Double-hop of reconfigurable intelligent surfaces-aided for wireless optical link under log-normal fading channels

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ABSTRACT

In optical wireless communication (OWC), the reconfigurable intelligent surfaces (RIS) are used to manipulate optical signals by controlling the phase shifts or amplitude of reflected beams, which helps improve signal quality. RIS units can be tailored to increase the strength and reliability of the communication link, especially in challenging fading conditions. The double-hop scenario involves two RIS-assisted segments, such as transmitter to RIS-1 and RIS-1 to RIS-2 or a receiver. Each hop encounters log-normal fading, which impacts the overall link performance. Log-normal fading models the irradiance fluctuation caused by turbulence, which is significant in free-space optical (FSO) systems, this fading model assumes that the received optical signal's amplitude varies with a log-normal distribution, making it more suited for weak to moderate turbulence. Numerical results are obtained under different of link distance, subcarrier quadrature amplitude modulation (QAM) is displayed quantitatively illustrate the average symbol error rate in the absence of RIS and with double-hop of RIS.

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1. INTRODUCTION

Optical wireless communication (OWC) relies heavily on line-of-sight (LOS) connectivity between the transmitter and receiver. This means that a clear, unobstructed path is required for the optical beam to travel directly from the source to the destination without interference. However, research and development efforts have led to innovations that make non-line-of-sight (NLOS) free-space optical (FSO) links feasible in certain conditions. NLOS FSO involves techniques to allow optical communication even when there is no clear direct path between the two endpoints [1]–[8]. While NLOS FSO links face several limitations compared to traditional LOS FSO systems, advances in technology continue to make them a viable solution for specific applications where conventional FSO or other forms of wireless communication may not be feasible [9]–[16].

Reconfigurable intelligent surfaces (RIS) are an emerging technology that has shown potential to improve FSO communication links, especially under challenging conditions where direct LOS is not available or where environmental factors impact the link quality. RIS-assisted FSO systems can provide more flexible, adaptive, and resilient FSO connections by actively managing how light propagates in the environment [17]–[24]. By offering an adaptable, controllable surface that manipulates light propagation, RIS technology significantly enhances FSO capabilities in dynamic or obstructed scenarios, broadening the potential applications of FSO in modern communication networks [25]–[32]. A double-hop RIS-assisted FSO link introduces a secondary RIS into the FSO system, creating two reflection points in the optical path between the transmitter and receiver. This setup enables greater flexibility and coverage by adding an intermediate hop that allows light to reach more challenging or distant locations without a direct LOS path.

Accordingly, this work presents a method for the execution of double-hop of RIS-aided for wireless optical link under log-normal fading channels. We theoretically analyzed the performance of system for different of link distance, subcarrier quadrature amplitude modulation (QAM) is shown to quantitatively illustrate the average symbol error rate (ASER) in the absence of RIS and with double-hop of RIS. The remainder of this paper is organized as follows. Section 2 describes the wireless optical link and the channel model. Section 3 presents the results and discussion. Finally, section 4 concludes the paper.

2. THE WIRELESS OPTICAL LINK AND CHANNEL MODELS

2.1. The wireless optical link

Double-hop RIS-assisted FSO links are an innovative solution for creating robust, flexible, and extended FSO communication paths in complex or obstructed environments. By adding a second RIS surface, these systems enable greater NLOS coverage, improved signal quality, and extended reach, making them valuable for urban, industrial, and emergency communication networks. However, they also come with added challenges in terms of alignment, power requirements, and system complexity. With advancements in control algorithms, signal processing, and RIS technology [1], [2], double-hop FSO systems could play an increasingly important role in next-generation optical communication networks. A model of double-hop RIS-aided wireless optical link shown in Figure 1.

