

Outage Performance of Free-Space Optical Communication Systems Over Turbulent Channels with Varying Atmospheric Visibilities

Rahat Ara¹, It Ee Lee^{1*}, Zabih Ghassemlooy², Gwo Chin Chung¹, Muhammad Sheraz¹, Teong Chee Chuah¹

¹ Faculty of Engineering

Multimedia University, Cyberjaya, 63100, MALAYSIA

² Department of Mathematics, Physics and Electrical Engineering

Northumbria University, Newcastle Upon Tyne, NE1 8ST, UNITED KINGDOM

*Corresponding Author: ielee@mmu.edu.my

DOI: <https://doi.org/10.30880/ijie.2025.17.02.001>

Article Info

Received: 10 November 2024

Accepted: 24 June 2025

Available online: 18 July 2025

Keywords

Free space optical (FSO) communications, atmospheric turbulence, optical scintillation, link visibility, pointing errors, probability of outage, optical power

Abstract

Free space optics is the technology where beams of light provide optical connection using a line-of-sight path for communication as a form of video, voice, and data information between two points. A few of the FSO system's limitations include atmospheric attenuation caused by weather, which is the most difficult issue to solve because it seriously impairs system performance and results in poor signal transmission. One of the important performance measures for analyzing and enhancing FSO functionality for various fading states associated with different data rates is outage probability. This article examines FSO in terms of transmission optical power, feasible bit rates, and outage probability under clear, hazy, and moderate to heavy rainy conditions. The MATLAB simulation is implemented to do the performance study. However, aperture diameters $D = \{20, 40, 80, 100\}$ mm and link distances $L = \{2.0, 3.5, 5.0\}$ mm are seen to be essential characteristics for evaluating system performance. For all scenarios, the system's power consumption can be minimized by using larger aperture diameters at lower bit rates, particularly in clear weather.

1. Introduction

Recently, free space optical (FSO) communications have become one of the most demanding technologies for modulating information or data as a signal between two locations that is propagated through an optical channel. According to its basic mechanism, the transmitter, atmospheric channel, and receiver are the main functional components where the completion of the data transmission procedure takes place. At the transmitter [1], the electrical signal is modulated by the modulator, commonly known as the intensity modulation method, and converted optically as a form of laser. The transmitted signal is attenuated in the atmospheric channel due to hazardous weather conditions resulting in turbulence, scattering, and absorption under haze, fog, rain, etc. The optical signal finally reaches the receiver part and is converted to electrical form through a photo detector, and the desired output form can be obtained after amplification, modulation, and demodulation.

Several features [2] have made FSO appealing to researchers and service providers, which are commonly cable-less, better speed than broadband connections, immunization against radio frequency interference, low cost, no licensing or tariff requirement, low power consumption during data transmission and a low bit error rate. Despite several merits, different weather conditions [3] make data transmission challenging, as the medium of

communication is free space. Common weather phenomena like fog, haze, and rain give rise to irradiance intensity fluctuations and beam degradation. Furthermore, absorption, scattering, path loss, pointing error, and scintillation lead to inferior communication performance.

System models [4], channel models [5], relaying methods [6], modulation techniques [7], and diversity [8] have become the main interests of research in free space optics, where turbulence and attenuation lowering and making the feature superior are the main intentions. Based on our information, [9] an analysis was conducted on the outage performance of a mixed RF-FSO system that used a variable-gain AF relaying mechanism. The system model's closed form statement for the outage probability was taken into consideration. Additionally, an investigation was conducted into the impact of several system characteristics on the outage behavior. Similarly, [10] Under various atmospheric turbulent conditions, the performance of the RF/FSO system over the Nakagami-m distribution with pointing error has been studied in terms of outage probability with respect to SNR under the IM/DD detection scheme. In a study [11], A unified analysis of the numerous variable-gain amplify-and-forward relays in the combined radio-frequency (RF)/free space optics (FSO) relaying system is offered. A reduced version of the outage probability statement is obtained for a few specific instances. Furthermore, approximate values with a high signal-to-noise ratio are given, which can be effectively utilized to ascertain the outage probability floor. In another article, [12] Analysis was done on the diversity reception of optical signals sent across terrestrial free-space optical (FSO) networks. The received signal's irradiance variations are represented by a Gamma-Gamma probability density function, the parameters of which are closely related to the propagation conditions. The numerical results show that with an outage probability of 10^{-7} , spatial correlation leads in a penalty in the electrical signal-to-noise ratio of roughly 5 dB. In a paper, [13] by obtaining closed-form formulas for uplink SATCOM and terrestrial communication scenarios, the outage probability of the adaptive combining technique is examined. Additionally, a switching threshold range was identified, during which the system provides maximum outage performance.

