

Closed-form ABER analysis of FSO links over a zero-boresight double Rician channel with adaptive optics

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This paper presents an analytical framework for modeling atmospheric turbulence in free-space optical (FSO) communication systems using the zero-boresight double Rician fading model. Unlike previous studies that characterize this model only in terms of irradiance statistics, this work derives a closed-form expression for the average bit error rate (ABER) under intensity modulation with direct detection (IM/DD) and on-off keying (OOK). The resulting expression enables efficient and accurate performance evaluation of FSO links across a wide range of turbulence conditions. To further improve link robustness, the influence of adaptive optics (AO) is incorporated into the double Rician fading model. The analysis considers the correction of different sets of Zernike modes and demonstrates how variations in their coefficients affect received signal stability and overall link quality. Numerical results show that compensating lower-order Zernike modes significantly reduces turbulence-induced fading and leads to notable improvements in ABER performance. These findings provide a practical basis for designing AO-assisted FSO systems capable of dynamic adaptation to varying atmospheric conditions.

Keywords: double Rician model, free space optics (FSO), adaptive optics, average bit error rate (ABER).

1. Introduction

Optical wireless communications (OWC) represent a modern approach to data transmission in which information is transferred using an optical carrier propagating through free space. Such systems offer several advantages, including cost-effectiveness, rapid deployment, and the use of unlicensed optical spectrum. OWC systems are generally categorized into two groups: visible light communications (VLC), which utilize the visible part of the spectrum, and free space optics (FSO), which operate in the infrared range. This paper focuses on FSO systems and the challenges associated with their operation. FSO links commonly span distances from 50 m to several kilometers, using wavelengths between 750 and 1550 nm, with data rates reaching tens of gigabits per second. They are particularly suitable in environments where fiber installation is impractical, such as remote or hard-to-access terrain, across rivers, or as rapid-deployment solutions in cases of fiber infrastructure failure. Since FSO communication relies on atmospheric propagation, the influence of atmospheric conditions is unavoidable. The dominant impairment is atmospheric turbulence, which causes random fluctuations in the received signal intensity. To characterize this phenomenon, various statistical models have been proposed, and the selection of the appropriate model depends on the prevailing turbulence regime. Among the commonly applied models are the log-normal distribution [1–3], Rician distribution [4–6], negative exponential distribution [7, 8], K-distribution [9], and Weibull distribution [10]. The Gamma–Gamma model [11–13] has been widely adopted due to its ability to jointly describe small-scale and large-scale fluctuations. While the Gamma–Gamma model has proven effective in describing irradiance fluctuations by separating large-scale and small-scale turbulence effects, it implicitly assumes that the received field results from a single dominant scattering structure. In contrast, in many practical FSO scenarios, particularly urban horizontal links, near-ground propagation, and channels with multiple beam wander and scattering layers, the received signal often contains multiple coherent components, each undergoing independent fading. The double Rician model captures this physical mechanism more accurately by representing the optical field as a superposition of two partially coherent Rician processes, leading to a statistically tighter match with measured irradiance distributions under strong or compound turbulence conditions. Building upon this framework, composite and generalized models have been introduced, including the double Rician model [14], which provides improved accuracy under certain turbulence conditions and serves as the basis for the analysis in this paper.

To mitigate turbulence effects, adaptive optics (AO) has proven to be an effective method for compensating wavefront distortions. In [15], relationships were established between FSOC system performance and AO parameters, including the number of corrected Zernike modes and correction bandwidth relative to the Greenwood frequency. It was shown that correcting approximately 35 modes and ensuring bandwidth greater than the Greenwood frequency significantly reduces the bit error rate (BER). Furthermore, authors in [16] analyzed FSO links implemented on high-altitude platforms using Zernike-based AO correction together with the Gamma–Gamma fading model,

