Indonesian Journal of Electrical Engineering and Computer Science
Vol. 40, No. 1, October 2025, pp. 173~180
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v40.i1.pp173-180

Performance analysis of wireless optical link with RIS aided and the implications of using Gaussian Q-function

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Article Info

Article history:

Received Oct 26, 2024
Revised Apr 23, 2025
Accepted Jul 3, 2025

Keywords:

ASER
QAM scheme
Q-function
RISs
Weibull distribution

ABSTRACT

This paper is concerned performance analysis of a wireless optical link with reconfigurable intelligent surfaces (RISs) aided and the implications of using the Gaussian Q-function. The Gaussian Q-function plays a critical role in the performance analysis of communication systems, particularly in scenarios involving noise and fading, including optical links and those aided by technologies like RISs. The analytical expression for performance is derived from the average of the symbol error rate (ASER) conditioned on the signal-to-noise ratio (SNR), incorporating the effects of noise and fading. Depending on the modulation scheme and fading model, the specific expressions for ASER can vary. The Gaussian Q-function significantly impacts the performance of systems; its mathematical properties and relationships with RISs and quadrature amplitude modulation (QAM) provide essential insights into system behavior under various conditions. The upper and lower bounds are commonly used to approximate the Gaussian Q-function, since the Gaussian Q-function doesn't have a closed-form solution, bounds and approximations are often used.

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1. INTRODUCTION

Free-space optical (FSO) communication systems use light to wirelessly transmit data through the atmosphere. They typically employ lasers or LEDs as the light source, transmitting data between two points (such as between buildings, satellites, or other line-of-sight locations) without relying on physical cables. These systems are gaining popularity due to their high data rates, security, and cost-effectiveness over shorter distances compared to fiber optics [1]-[7]. Deploying FSO communication systems requires careful planning, site assessment, and specialized equipment to ensure optimal performance. Given the unique challenges posed by atmospheric conditions, alignment, and distance, FSO deployment demands considerations that balance technical requirements and environmental factors [8]-[15].

The use of reconfigurable intelligent surfaces (RISs) is a promising technique in wireless communication, showing notable superiority in enhancing signal quality, coverage, and spectral efficiency. However, as you pointed out, some transmission parameters, such as modulation schemes like quadrature amplitude modulation (QAM) and performance metrics like the average symbol error rate (ASER), are essential yet often under-evaluated in the RIS context. Incorporating these aspects could lead to a more comprehensive understanding of RIS effectiveness under different modulation schemes and provide insights into practical performance [16]-[24]. In FSO communication, the Gaussian Q-function is frequently used to model the probability of signal errors due to fading and turbulence in the channel. Because FSO systems often operate over long distances and are subject to atmospheric disturbances (like fog, rain, and turbulence), the Q-function's upper and lower bounds become essential tools for approximating error probabilities in these systems [25]-[31].

In fading channels, the ASER analysis accounts for the fact that the signal experiences random variations in amplitude and phase due to multipath propagation. Since symbol error rates depend on the signal-to-noise ratio (SNR), which itself fluctuates due to fading, calculating ASER requires an averaging process. The ASER analysis over atmospheric turbulence channels involves averaging the Gaussian Q-function with a random variable due to fading, the Gaussian Q-function, defined by [1].

$$Q(x) = \frac{1}{2\pi}\int_{x}^{\infty} exp\left(-\frac{t^2}{2}\right)dt, \quad x \geq 0 \tag{1}$$

One common technique in ASER analysis is to use an alternative representation of the Gaussian Q-function to simplify integration. This often involves expressing the Q-function in a form that makes averaging over the fading distribution more manageable. One approach is to make use of an alternative representation of (1), and this has resulted, derived by Craig [2], as (2).

$$Q(x) = \frac{1}{\pi}\int_{x}^{\pi/2} exp\left(-\frac{x^2}{2Sin^2\psi}\right)d\psi, \quad x \geq 0 \tag{2}$$

This study, we theoretically performance analysis of wireless optical link with RIS aided and the implications of using Gaussian Q-function, the study is organized as follows. System and channels model is present in section 2. In section 3 presents the ASER. In section 4, the numerical results and discussions are presents. The study is included in section 5.

2. THE SYSTEM MODEL AND CHANNEL FADING

The system model, it sounds like you're describing a setup where a FSO communication link is enhanced with the help of RISs. In such a system, the RISs are typically placed strategically along the optical link to assist in redirecting, reflecting, or focusing the optical signals, thus helping to mitigate issues like atmospheric turbulence, scattering, and alignment problems that are common in FSO links. The system model under study is shown in Figure 1.

