAM modulation orders are considered in Figure 4. The two sub-channels are assumed to experience the same refractive-index structure parameter. The parameters and constants used in the numerical analysis are summarized in Table 1.

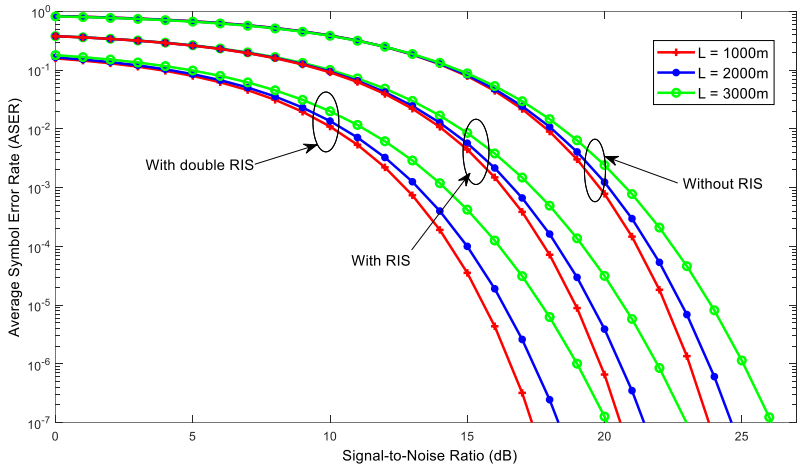


Figure 3. Impact of link distance on ASER performance versus SNR

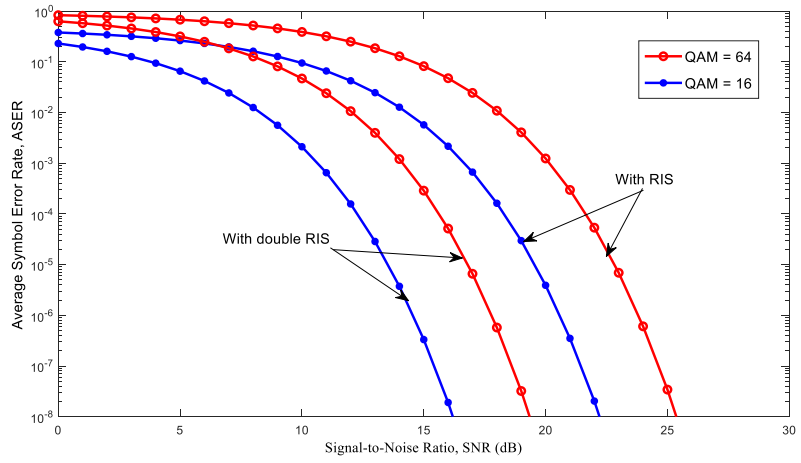


Figure 4. SER Performance under different QAM modulation schemes

Table 1. System parameters and relevant constants

Parameter	Symbol	Value
Wavelength	λ	1550 nm
Responsivity of photodetector	$\Re$	1 A/W
Modulation Index	κ	1
QAM modulation	$M_I \times M_Q$	$16,64$
Index of refraction structure	C_n^2	$3.10^{-14}m^{-2/3}$

Figure 3 illustrates the ASER performance for different link distances. As expected, the ASER generally decreases with increasing SNR, indicating improved transmission reliability. However, increasing the link distance results in greater propagation loss and reduced received signal power, leading to a degradation in SNR and consequently higher ASER. The overall performance is also influenced by other system parameters, including the modulation order, atmospheric turbulence, and channel conditions.

Figure 4 illustrates the ASER performance for different QAM schemes. The results show that RIS-assisted systems achieve notable improvements in ASER across all considered modulation orders. This enhancement enables greater flexibility in modulation selection, improved energy efficiency, and more reliable high-data-rate transmission. For each QAM scheme, the ASER versus SNR curve of the RIS-aided system is clearly shifted to the left compared to the non-RIS case. This leftward shift indicates that a lower SNR is required to achieve the same ASER performance level. Consequently, the system can operate with reduced transmit power or support longer communication distances.

4. CONCLUSION

This paper performance analysis for RIS-aided double-hop optical links operating over Gamma-Gamma fading channels, targeting future 6G IoT applications. The considered system employs a two-hop transmission mechanism, where the optical signal propagates from the source to the destination via an intermediate RIS, effectively enhancing link quality and reliability. In this architecture, the RIS adaptively controls the reflected optical wave to optimize signal power, directionality, and coverage. The analytical and numerical results confirm that the integration of RIS significantly mitigates the adverse effects of atmospheric turbulence modeled by Gamma-Gamma fading. As a result, the proposed system achieves improved error performance and enhanced communication robustness compared to conventional non-RIS schemes.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Duong Huu Ai	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Viet Truong Le		✓		✓		✓				✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The following sources contain the data that support the findings of this study:

- Relevant data are openly accessible in [Taylor and Francis, Springer Nature] at doi: 10.1080/24751839.2020.1732734 [3], doi: 10.1007/978-3-662-49390-8_59 [5].
- Supporting datasets can be found in [IEEE] at doi: 10.1109/NICS.2016.7725640. [15].
- Additional data related to this study are openly available in [IEEE] at doi: 10.1109/TITS.2024.3402121 [30] and doi: 10.1109/TVT.2024.3414850.

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