deriving outage and performance expressions and confirming significant improvement when AO is employed. In [4] is additionally examined coherent detection schemes and demonstrated how fluctuations in phase and amplitude influence performance depending on the aperture-to-coherence-length ratio and AO correction capability. Although the Gamma-Gamma model remains the dominant analytical framework for evaluating FSO system performance under atmospheric turbulence, recent studies have shown that in scenarios involving multiple scattering clusters or strong refractive index fluctuations, the double Rician model provides a more accurate representation of irradiance fluctuations [14]. However, existing research involving the double Rician model is mostly limited to the derivation of irradiance probability distributions, without providing closed-form expressions for key performance metrics such as the average bit error rate (ABER) in IM/DD-based systems. Furthermore, the application of adaptive optics (AO) to mitigate turbulence effects is predominantly analyzed under the Gamma-Gamma turbulence assumption [15–16], while the combined effect of double Rician fading and AO-based wavefront correction has not been analytically addressed. This research gap motivates the development of the ABER expression and performance evaluation framework proposed in this paper. Motivated by these studies, this paper applies the zero-boresight double Rician model [14] to derive a new closed-form expression for the average bit error rate (ABER) under intensity modulation with direct detection and OOK signaling. The corrective influence of adaptive optics is incorporated through Zernike modal decomposition, enabling evaluation of performance improvements as a function of the number and type of corrected modes. The aim of this paper is therefore to analyze the performance of an FSO system affected by atmospheric turbulence using the zero-boresight double Rician fading model, and to demonstrate the improvement achieved through adaptive optics correction based on Zernike modes.

2. System model

2.1. Atmospheric channel model

The zero-boresight double Rician model is used for modeling atmospheric turbulence and can be expressed as:

$$f_I(I) = \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{(1+K_1)(1+K_2)K_1^p K_2^q \exp(-K_1-K_2)\zeta^2}{\Omega_1 \Omega_2 A_0 \Gamma(p+1) \Gamma(q+1) p! q!} G\left(\zeta^2 \middle| \frac{(1+K_1)(1+K_2)t}{\Omega_1 \Omega_2 A_0}\right) \quad (1)$$

The indices p and q represent non-negative integer summation variables arising from the series representation of the double Rician fading model, and due to the rapid convergence of the series, retaining only the first 10–15 terms ensures numerical accuracy up to the fifth decimal digit. The parameter Ω represents the total received signal power,

while K_j is the Rician factor that describes the ratio between the power of the dominant component and the scattered components, and it can be obtained from the following expression:

$$K_j = \left(\frac{\bar{\alpha}_{rj}^2 + \sigma_{rj}^2 + \sigma_{ij}^2}{\sqrt{\bar{\alpha}_{rj}^4 + 2\bar{\alpha}_{rj}^2(\sigma_{ij}^2 - \sigma_{rj}^2)} - (\sigma_{ij}^2 - \sigma_{rj}^2)^2} - 1 \right)^{-1} \quad (2)$$

where $\bar{\alpha}_{rj}^2$ denotes the mean value of the real part of the effective turbulence coefficients, while σ_{rj}^2 and σ_{ij}^2 respectively represent the variances of the real and imaginary parts of the effective turbulence coefficients, for $j = 1, 2$:

$$\bar{\alpha}_{rj}^2 = \exp\left(-\frac{\sigma_{xj}^2 + \sigma_{\phi j}^2}{2}\right) \quad (3)$$

and $\sigma_{\phi j}^2$ represents the residual phase deviations and can be obtained from the following expression:

$$\sigma_{\phi j}^2 = C_j \left(\frac{D}{r_0} \right)^{5/3} \quad (4)$$

where C_j represents the Zernike coefficient, whose value is determined based on the number of terms (modes), D denotes the aperture diameter, and $r_0 = 1.68(C_n^2 L K^2)^{-3/5}$ represents the generalized Fried parameter, which defines the diameter of the coherent wavefront. The log-amplitude variance can be determined from the expression for the scintillation index $\sigma_i^2 = \exp(4\sigma_{xj}^2) - 1$.