In another approach, [14] analytical research has been done on the outage likelihood of a dual-hop FSO system using AF fixed gain relaying operating under both IM/DD and heterodyne detection, including pointing error effects. Furthermore, in terms of basic functions, precise asymptotic solutions for the outage probability at high SNR have been given. Similarly, [15] research has been done on the outage performance of FSO communication systems over heavy turbulence channels using DF parallel relay nodes. The outage likelihood was assessed and examined using an aggregated channel model that took into account the combined effects of atmospheric attenuation, atmospheric turbulence, and pointing errors. It has been shown that using parallel relay transmission is a viable way to improve the FSO communications' outage performance. Additionally, the simulation results demonstrate that the analytical expression may precisely approximate the simulation findings and is sufficiently accurate. In a paper, [16] novel analytical expressions for overall outage probability of a hybrid FSO/WiMAX system and numerical results with Monte-Carlo simulations have been derived. On the basis of the results, the conclusion is that the effect of optimal selection of laser beam radius at the waist on outage probability becomes stronger with decreasing of misalignment and turbulence strength over FSO link, as well as with decreasing of shadowing spread and multipath fading severity over RF link. In a research, [17] an investigation of the free space optical communication system's performance in terms of outage probability and ergodic channel capacity is conducted. As a result, by replacing the variables with equivalent values, the results may be used to generate the equations for the channel capacity and outage probability of gamma-gamma and K-distribution channels. Similarly, [18] another research investigates the performance of a DCO-OFDM based FSO system with the log-normal distribution for channel turbulence. The model facilitates the investigation of the relationship between optical intensity, which influences the average BER and outage probability at the receiver aperture, and the properties of the OFDM signal and beam. Based on our information, the individual FSO and RF systems are created, and the outage probability of the proposed system is analyzed in a paper [19]. The analysis is supported by the reported simulation findings. It is demonstrated that the suggested system performs better than the separate RF and FSO systems and provides a 3dB power gain across a range of receive antennas.

The objective of this research project is to analyze and optimize the probability of an outage for FSO considering the economic consumption of transmitted optical power and optimized data transmission rates. The performance testing method is MATLAB simulation study where achievable bit rate, link distances, aperture diameter etc. are taken into account as crucial parameters. The overall performances are observed and analyzed considering haze, moderate rain and heavy rain for 2.0 km, 3.5 km and 5.0 km link distances, data rates of 0.2, 0.5, 0.8 and 1.0 bits/channel and aperture diameters of 20, 40, 80 and 100 mm. In every instance, optical power consumption can be optimized by selecting the proper link distance and bit rates.

The remaining portion of the paper is structured as follows: Section II presents overview of the FSO system and outlined the components the atmospheric channel. In Section III, instantaneous channel capacity, achievable bit rate, and outage probability of the channel is analyzed. Next, the numerical results of our simulation works are focussed and discussed in Section IV. Finally, our concluding remarks are presented in Section V.

2. System Description

2.1 Methodology

The methodology presented (see Fig. 1) utilizes a MATLAB-based simulation approach to systematically model the FSO system. This approach is designed to analyze the system's performance and behavior across a range of environmental and operational conditions, facilitating the evaluation and feasibility analysis of the FSO solution. The simulation framework begins by developing an extensive model of the FSO system, which incorporates the FSO link. Building upon the standard point-to-point SISO link configuration detailed in Section 2.2, the FSO channel characteristics are modeled according to Equation (2), considering key factors that impact system performance, such as atmospheric losses, turbulence-induced optical scintillation, and pointing errors.

Outage probability is chosen as the primary performance metric for this simulation, enabling the assessment and comparison of the reliability of a standalone FSO system. The outage analysis provides statistical insights into the likelihood of signal degradation when received signal quality falls below a predetermined threshold due to unfavorable channel conditions. The simulation parameters are selected to represent practical scenarios, covering a variety of environmental and system configuration variations. This methodology offers a comprehensive understanding of the FSO system's potential, showcasing its ability to deliver reliable and high-performance communication under diverse and challenging conditions.