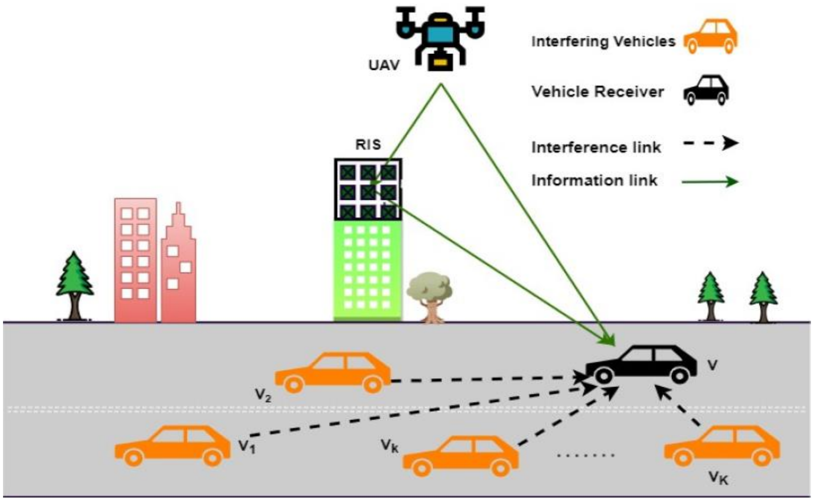

Figure 1. A diagram of system model

The Weibull distribution is a versatile statistical model often used to characterize fading in wireless communication channels, including FSO. The Weibull distribution is a versatile probability distribution often used in reliability analysis, failure time analysis, and modeling various types of data, particularly in fields such as engineering, weather forecasting, and telecommunications. The probability density function (PDF) is given by [3].

$$f_W(I;\beta,\eta) = \frac{\beta}{\eta}\left(\frac{I}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{I}{\eta}\right)^{\beta}\right] \quad (3)$$

where $\eta > 0$ is a critical component of the Weibull distribution, influencing its shape and behavior, $\beta > 0$ is a crucial aspect of the Weibull distribution that significantly influences its form and characteristics. The $n-th$ irradiance moment is given by,

$$\langle I^n\rangle = \eta^n \Gamma\left(1+\frac{n}{\beta}\right) \quad (4)$$

where $\Gamma(\,)$ is the gamma function is a special function that extends the concept of factorials to non-integer values. The scintillation index is a measure of the degree of fluctuations in the intensity of light due to atmospheric turbulence, is given by,

$$\sigma_I^2 = \frac{\Gamma(1+2/\beta)}{\Gamma(1+2/\beta)^2} - 1 \approx \beta^{-11/6} \quad (5)$$

Which simplifies the proof or analysis, while still covering all relevant scenarios, setting $n = 1$ and the irradiance data is normalized in the sense that $\langle I\rangle = 1$.

$$\eta = \frac{1}{\Gamma(1+1/\beta)} \quad (6)$$

2.2. Closed form statistical analysis

In the context of FSO or optical communication systems, the signal received at the destination node can be affected by several factors, including atmospheric turbulence, the characteristics of the transmitted signal, and the presence of noise. The mathematical representation of the signal received at the destination node generally includes the transmitted signal, attenuation, and any distortion or noise introduced during transmission. The signal at destination node is given as [4].

$$y = \sqrt{E_s}(p\mu e^{j\theta} q)x + n \quad (7)$$

Where, E_s is symbol energy refers to the amount of energy associated with a symbol in a digital communication system, $\eta e^{j\phi}$: characterizes the RISs element, η is the amplitude reflection coefficient is a key parameter in wave propagation, particularly in the fields of optics, telecommunications, and microwave engineering. The value of SNR is computed by [4].

$$\gamma = \bar{\gamma}\left|p\mu e^{j\theta} q\right|^2 \quad (8)$$

The PDF of SNR can depend on several factors, including the nature of the noise, the modulation scheme, and the channel characteristics. The PDF is evaluated as [5].

$$f_\gamma(\gamma) = \int_0^\infty f_{\gamma_p}(t) f_{\gamma_q}\left(\frac{\gamma}{t}\right)\frac{1}{t}dt \quad (9)$$

Were, $f_{\gamma_p}(\cdot)$: the PDF of the source-RISs, $f_{\gamma_q}(\cdot)$: the PDF of the RIS-destination.