$$\sigma_{rj}^2 = \frac{1 + \exp(-2\sigma_{\phi j}^2) - 2\exp(-\sigma_{xj}^2 - \sigma_{\phi j}^2)}{2N} \quad (5)$$

$$\sigma_{ij}^2 = \frac{1 - \exp(-2\sigma_{\phi j}^2)}{2N} \quad (6)$$

where $\sigma_{\phi j}^2$ and σ_{xj}^2 denote the variance of the phase and amplitude fluctuations, respectively, while N represents the number of statistically independent cells on the receiving aperture (RA) and can be expressed as:

$$N = \left(1.09 \left(\frac{r_0}{D} \right)^2 \Gamma\left(\frac{6}{5}, 1.08 \left(\frac{D}{r_0} \right)^{5/3} \right) \right)^{-1} \quad (7)$$

where $\Gamma(a, x)$ denotes the lower incomplete Gamma function.

The application of adaptive optics reduces phase distortions in the received wavefront, effectively increasing the equivalent Rician K -factor. This results in a narrower irradiance distribution and reduced intensity fluctuations, which directly leads to lower ABER values in IM/DD systems.

T a b l e 1. Classification of Zernike polynomials by modes.

Order n	Designation Z_n^m	Primary aberrations	Role of correction in FSO systems
0	Z_0^0	Piston	No correction required (no impact on quality).
1	Z_1^{-1}, Z_1^1	Tip and tilt	Correction reduces beam wander – the beam remains centered on the receiver – lower energy losses.
2	Z_2^{-2}, Z_2^0, Z_2^2	Defocus, astigmatism	Correction improves beam focusing – more energy on the aperture – more stable SNR and better BER.
3	$Z_3^{-3}, Z_3^{-1}, Z_3^1, Z_3^3$	Coma	Correction eliminates beam “tail” – more energy concentrated at the center – increased detection efficiency.
4	$Z_4^{-4}, Z_4^{-2}, Z_4^0, Z_4^2, Z_4^4$	Spherical aberration and higher-order astigmatism	Correction reduces wavefront interference – decreased scintillation – more stable data transmission.
5	$Z_5^{-5} \dots Z_5^5$	Higher-order coma and astigmatism	Correction removes complex distortions – significant improvement under strong turbulence and for long-range links.
6 or more	$Z_6^m, Z_7^m, \dots$	Higher-order aberrations	Correction enables high wavefront resolution – critical for high-capacity FSO systems and 5G/6G applications.

To evaluate the level of aberration, Table 1 is presented that classifies the Zernike polynomials according to their orders n and indices m , along with their physical interpretation in terms of optical aberrations.

The aberration order n indicates the complexity of the aberration; the higher the order, the more complex the wavefront, containing more waves across the aperture. The azimuthal symmetry index m determines the symmetry along the circular aperture, and the numerical index is obtained from the expression $j = 0.5(n^2 + n) + |m|$ [17].

2.2. Determination of the PDF as a function of SNR when using IM/DD with OOK modulation

In FSO systems with IM/DD and OOK modulation, the signal is first intensity-modulated and then transmitted through the atmospheric channel. The received optical sig-

nal at the photodetector converts the optical power intensity into a current, which is then detected. The detected current can be expressed as:

$$y_T(t) = x(t)RI + n \quad (8)$$

where $x(t)$ denotes the transmitted signal envelope, R represents the photodiode responsivity, I denotes the signal intensity fluctuation, and n represents zero-mean white Gaussian noise (AWGN – additive white Gaussian noise) with variance σ_n^2 .

The SNR can be expressed using the following expression:

$$\gamma = \frac{(2PRI)^2}{2\sigma_n^2} \quad (9)$$

as well as the average SNR [18]:

$$\bar{\gamma} = E[\gamma] = E\left[\frac{(2P_T RI)^2}{2\sigma_n^2}\right] = \frac{(2P_T R)^2}{2\sigma_n^2} E[I^2] \quad (10)$$

where $E[\cdot]$ denotes the mathematical expectation, and P_T represents the average transmitted power.

