Effects of atmospheric turbulence and reconfigurable intelligent surfaces on near terrestrial optical link for internet of things

Duong Huu Ai[1], Hoang Huu Duc[2], Khanh Ty Luong[3], Ngoc Dat Vo[3]
[1]Department of Electronics Engineering, Faculty of Computer Engineering and Electronics, The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang, Vietnam
[2]Department of Computer Network, Faculty of Computer Engineering and Electronics, The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang, Vietnam
[3]Department of Multimedia Communication, Faculty of Computer Science, The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang, Vietnam

Article Info

Article history:

Received Jul 12, 2024
Revised Oct 24, 2024
Accepted Nov 26, 2024

Keywords:

Atmospheric turbulence
Average channel capacity
Optical communication
Quadrature amplitude modulation
Reconfigurable intelligent surfaces

ABSTRACT

Near terrestrial free-space optical (NT-FSO) communication refers to the use of light to transmit data wirelessly through the atmosphere over relatively short distances, typically within the earth's atmosphere. It is an alternative to traditional radio frequency (RF) communication and fiber optics, providing high-speed data transmission without the need for physical cables. NT-FSO is an attractive solution for high-speed, short-distance wireless communications where physical infrastructure like fiber is impractical. Reconfigurable intelligent surfaces (RIS) are a cutting-edge technology that enhances wireless communication systems by dynamically controlling how electromagnetic waves propagate through an environment. RIS technology is increasingly relevant in modern communication systems like 5G and beyond, aiming to improve the efficiency, coverage, and energy usage of wireless networks. This study investigates the effects of atmospheric turbulence and RIS on near terrestrial optical link for internet of things. Several numerical outcomes obtained for different link distance and average electrical signal signal-to-noise ratio (SNR) are shown to quantitatively illustrate the average spectral efficiency.

Corresponding Author:

Duong Huu Ai
Department of Electronics Engineering, Faculty of Computer Engineering and Electronics
The University of Danang, Vietnam-Korea University of Information and Communication Technology
Danang, Vietnam
Email: dhai@vku.udn.vn

1. INTRODUCTION

Near terrestrial free space optical (FSO) communication link refers to an optical communication system that transmits data using light through the atmosphere, rather than through fiber-optic cables or radio frequencies, typically over relatively short distances on or near the earth's surface, FSO links are particularly useful in urban environments or locations where physical cabling is expensive or impractical [1]–[5]. Recent works in FSO communications have been focusing on addressing two significant challenges: pointing errors and atmospheric turbulence. These issues severely degrade the performance of FSO systems by affecting the alignment and the integrity of the signal [6]–[12].

In recent years, reconfigurable intelligent surfaces (RIS) have emerged as a promising technology to enhance the performance of FSO communication systems. RIS involves the use of surfaces embedded with programmable elements that can dynamically manipulate electromagnetic waves, including light in the case of FSO, to improve the signal transmission and reception process [13]–[19]. By adjusting the phase, amplitude, and polarization of the incident wave, RIS can help to overcome some of the key challenges in FSO communication, such as pointing errors, atmospheric turbulence, and blockages [20]–[26]. RISs offer several significant advantages to wireless communication systems, particularly in enhancing signal quality, reliability, and energy efficiency. RIS technology is transforming how wireless signals are transmitted and received by using programmable surfaces to control electromagnetic waves, including radio and optical waves [27]–[32].

This study suggests a method for the execution of average channel capacity (ACC) analysis for RIS-aided FSO links over gamma-gamma and log-normal distribution and misalignment fading. The paper's rest is organized as follows. Section 2 describes the system model and channel fading. Section 3 presents the average channel capacity. Section 4 presents results and discussions. We conclude the study in section 5.

2. THE SYSTEM MODEL AND CHANNEL FADING

2.1. An overview of the system model

A model of an RIS-aided FSO communication system incorporates a RIS to enhance the performance of communication link is shown in Figure 1. The RIS acts as a passive, programmable surface that can control the propagation of optical signals, allowing it to mitigate some of the key challenges in FSO systems, such as pointing errors, atmospheric turbulence, and non-line-of-sight (NLOS) communication. The model involves optimizing the RIS's reflection properties to enhance the FSO link's performance, leading to a more resilient and efficient wireless optical communication system.