Thirdly, assuming that with stable weather conditions, the channel models are represented by Weibull distribution, $f_{\gamma_i}(\gamma_i)$ is expressed as.

$$f_W(\gamma_i;\beta,\eta) = \frac{\beta}{\eta}\left(\frac{\gamma_i}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{\gamma_i}{\eta}\right)^{\beta}\right] \quad (10)$$

Where $i \in \{h, g\}$, perform variable change γ_i by t and $\frac{\gamma}{t}$ in (8), and PDF function of channels for $f_{\gamma_p}(t)$ and $f_{\gamma_q}(\frac{\gamma}{t})$ respectively as;

$$f_W(t;\beta,\eta) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (11)$$

$$f_W(\tfrac{\gamma}{t};\beta,\eta) = \frac{\beta}{\eta}\left(\frac{\gamma}{\eta t}\right)^{\beta-1} exp\left[-\left(\frac{\gamma}{\eta t}\right)^{\beta}\right] \quad (12)$$

We substitute (9) and (10) in to (7), the PDF of end-to-end SNR, $f_\gamma(\gamma)$, can be evaluated as,

$$f_\gamma(\gamma) = \int_0^\infty \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \times \frac{\beta}{\eta}\left(\frac{\gamma}{\eta t}\right)^{\beta-1} exp\left[-\left(\frac{\gamma}{\eta t}\right)^{\beta}\right]\frac{1}{t}dt \quad (13)$$

Perform calculations [8], the exact PDF of SNR, $f_\gamma(\gamma)$, as (14).

$$f_\gamma(\gamma) = \left(\frac{\beta}{\eta}\right)^2\left(\frac{\gamma}{\eta^2}\right)^{\beta-1} \lim_{n\to\infty}\sum_{k=1}^{n} exp\left[-\left(\frac{e^{\gamma_k}}{\eta}\right)^{\beta} - \left(\frac{\gamma_k}{\eta e^{\gamma_k}}\right)^{\beta}\right](z_k - z_{k-1}) \quad (14)$$

3. PERFORMANCE ANALYSIS OF FADING CHANNEL

The ASER for a FSO communication system using QAM can be analyzed based on several factors, including the modulation order, the SNR, and the channel conditions. It is counted as [7].

$$\bar{P}(\gamma) = \int_0^\infty P(\gamma)f(\gamma)d\gamma \quad (15)$$

where $f(\gamma)$ is the PDF of SNR, $P(\gamma)$ is the conditional error probability (CEP). The CEP in the context of communication systems, particularly in modulation schemes like QAM, refers to the probability of symbol error given a specific value of the SNR, the CEP is presented as,

$$P(\gamma) = 1 - [1 - 2q(M_I)Q(A_I\sqrt{\gamma})] \times \left[1 - 2q(M_Q)Q(A_Q\sqrt{\gamma})\right] \quad (16)$$

where, $A_I = \sqrt{6/\{(M_I^2-1) + r^2(M_Q^2-1)\}}$, $A_Q = \sqrt{6r^2/\{(M_I^2-1) + r^2(M_Q^2-1)\}}$,$q(x) = 1 - \frac{1}{x}$, $Q(x)$ is Gaussian Q-function.

The Q-function is critical in evaluating performance metrics in communication systems, particularly for symbol error rates in modulation schemes like QAM. The approximations and bounds on the Q-function allow for easier calculations while maintaining reasonable accuracy. Depending on the context and the required precision, different approximations can be selected. We use tight approximations on upper bound $Q_{ub}(\cdot)$ and lower bound $Q_{lb}(\cdot)$ given in [9] and in [10].

$$Q_{ub}(x) = \frac{1}{\sqrt{2\pi}x} exp\left(-\frac{x^2}{2}\right) - \frac{1}{2\sqrt{2\pi}x}\exp(-x^2) - \frac{1}{6\sqrt{2\pi}x}\exp(-3x^2) \quad (17)$$

$$Q_{lb}(x) = \frac{x}{3\sqrt{2\pi}}\exp\left(-\frac{37}{54}x^2\right) + \frac{2x}{3\sqrt{2\pi}}\exp\left(-\frac{38}{27}x^2\right) + \sqrt{\frac{2}{\pi}}x\exp(-\frac{14}{3}x^2) \quad (18)$$

Here's the CEP of optical wireless systems, $P(\gamma)$ determined by (15), (16) of ASER, $\bar{P}$ can be represented as;

$$\bar{P}(\gamma) = \int_0^\infty 2q(M_I)Q(A_I\sqrt{\gamma})f(\gamma)d\gamma + \int_0^\infty 2q(M_Q)Q(A_Q\sqrt{\gamma})f(\gamma)d\gamma - \int_0^\infty 4q(M_I)q(M_Q)Q(A_I\sqrt{\gamma})Q(A_Q\sqrt{\gamma})f(\gamma)d\gamma \quad (19)$$

Computing the ASER often requires working with integrals that involve the Gaussian Q-function, particularly in communication systems like those using QAM under various conditions such as noise and fading.