In the literature, the electrical SNR is often used, which can be expressed by the following equation:

$$\mu = \frac{(2P_T R)^2}{2\sigma_n^2} E^2[I] \quad (11)$$

where

$$\gamma = \frac{\mu}{E^2[I]} I^2 \quad (12)$$

The PDF as a function of SNR can be obtained from the following expression:

$$f_\gamma(\gamma) = \frac{f_I(I)}{\partial\gamma/\partial I} \quad (13)$$

By substituting expressions (1) and (9) into equation (13) and applying the rule from [19, 07.34.16.0002.01], the expression for the PDF as a function of SNR for IM/DD with OOK modulation is obtained:

$$f_\gamma(\gamma) = \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{K_1^p K_2^q \exp(-K_1) \exp(-K_2) \xi^4}{2\sqrt{\gamma} \Gamma(p+1) \Gamma(q+1) p! q!} G_{1,3}^{3,0} \left(\begin{matrix} \xi^2 + 1 \\ \xi^2, p+1, q+1 \end{matrix} \middle| \frac{(1+K_1)(1+K_2)\sqrt{\gamma}}{(\xi^2+1)\sqrt{\mu}} \right) \quad (14)$$

2.3. Determination of the scintillation index

The scintillation index is used as a measure to assess the quality of the channel in FSO communication systems, as it indicates the extent to which the atmospheric channel is affected by atmospheric turbulence. The level of scintillation can be expressed as:

$$\sigma_i^2 = \frac{E[I^2]}{E^2[I]} - 1 \quad (15)$$

where σ_i^2 is the scintillation index (Scintillation Index), where $E[\cdot]$ denotes the mathematical expectation and I represents the signal intensity fluctuation. It is noted that the scintillation index expression used here is valid under weak-to-moderate turbulence conditions, where the Rytov variance remains below unity ($\sigma_R^2 < 1$), ensuring that the irradiance fluctuations can be accurately modeled by the adopted statistical formulation. From expression (1), the scintillation index can be easily determined by calculating the mathematical expectation:

$$E[I] = \int_0^\infty I f_I(I) dI = \frac{A_0 \Omega_1 \Omega_2 \xi^2}{1 + \xi^2} \quad (16)$$

$$E[I^2] = \int_0^\infty I^2 f_I(I) dI = \frac{A_0 \Omega_1^2 \Omega_2^2 \xi^2 (2 + 4K_1 + K_1^2)(2 + 4K_1 + K_2^2)}{(2 + \xi^2)(1 + K_1)^2(1 + K_2)^2} \quad (17)$$

$$\sigma_i^2 = \frac{E[I^2]}{E^2[I]} - 1 = \frac{(1 + \xi^2)^2}{(2 + \xi^2)\xi^2} \frac{(2 + 4K_1 + K_1^2)(2 + 4K_1 + K_2^2)}{(1 + K_1)^2(1 + K_2)^2} - 1 \quad (18)$$

2.4. Determination of ABER as a function of SNR when IM/DD with OOK modulation is applied

The ABER for IM/DD with OOK modulation is determined from the following expression:

$$P_e = \int_0^\infty \frac{1}{2} \operatorname{erfc}\left(\frac{\sqrt{\gamma}}{2}\right) f_\gamma(\gamma) d\gamma \quad (19)$$

where, according to [19, Eq.06.27.26.0006.01]:

$$\operatorname{erfc}\left(\frac{\sqrt{\gamma}}{2}\right) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left(\frac{1}{0, \frac{1}{2}} \middle| \frac{\gamma}{4}\right) \quad (20)$$

By substituting Eqs. (14) and (20) into Eq. (19) and applying the rule from [19, 07.34.21.0013.01], the solution of the given integral is obtained, which simultaneously represents the expression for ABER as a function of SNR:

$$P_e(\mu) = \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{2^{b+p-2} K_1^p K_2^q \exp(-K_1) \exp(-K_2) \xi^4}{\pi^{9/2} \Gamma(p+1) \Gamma(q+1) p! q!}$$

$$G_{3,6}^{5,2} \left(\begin{matrix} \frac{1}{2}, 0, \frac{1+\xi^2}{2} \\ \frac{\xi^2}{2}, \frac{p+1}{2}, \frac{p+2}{2}, \frac{q+1}{2}, \frac{q+2}{2}, -\frac{1}{2} \end{matrix} \middle| \frac{(1+K_1)^2 (1+K_2)^2}{4(\xi^2+1)^2 \mu} \right) \quad (21)$$

3. Numerical results

For obtaining the results, the parameters from Table 2 were used. Other parameter values are presented in the paper.