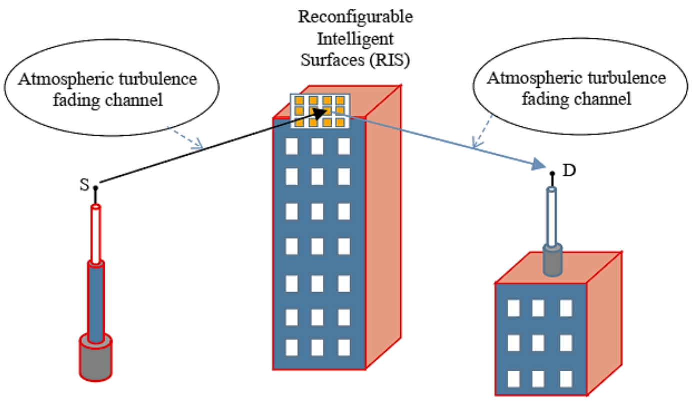

Figure 1. An overview of the system model

In an FSO link, atmospheric turbulence (h_l), weather conditions (h_a), and pointing errors (h_p) are three major elements of channel fading, that is critical challenges that need to be addressed to ensure the reliability and efficiency of FSO communication systems. Various techniques such as adaptive optics, diversity techniques, and alignment mechanisms are often used to mitigate these impairments and maintain the quality of the FSO link.

$$h = h_l \times h_a \times h_p \tag{1}$$

When weather conditions like rain or fog are combined with shadowing, the overall signal degradation becomes more pronounced. The signal-to-noise ratio (SNR) drops significantly due to both the direct attenuation from weather and the variation in signal strength modeled by log-normal fading [18], $f_{h_a}(h_a)$, it is expressed by (2):

$$f_{h_a}(h_a) = \frac{1}{h_a \sigma_S \sqrt{2\pi}} exp\left(-\frac{[ln(h_a)+0.5\sigma_S^2]^2}{2\sigma_S^2}\right) \tag{2}$$

The scintillation index, σ_S is a measure used to quantify the level of turbulence in the atmosphere and its effect on the propagation of light, particularly in optical communication and astronomy [18]. It can be mathematically represented as: $\sigma_S = exp(\omega_1 + \omega_2) + 1$.

$$\omega_1 = \frac{0.49\sigma_2^2}{(1+0.18d^2+0.56\sigma_2^{12/5})^{7/6}} \tag{3}$$

$$\omega_2 = \frac{0.51\sigma_2^2(1+0.69\sigma_2^{12/5})^{-5/6}}{1+0.9d^2+0.62d^2\sigma_2^{12/5}} \tag{4}$$

Moderate to strong turbulence introduces significant challenges to transmission channels by affecting signal integrity and reliability. Understanding and modeling these effects is crucial for designing robust communication systems, especially in environments prone to atmospheric disturbances.

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a}\right) \tag{5}$$

The parameter β is often used to represent the effects of small-scale turbulence or scattering cells, this can refer to localized disturbances in the atmosphere. The parameter α typically represents the effects of large-scale turbulence or scattering cells. These may involve broader atmospheric phenomena, such as larger weather systems, which affect the overall stability and uniformity of the atmosphere.

$$\alpha = [exp(\omega_1) - 1]^{-1}, \beta = [exp(\omega_2) - 1]^{-1} \tag{6}$$

Atmospheric attenuation becomes a critical factor in wireless communication systems. It refers to the reduction in the intensity of electromagnetic waves as they pass through the earth's atmosphere, and it is expressed by (7):

$$h_l = exp(-\sigma_l L_a) \tag{7}$$

The attenuation coefficient, often represented as σ_l, quantifies the reduction in intensity of a wave (such as light, sound, or electromagnetic radiation) as it travels through a medium. It is a crucial parameter in various fields, including physics, engineering, and telecommunications, it is given by (8):

$$\sigma_l = \frac{3{,}91}{V[\text{km}]}\left(\frac{\lambda[\text{nm}]}{550}\right)^{-q} \tag{8}$$

The pointing error model addresses the misalignment between transmitting and receiving antennas or optical systems, particularly in systems that rely on precise directional alignment, such as satellite communications, free-space optical communications, and laser systems. Pointing errors can occur due to mechanical inaccuracies, environmental factors (like wind), or thermal effects that cause physical changes in the system. In optical wireless communication, the pdf of pointing error fading models, $f_{h_p}(h_p)$, [18], it is given by (9):

$$f_{h_p}(h_p) = \frac{\xi^2}{A_0^{\xi^2}} h_p^{\xi^2-1}, \qquad 0 \le h_p \le A_0 \tag{9}$$

In there, the power at radial distance $z = 0$, $A_0 = [\text{erf}(v)]^2$, it helps quantify how much of the transmitted optical signal is captured at the receiver, considering pointing errors or beam wandering effects. $v = \sqrt{\pi}r/(\sqrt{2}\omega_z)$, ω_z is beam waist at the distance z, ω_{zeq} can be given by (10):

$$\omega_{zeq} = \omega_z(\sqrt{\pi}\, erf(v)/2v \times exp(-v^2))^{1/2} \tag{10}$$