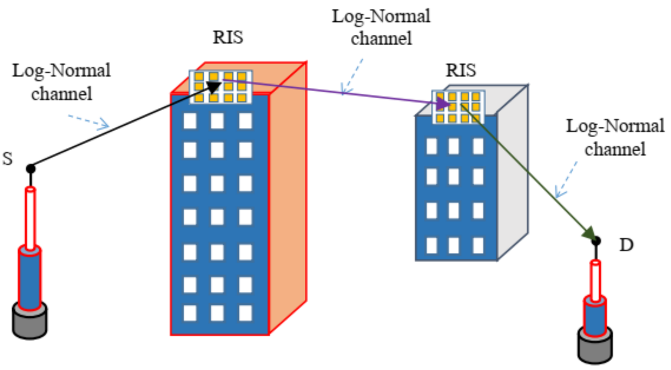

Figure 1. A model of double-hop RIS-aided wireless optical link

Figure 2 overview of double-hop RIS-aided, first RIS hop: the optical signal from the transmitter is directed to the first RIS, which reflects it toward the second RIS. Second RIS hop: the second RIS then redirects the signal toward the final receiver. Resulting path: this two-step reflection process allows the signal to travel around obstacles that would block a direct or single-hop path.

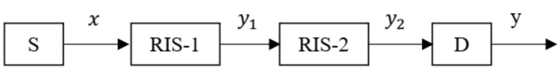

Figure 2. Overview of double-hop RIS-aided

In a double-hop RIS-aided communication model, the transmission from a source (S) to a destination (D) is achieved indirectly, via two cascaded reflection paths facilitated by two RISs. This setup extends beyond a single-hop RIS system, where only one RIS is used to reflect signal directly from S to D. The overall channel coefficient is given in (1).

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

Where $h_{S,RIS1}$ is the source-to-RIS-1 channel matrix, $h_{RIS1,RIS2}$ is channel matrix between RIS-1 and RIS-2, and $h_{RIS2,D}$ is the RIS-2-to-destination channel matrix.

The received signal at the destination y can be modeled as (2).

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

Where y_1 and y_2 are diagonal matrices representing the phase shifts applied by RIS-1 and RIS-2, respectively, x is the transmitted signal from the source, and n is the noise at the destination.

2.2. The channel fading model

The signal-to-noise ratio (SNR) probability density function (PDF) of the system, $f_\gamma(\gamma)$, is obtained from the SNRs, γ_h, and γ_g. The gain of system is given by $h\mu e^{j\theta} g$, where the parameter $\mu e^{j\theta}$ is deterministic as opposed to h and g. They are random variables. The PDF of SNR's system, $f_\gamma(\gamma)$, is expressed as (3) [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 $f_{\gamma_h}(\cdot)$ is the PDFs of the source S to RIS-1, and $f_{\gamma_g}(\cdot)$ is the RIS-2 to destination D sub-channel's SNRs. Under the assumption of similar weather conditions across both channel links, a unified distribution is employed to characterize turbulence effects, pointing errors, and atmospheric attenuation. The PDF, $f_{\gamma_i}(\gamma_i)$ is expressed as (4) [16].

$$f_{\gamma_i}(\gamma_i) = \frac{\ln(\gamma)}{8\pi\sigma_S^2\gamma} \times \exp\left(-\frac{2\,ln(\frac{\gamma}{\bar{\gamma}})[1+\sigma_S^2]+2\sigma_S^4}{8\sigma_S^2}\right) \tag{4}$$

We apply the substitutions sequentially γ_i by t and $\frac{\gamma}{t}$ in (4), thereby obtaining $f_{\gamma_h}(t)$ and $f_{\gamma_g}(\frac{\gamma}{t})$ respectively as (5) and (6).

$$f_{\gamma_h}(t) = \frac{\ln(t)}{8\pi\sigma_S^2 t} \times \exp\left(-\frac{2\,ln(\frac{t}{\bar{\gamma}})[1+\sigma_S^2]+2\sigma_S^4}{8\sigma_S^2}\right) \tag{5}$$

$$f_{\gamma_g}(\frac{\gamma}{t}) = \frac{\ln(\frac{\gamma}{t})}{8\pi\sigma_S^2\frac{\gamma}{t}} \times \exp\left(-\frac{2\,ln(\frac{\gamma}{t.\bar{\gamma}})[1+\sigma_S^2]+2\sigma_S^4}{8\sigma_S^2}\right) \tag{6}$$