T a b l e 2. Values of the parameters used for numerical calculations.

Parameter description	Symbol	Value		
		Weak	Moderate	Strong
Refractive index – turbulence strength	C_n^2 [m ^{-2/3}]	6×10^{-15}	2×10^{-14}	1.2×10^{-13}
Wavelength	λ [nm]	1550		
Distance between transmitter and receiver	L [m]	1500		
Received power at the receiver	$\mathcal{Q}$ [W]	1		
Radius of the circular detector	a [m]	0.05		
Radius of the optical beam at the receiver	w_L [m]	0.5		

Figure 1 illustrates the impact of atmospheric turbulence on FSO communication systems.

From the presented figure, it can be observed that the FSO system achieves the lowest ABER, *i.e.*, the best performance, under conditions of weak atmospheric disturbances. As the intensity of atmospheric turbulence increases, the performance of the FSO system progressively deteriorates, with the worst performance recorded under strong turbulence conditions. This highlights the need to apply appropriate turbulence mitigation techniques in scenarios with pronounced atmospheric effects.

By applying expression (21), the results for the ABER were obtained as a function of the ratio of the normalized receiver aperture diameter to the coherence length (Fried parameter). Amplitude fluctuations were neglected under the assumption that $\sigma_i^2 = 0$, meaning that only the phase component of turbulence remains in the model.

The ratio D/r_0 is a key parameter for characterizing the performance of an optical receiver under atmospheric turbulence conditions. From the graph, it can be observed that when $D \gg r_0$, the ABER is higher, meaning the system performance is poorer. In this case, the receiver aperture encompasses more distorted portions of the wavefront, leading to greater phase variations and more pronounced aberrations. On the other

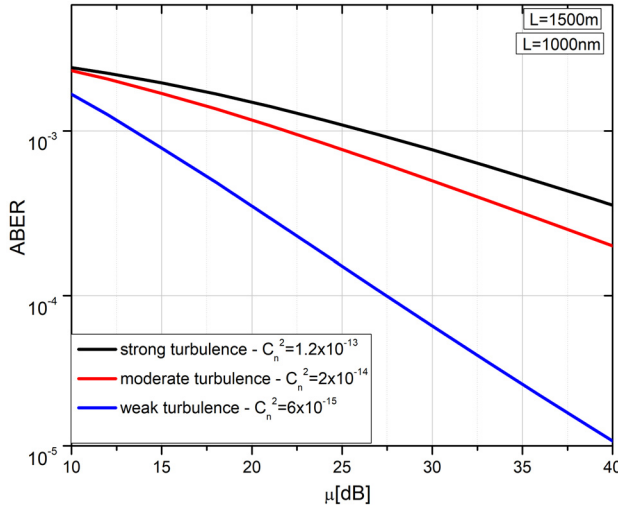


Fig. 1. ABER of the zero-boresight double Rician mathematical model for different effects of atmospheric turbulence.