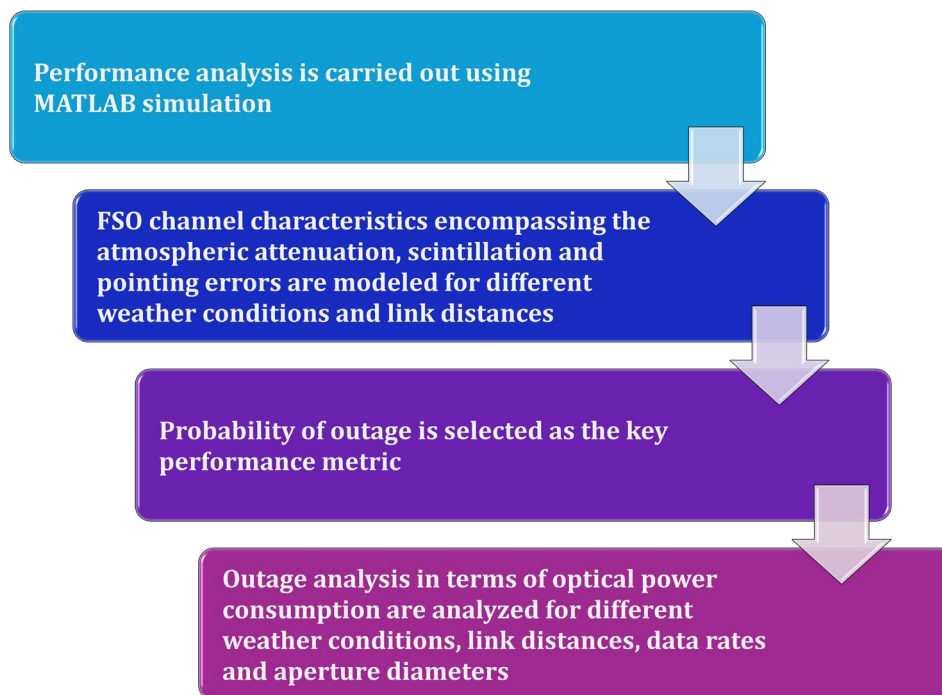


Fig. 1 Flow chart illustrating proposed methodology of FSO communication system

2.2 System Model

Fig. 2 illustrates the main building blocks encompassing a horizontal path FSO communication system operating in the single-input single-output (SISO) configuration, whereby the intensity modulation with direct detection (IM/DD) scheme and the non-return-to-zero on-off-keying (NRZ-OOK) technique are considered [19,20]. At the transmitter, electrical signals carrying information in the form of binary data are sent to a pulse shaping filter, which alters and optimizes the input waveforms. These modified waveshapes are modulated onto the instantaneous intensities of the optical laser beam, and propagates along the atmosphere in the presence of different channel effects, which include: (1) beam extinction caused by absorption and scattering of atmospheric particulates, (2) turbulence-induced optical scintillation, and (3) geometric spread and pointing errors. At the receiver, the optical signals are collected and focused onto a photodetector via a circular Gaussian lens of diameter D , thereby enabling the optical-to-electrical conversion. By utilizing a transimpedance amplifier, the resultant photocurrents are converted into output voltages, which are then applied to a matched filter detection module to recover the binary inputs.

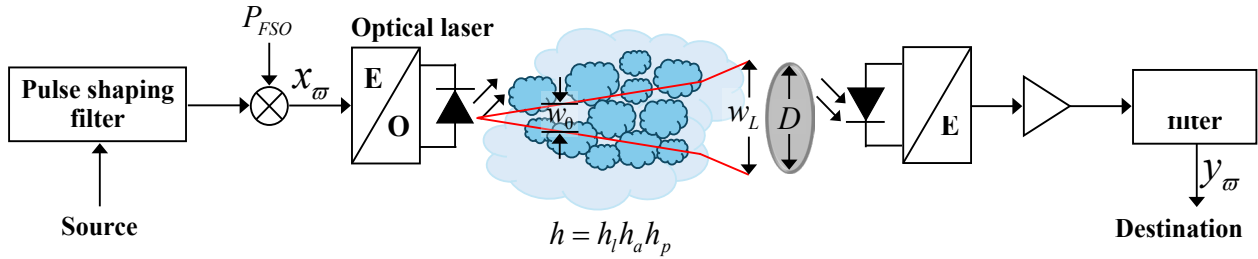


Fig. 2 Main building blocks encompassing a point-to-point FSO communication system

By adopting the conventional channel model, the received electrical signal can be defined as:

$$y_\omega = \gamma x_\omega + n_0 ; \tag{1}$$

where γ is the photodetector responsivity (in unit of A/W), and $x_\omega \in \{0, 2P_{FSO}\}$ is the transmitted optical signal with P_{FSO} resembling the average transmitted optical power. The additive white Gaussian noise (AWGN) n_0 has a mean of zero and standard deviation of σ_0 . The channel state h models the randomly fluctuating optical intensities of the laser beam, which can be described by the relation:

$$h = h_l h_a h_p ; \tag{2}$$

where h_l , h_a , and h_p refers to the propagation path loss, scintillation effect, and pointing error loss, respectively.