Where $\bar{\gamma}_h$ and $\bar{\gamma}_g$ are average values of the SNRs γ_h and γ_g, respectively. We apply the substitution (5) and (6) in to (3), the pdf of SNR, $f_\gamma(\gamma)$, is evaluated as (7).

$$f_\gamma(\gamma) = \int_0^\infty \frac{\ln(t)}{8\pi\sigma_S^2 t}\exp\left(-\frac{2\,ln(\frac{t}{\bar{\gamma}})[1+\sigma_S^2]+2\sigma_S^4}{8\sigma_S^2}\right) \times \frac{\ln(\frac{\gamma}{t})}{8\pi\sigma_S^2\frac{\gamma}{t}}\exp\left(-\frac{2\,ln(\frac{\gamma}{t.\bar{\gamma}})[1+\sigma_S^2]+2\sigma_S^4}{8\sigma_S^2}\right)\frac{1}{t}dt \tag{7}$$

2.3. Performance analysis of average symbol error rate

Single-carrier (SC)-QAM is a modulation technique often used in wireless communication systems, especially in scenarios where efficient spectral use and reliable signal transmission in challenging environments are required. SC-QAM combines the principles of SC modulation with QAM. ASER is the average probability that a transmitted symbol will be incorrectly decoded at the receiver. It reflects how often symbols are received incorrectly on average across the entire communication system [19]. The ASER expression is given in (8).

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

Where $P_e(\gamma)$ is the conditional error probability (CEP). The CEP is described as (9) [27].

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

The turbulence processes associated with the single-input single-output (SISO) sub-channels are assumed to be independent, uncorrelated, and identically distributed, PDF $f_\gamma(\gamma)$ can be expressed as the product of the first-order PDFs of the individual elements. ASER is crucial for understanding the system's performance and reliability, especially in high-data-rate applications. A lower ASER typically implies a more robust communication system with fewer errors, translating to better data integrity. The closed-form expression of the average symbol error probability is given in (10) [27].

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

3. NUMERICAL RESULTS AND DISCUSSION

From (7) and (10), we show numerical outcomes for ASER analysis of the double-hop of RIS-aided FSO systems. We consider a wireless optical link over turbulence channel in which S and D are situated at the same distance, $L = 1000$ m, $L = 2000$ m, $L = 3000$ m, as shown in Figure 3, and QAM level as shown in Figure 4. The two system's sub-channels are characterized by the same index of refraction structure, C_n^2. Parameters and constants considered in our analysis are presented in Table 1.

Table 1. System constans and parameters

Parameter	Symbol	Value
The optical wavelength	λ	1550 nm
The responsivity of the photodetector	$\Re$	1 A/W
The modulation factor	κ	1
The variance of the noise	N_0	10^{-7}A/Hz
The QAM modulation scheme	$M_I \times M_Q$	$16, 32, 64$
The receiver aperture diameter	D	$0.06m$
Refractive index structure	C_n^2	$10^{-15}m^{-2/3}$

Figure 3 shows the ASER performance versus the SNR for different values of link distance. The performance of ASER as a function of SNR is an essential aspect of assessing the reliability of a communication link. Link distance, which affects path loss and, subsequently, the received signal power, plays a significant role in ASER performance as well. ASER performance versus SNR for different link distances is an important factor in evaluating the robustness and efficiency of a communication system. As link distance increases, the received SNR generally decreases, leading to higher ASER values. The relationship between ASER and SNR as a function of link distance can vary significantly based on system parameters like modulation scheme, channel conditions, and path loss.