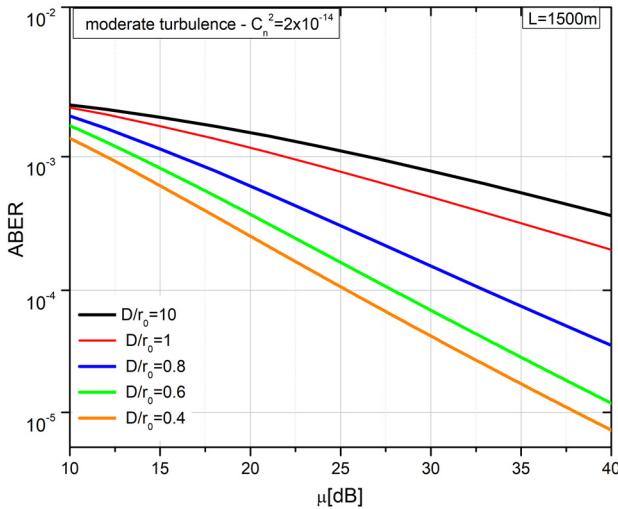


Fig. 2. ABER of the zero-boresight double Rician mathematical model for different values of the ratio of the normalized receiver aperture diameter to the Fried parameter.

hand, for $D \approx r_0$, the impact of phase aberrations is somewhat reduced, resulting in a slight improvement in FSO system performance. When the ratio $D/r_0 \ll 1$, the effect of phase aberrations becomes minimal, leading to a progressive decrease in ABER and a significant improvement in system performance. The numerical results clearly illustrate how atmospheric turbulence parameters and AO correction depth jointly influence the system performance. In Figs. 1 and 2, stronger turbulence (or larger values of the normalized aperture parameter D/r_0) leads to more pronounced irradiance fluctuations,

which directly increases the ABER. Physically, this reflects the fact that a larger receiver aperture captures a greater portion of the distorted wavefront, introducing stronger phase inhomogeneities and thus degrading detection performance. Conversely, when D/r_0 is small, the received wavefront remains more coherent, resulting in reduced scintillation and lower ABER.

Figures 3 and 4 present the results for ABER as a function of the number of modes, whose application corresponds to the use of adaptive optics. Two approaches are con-

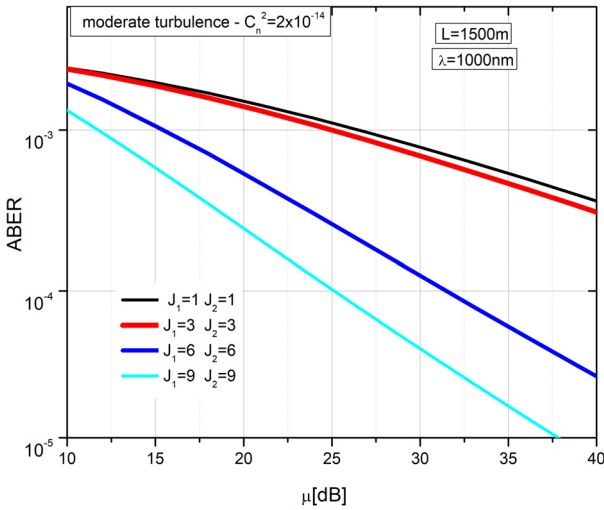


Fig. 3. ABER under moderate turbulence conditions as a function of the number of modes in the symmetric approach.

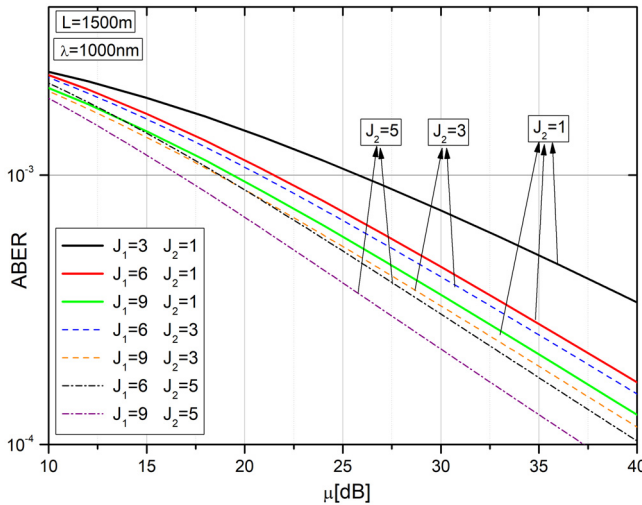


Fig. 4. ABER under moderate turbulence conditions as a function of the number of modes in the asymmetric approach.