4. RESULTS AND DISCUSSION

In this section, using previous derived expression, to present numerical results for the ASER analysis of a FSO system utilizing the Q-function, we can follow a structured approach based on the previously derived expressions. Using the above closed mathematical forms as shown in (19) can estimate the ASER of system over atmospheric turbulence channel with weibull distribution, to accurately approximate the above ASER evaluation. Figure 2 show the mathematical results of the performance of FSO system with and without the assistance of RIS using the Q-function. When using higher modulation levels, like 32-QAM or 64-QAM, the symbols are packed closer together in the constellation diagram. This makes the system more susceptible to noise and distortions, increasing the ASER if power levels are not sufficient. To ensure a low ASER under high modulation, increasing the transmitted optical power can help enhance the SNR, which counteracts the vulnerability from using higher modulation levels. However, it's essential to balance this increase carefully, as excessive optical power can introduce nonlinear effects like self-phase modulation or cross-phase modulation, which may degrade system performance.

Figure 3 shows that ASER is an average electrical SNR function, the ASER in a free space optical system is indeed a function of the average electrical SNR. When analyzing the performance of such systems, it's essential to highlight how ASER relates to average electrical SNR, especially when considering transmission distance and environmental conditions. ASER performance as function of the transmission link distance, This analysis provides a visual representation of how transmission distance affects the ASER in an FSO system. As distance increases, the challenges posed by atmospheric conditions lead to higher error rates, emphasizing the need for strategies (like RIS or advanced modulation techniques) to mitigate these effects. It can be seen from the figure that the ASER increases when the transmission link distance is longer.

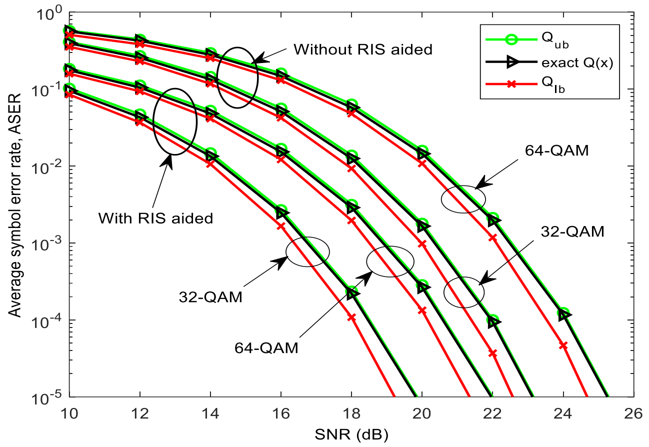

Figure 2. ASER performance against the SNR for upper and lower bounds with RIS and without RIS aided for values of QAM schemes

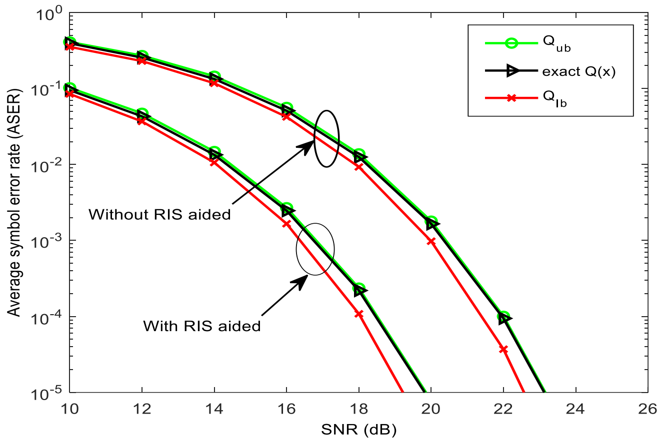

Figure 3. ASER performance against the SNR for upper and lower bounds with RIS and without RIS aided

5. CONCLUSION

In this paper, have theoretically performance analysis of wireless optical link with RIS aided and the implications of employing SC-QAM signals and Gaussian Q-function bounds. The results present the theoretical expressions for ASER performance of communication systems taking into account the QAM schemes, link distance, lower and upper bounds of Q-function, the system's ASER have been applied to compare the exact, lower and upper bounds of average symbol error probabilities. RIS technology can significantly enhance the performance of FSO systems by providing SNR gain and diversity, which in turn lower the ASER when using SC-QAM signals. Employing Gaussian Q-function bounds offers practical, analytical estimates for ASER, allowing for efficient system design and modulation scheme selection.

FUNDING INFORMATION

Authors state no funding involved.

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	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Khanh Ty Luong		✓		✓		✓				✓	✓	✓		
Viet Truong Le	✓		✓			✓	✓			✓	✓	✓		
Ngoc Dat vo		✓	✓	✓		✓	✓			✓	✓			

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 data that support the findings of this study are openly available in [Optics Communications] at doi: https://doi.org/10.1016/j.optcom.2018.04.049, reference number [3].
- The data that support the findings of this study are openly available in [IEEE] at doi: 10.1109/LCOMM.2020.3014820, reference number [4].
- The data that support the findings of this study are openly available in [IJECE] at doi: doi: 10.11591/ijece.v13i1.pp571-578, reference number [7].

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