2.2. The signal-to-noise ratio of system

In the scenario where a RIS module acts as a perfect reflector of an optical signal, with negligible signal absorption, and assuming perfect knowledge of channel phases at both the RIS and the transmitter node, we can derive the expression for the detected signal at the receiver node [22], it can be given by (11):

$$y = \sqrt{E_s}(h\mu e^{j\theta} g)x + n \tag{11}$$

Where, E_s is the symbol energy refers to the energy associated with the transmission of one symbol during digital communication, h and g are complex channel vectors, these vectors account for various impairments such as fading, delay, phase shifts, and interference, which affect the signal as it travels through the channel, it can be given by (12):

$$\gamma = \bar{\gamma}\left|h\mu e^{j\theta}g\right|^2 \tag{12}$$

Where $\bar{\gamma} = \frac{E_s}{N_0}$ represents the average electrical SNR, is a critical performance measure in communication systems, N_0 the power per unit of bandwidth of noise in a communication system.

2.3. The probability density function of system

The probability density function (PDF) of a system describes the likelihood of different outcomes or values of a random variable in a continuous system, $f_\gamma(\gamma)$, is computed from the SNRs, γ_h, and γ_g. The gain of system is given by $h\mu e^{j\theta}g$, where the quantity $\mu e^{j\theta}$ is deterministic in contrast to h and g. That is evaluated as [23]:

$$f_\gamma(\gamma) = \int_0^\infty f_{\gamma_h}(t) f_{\gamma_g}\left(\frac{\gamma}{t}\right)\frac{1}{t}dt \tag{13}$$

Where $f_\gamma(\cdot)$ is the PDF of the channels, that is combined distribution including weather conditions, atmospheric turbulence, and pointing errors. The SNR of system can be given by (14):

$$f_\gamma(\gamma) = \frac{\xi^4}{(X_l A_0)^{\xi^4}\left(\Gamma(\alpha)\Gamma(\beta)\right)^2} \times H_{2,6}^{4,2} \left(\frac{(\alpha\beta)^2\gamma}{(A_0 X_l)^2\bar{\gamma}_h\bar{\gamma}_g}\middle| \begin{matrix}(1+\xi^2,1),(1-\alpha,-1),(1-\beta,-1),(1-\xi^2,-1)\\ (\alpha,1),\ (\beta,1),(-\xi^2,-1),(\xi^2,1)\end{matrix}\right) \tag{14}$$

From (14) we can express the exact unified function as (15):

$$f_\gamma(\gamma) = \frac{\xi^4}{4(X_l A_0)^{\xi^4}} \frac{\gamma^{(\xi^2/2)-1}}{(\bar{\gamma}_g\bar{\gamma}_h)^{\xi^2/2}} \frac{\ln\gamma}{\pi} e^{2b} \times \exp\left\{-c_1\left(\frac{2a+0.5\ln\left[\gamma/(X_l^4 A_0^4\bar{\gamma}_h\bar{\gamma}_g)\right]}{\sqrt{2}\sigma_I}\right) - c_2\left(\frac{4a^2+\ln\left[\gamma/(X_l^4 A_0^4\bar{\gamma}_h\bar{\gamma}_g)\right](1+2a)}{2\sigma_I^2} - 2\frac{2a+0.5\ln\left[\gamma/(X_l^4 A_0^4\bar{\gamma}_h\bar{\gamma}_g)\right]}{\sqrt{2}\sigma_I}\right)\right\} \tag{15}$$

3. THE AVERAGE CHANNEL CAPACITY

The ACC can be calculated using the Shannon capacity formula, which provides the maximum data rate that can be transmitted over a communication channel with a given bandwidth and SNR. The exact calculation for the ACC depends on the specific distribution of SNR and its parameters. Average spectral efficiency is a measure of how effectively a communication system uses the available bandwidth to transmit data. It quantifies the amount of data transmitted per unit of bandwidth [24]:

$$\left\langle \bar{C} \right\rangle = \int_0^\infty \mathrm{B}\log_2\left(1+\gamma\right)\times f(\gamma)d\gamma,\ \text{[bit/s/Hz]} \tag{16}$$

Where B is the channel's bandwidth and $f_\gamma(\gamma)$ is the pdf of SNR.

4. NUMERICAL RESULTS AND DISCUSSIONS

In a reconfigurable intelligent surface aided system, annual sunlight exposure (ASE) is a critical performance metric in communication systems, measuring the efficiency of data transmission over a communication channel in relation to the bandwidth utilized. From (14) to (16), we consider a RIS aided FSO link over atmospheric turbulence channel, $L = 3000$ m, from the RIS as shown in Figure 2. In the context of FSO, RIS can be used to enhance the optical signal's performance, mitigating issues such as diffraction, scattering, and interference. Atmospheric turbulence can cause fluctuations in the index of refraction, leading to fading and distortion of optical signals. In our analysis, the parameters and constants are presented in Table 1.