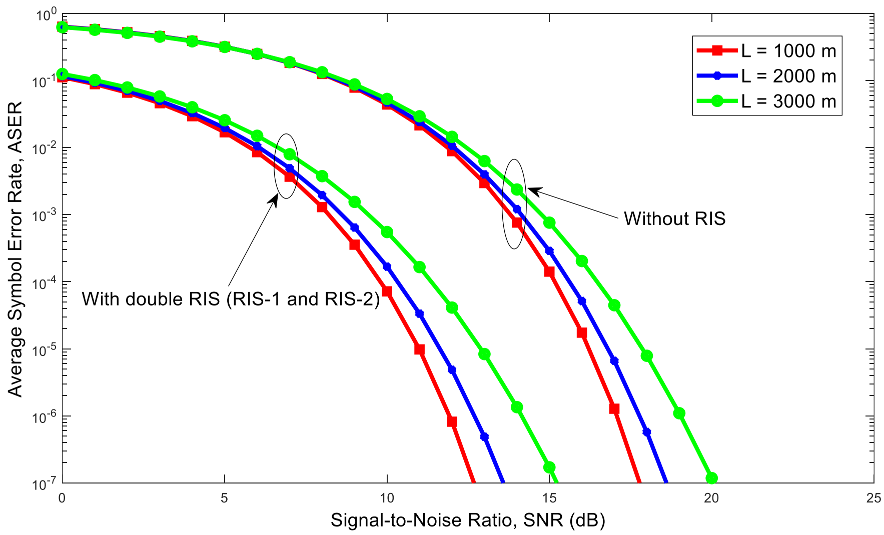

Figure 3. ASER performance versus the SNR for different values of link distance

RIS-aided systems show improved ASER performance over varying distances, enabling more flexible modulation choices and reliable transmission with lower power requirements. By improving SNR over double-hop links, RIS-aided systems make high-quality, long-distance communication feasible without significant increases in power or complexity. This makes them ideal for future communication networks like 5G and beyond.

Figure 4 shows the ASER performance against the SNR for different values of QAM scheme. RIS-aided systems enable significant ASER improvements across different QAM schemes, allowing for efficient modulation flexibility, better energy management, and reliable high-data-rate communication across various environments and distances. For each QAM scheme, the RIS-aided system shifts the ASER vs. SNR curve to the left compared to non-RIS systems. This shift indicates that less SNR is needed to achieve the same ASER, allowing for reduced power requirements or extended communication range.

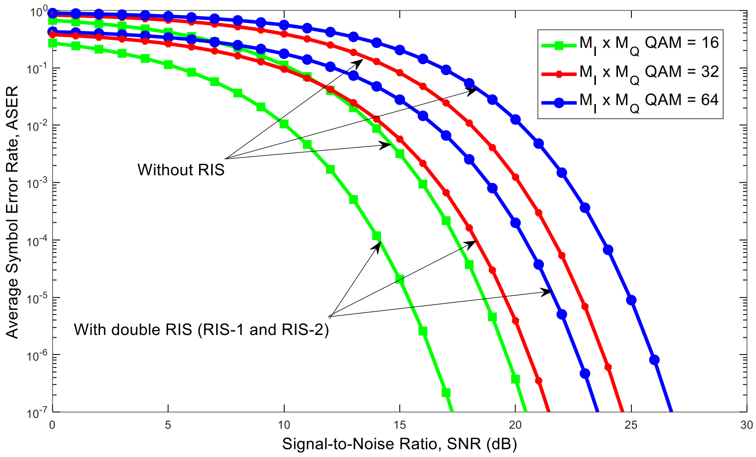

Figure 4. ASER performance against the SNR for different values of QAM scheme

4. CONCLUSION

This study presents unified closed-form expressions and a performance analysis of double-hop of RIS-aided for wireless optical link under log-normal fading channels. In a double-hop reconfigurable intelligent surface aided wireless optical communication system, signals are transmitted in two distinct hops with an intermediate RIS used to improve link quality and reliability. Here, "double-hop" means that optical signal travels from the transmitter to the RIS and then from the RIS to the receiver. Utilizing a RIS in such systems is advantageous because it can adaptively reflect the optical signal to optimize power, directionality, and coverage, which is especially useful in challenging environments like log-normal fading channels.

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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	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Van Loi Nguyen		✓		✓		✓				✓	✓	✓		
Khanh Ty Luong	✓		✓		✓		✓			✓	✓		✓	

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 at http://doi.org/10.1080/24751839.2020.1732734, reference [3], and http://doi.org/10.1007/978-3-662-49390-8_59, reference [7].
- Supporting datasets can be found at http://doi.org/10.1109/ICIST.2017.7926500, reference [16].
- Additional data related to this study are openly available at http://doi.org/10.1109/TITS.2024.3402121, reference [30], and http://doi.org/10.1109/TVT.2024.3414850, reference [32].

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