sidered in the study: a symmetric and an asymmetric approach. In the first approach, adaptive optics generates an identical response for both large-scale and small-scale fluctuations, and for this reason, the number of modes is the same (Fig. 3). The second approach considers different impacts of the modes on large-scale and small-scale vortices. Since small-scale modes correspond to faster phase variations, a structure with a larger number of modes is applied. In contrast, large-scale modes are characterized by slower changes, so the use of a large number of modes is feasible only in a theoretical sense (Fig. 4). At low numbers of corrected modes, only coarse aberrations such as beam wander and basic astigmatism are mitigated, which produces a modest but noticeable performance improvement. As the number of compensated modes increases, higher-order phase distortions are corrected, leading to a narrower irradiance distribution and consequently lower ABER.

The presented figures analyze the impact of the number of modes, in terms of complexity, on the performance of FSO communication systems in the presence of adaptive optics. Figure 3 illustrates the effect of adaptive optics using the symmetric approach. It can be observed from the figure that increasing the number of modes significantly improves the performance of the FSO system. The graph shows that the system performance is worst for $J_1 = J_2 = 1$, *i.e.*, in the absence of any correction. Already at $J_1 = J_2 = 3$, there is a significant reduction in ABER, indicating improved system performance. This value can be considered as tilt compensation, where the wavefront is corrected in both the horizontal (x) and vertical (y) directions. This represents the simplest form of aberration, as it involves only beam displacement correction without correcting more complex deformations.

Furthermore, for $J_1 = J_2 = 6$, there is an additional reduction in ABER, indicating further improvement in system performance. This number of modes allows for the correction up to the level of astigmatism, including compensation for defocus, which occurs due to light propagation through media with varying refractive indices. This compensation mitigates wavefront distortions caused by atmospheric turbulence.

At $J_1 = J_2 = 9$, further improvement is achieved, as this level enables the correction of complex distortions, eliminating the beam “tail” and concentrating more energy at the center, which leads to increased detection efficiency. Increasing the number of modes allows for significant enhancement of system performance; however, it also requires a more complex design and implementation of adaptive optics.

Figure 4 illustrates different numbers of large-scale and small-scale modes. An approach was used in which the number of small-scale modes is greater than that of large-scale modes. Lower values of large-scale modes were deliberately chosen because large-scale fluctuations are slower and milder, requiring fewer modes for adequate compensation. From the graph, it can be observed that a higher number of both small-scale and large-scale modes enables better FSO system performance. Additionally, combining different values of these modes provides the possibility for finer system tuning and a more diverse representation of the impact of increasing the number of modes. For practical deployment, compensating approximately 6–9 Zernike modes provides a favorable trade-off between performance gain and implementation com-

plexity. Further correction improves ABER but requires a disproportionately higher number of actuators, increasing cost and system latency.

4. Conclusion

The results obtained in this work demonstrate that the application of adaptive optics can significantly improve the performance and reliability of FSO communication systems operating under atmospheric turbulence. By compensating a limited number of Zernike modes, notable reduction of wavefront distortions and signal fading can be achieved, even without full wavefront correction. This leads to improved link stability and reduced bit error rate, which is especially important in practical deployments such as dense urban environments, remote sensing links, high-security optical communication, and military communication scenarios where consistent throughput is essential. Nonetheless, while increasing the number of corrected modes further enhances performance, practical implementation introduces several constraints. Higher-order correction requires deformable mirrors with a proportional increase in the number of actuators, which results in increased system complexity, more sophisticated control electronics, higher energy consumption, and overall cost escalation. For this reason, the selection of the number of compensated modes must represent a balance between desired performance gain and system feasibility. In summary, the analysis confirms that integrating the double Rician statistical model with adaptive optics provides an effective framework for performance evaluation and turbulence mitigation in FSO systems, and can serve as a foundation for the design of optimized, cost-efficient optical links adapted to varying atmospheric conditions.

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