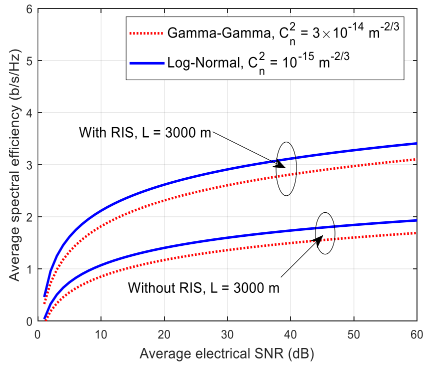

Figure 2. Illustrate the average spectral efficiency versus average electrical SNR

Table 1. The parameters and constants of system

Parameter	Symbol	Value
Wavelength	λ	1550 nm
Responsivity of photodetector	$\Re$	1 A/W
Index of modulation	κ	1
Total noise variance	N_0	10^{-7}A/Hz
Modulation level	$M_I \times M_Q$	8×4
Diameter of receiver	D	0.06 m
Refraction structure index	C_n^2	$10^{-15}m^{-2/3}, 3 \times 10^{-14}m^{-2/3}$

Figure 2 show various the ASE for NT-FSO link with RIS aided and without RIS aided respect to $\bar{\gamma}$, for various values of index of refraction structure, C_n^2, and link distances $L = 3000$ m. Indeed, the average spectral efficiency of a communication system can be significantly enhanced through the deployment of a reconfigurable intelligent surface, especially in the context of free space optics systems. Obviously, with longer link distance, the pointing error fading effects on ASE is greater. It has been that noticed that when the without RIS aided, the capacity performance of the system degrades.

Figure 3 illustrate the ASE performance versus link distance for various values of index of refraction structure, C_n^2, in case with RIS and without RIS. The impact of pointing errors on ASE and the overall capacity of FSO systems becomes more significant as link distances increase. However, by incorporating RIS technology, these challenges can be effectively mitigated. RIS enhances signal alignment, reduces the adverse effects of pointing errors, and improves overall system performance. This leads to higher capacity and more reliable communication, making it an essential technology for modern FSO applications.

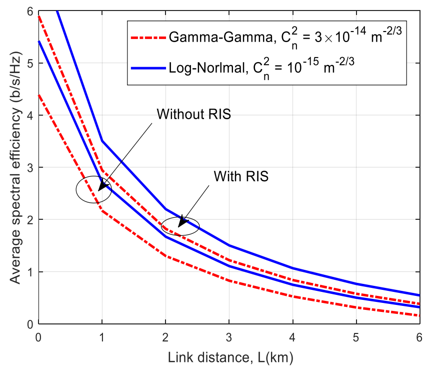

Figure 3. Illustrate the average spectral efficiency versus link distance

5. CONCLUSION

This study, we introduced the performance analysis of the ACC of free space optics links over atmospheric turbulence channels is an important area of study due to the increasing interest in FSO communications for high-speed data transfer in urban and outdoor environments. Atmospheric turbulence can significantly impact the performance of FSO systems, leading to variations in channel capacity. Incorporating

RIS into the analysis of FSO links over atmospheric turbulence channels opens up new possibilities for enhancing communication performance. By effectively manipulating the signal paths, RIS can significantly improve the ACC, making FSO systems more robust in adverse conditions.

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BIOGRAPHIES OF AUTHORS

Duong Huu Ai received the Master of Electronic Engineering from Danang University of Technology, Vietnam, in 2011, and the Ph.D. degree in Electronics and Telecommunications from Hanoi University of Technology, Vietnam, in 2018. Currently, he is a lecturer at The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang City, Vietnam. His research interests include optical wireless communications, optical and quantum electronics, 5G wireless communications and broadband networks, and IoT. He can be contacted at email: dhai@vku.udn.vn.

Hoang Huu Duc received his Master of Engineering in Computer Science from the University of Danang, Vietnam in 2013, a Ph.D. degree from Soongsil University in 2017. Currently, he is a lecturer at The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang City, Vietnam. His research interests include multimedia, information retrieval, artificial intelligence, and IoT. He can be contacted at email: hhduc@vku.udn.vn.

Khanh Ty Luong received his Master of Engineering in Computer Science from the University of Danang, Vietnam in 2012. Currently, he is a lecturer at The University of Danang-Vietnam-Korea University of Information and Communication Technology, Danang City, Vietnam. His research interests include database, artificial intelligence, IoT, and optical wireless communications. He can be contacted email: lkty@vku.udn.vn.

Ngoc Dat Vo received his Master of Science in Informatics from Da Nang University, Vietnam in 2007. Currently, he is a lecturer at The University of Danang, Vietnam-Korea University of Information and Communication Technology, Danang, Vietnam. His research interests include database, web design, technology and web programming, and cross-platform mobile app development. He can be contacted email: vndat@vku.udn.vn.