Assuming OOK-modulated optical signals are transmitted across a non-ergodic slow-fading wireless communication channel, the corresponding electrical signal-to-noise ratio (SNR) at the receiver is given by:

$$SNR(h) = \frac{2P_{FSO}^2 \gamma^2 h^2}{\sigma_0^2} . \tag{3}$$

2.3 Channel Model

2.3.1 Atmospheric Loss

The Beers Lambert law models the atmospheric loss resulting from the absorption and scattering effects, and is given by:

$$h_l = e^{-\sigma L} ; \tag{4}$$

where L is the propagation distance, and σ refers to the attenuation coefficient.

The coefficient σ varies according to the laser wavelength and weather-dependent parameters, and hence the Kim's model is adopted to determine the corresponding values under different weather conditions as follows:

$$\sigma = \begin{cases} \frac{3.91}{V} \left(\frac{\lambda}{550} \right)^{-q} & \text{for clear weather and haze, and} \\ \frac{2.9}{V} & \text{for rain;} \end{cases} . \tag{5}$$

where V is the link visibility (in km), λ is the optical laser wavelength (in nm), and q is a parameter associated with the particle size and visibility.

2.3.2 Optical Scintillation

When the optical beam propagates through the atmospheric channel, turbulence-induced scintillation effect causes significant power losses and signal fading below a detectable threshold at the receiver, which severely degrades the performance of FSO communication systems. Numerous statistical models have been examined and proposed, in order to predict the stochastic nature of the optical intensity fluctuations and deduce the reliability of the system under most possible atmospheric conditions. For our analysis which considers the weak-to-moderate turbulence conditions, the log-normal distribution is well suited to model the randomly fading characteristics of optical irradiance signals. The probability density function (PDF) of the irradiance intensity in the turbulent medium [9,20,21] is:

$$f_{h_a}(h_a) = \frac{1}{\sqrt{2\pi\sigma_l^2(D)}h_a} \exp \left\{ -\frac{\left[\ln(h_a) + \frac{1}{2}\sigma_l^2(D) \right]^2}{2\sigma_l^2(D)} \right\} ; \tag{6}$$

where the aperture-averaged scintillation index $\sigma_I^2(D)$ can be determined by taking:

$$\sigma_I^2(D) = A_G \times \sigma_I^2(0) ; \quad (7)$$

in which A_G is the aperture-averaging factor. Considering a Gaussian-beam wave model and an optical receiver with aperture dimension D , the point-received scintillation index (i.e., $D \sim 0$) is approximated by the relation [21]:

$$\begin{aligned} \sigma_I^2(0) \cong & 4.42\sigma_R^2\Lambda_L^{5/6} \frac{\rho^2}{w_L^2} + 3.86\sigma_R^2\{0.4[(1+2\Theta_L)^2 + 4\Lambda_L^2]^{5/12} \\ & \times \cos\left[\frac{5}{6}\tan^{-1}\left(\frac{1+2\Theta_L}{2\Lambda_L}\right)\right] - \frac{11}{16}\Lambda_L^{5/6}\} . \end{aligned} \quad (8)$$

Upon propagating through a link distance L , the Rytov variance for a plane wave is given by:

$$\sigma_R^2 = 1.23C_n^2(2\pi/\lambda)^{7/6}L^{11/6} ; \quad (9)$$

where C_n^2 (in $m^{-2/3}$) refers to the refractive index structure parameter signifying the atmospheric turbulence strength, and is assumed constant for a horizontal path FSO system. Correspondingly, the received optical beam width becomes:

$$w_L = w_0\sqrt{\Theta_n + \xi\Lambda_n^2} ; \quad (10)$$

where w_0 is the beam width at the optical transmitter, and the optical beam parameters are defined as follows:

$$\text{Normalized: } \Theta_n = 1 - \frac{L}{F_0} \text{ and } \Lambda_n = \frac{\lambda L}{\pi w_0^2} ; \quad (11a)$$

$$\text{Received: } \Theta_L = 1 + \frac{L}{F_L} \text{ and } \Lambda_L = \frac{\lambda L}{\pi w_L^2} ; \quad (11b)$$

with F_0 denoting the transmitter phase front radius of curvature. The phase front radius of curvature at the optical receiver is given by:

$$F_L = \frac{L(\Theta_n^2 + \xi\Lambda_n^2)}{\phi\Lambda_n - \xi\Lambda_n^2 - \Theta_n^2} , \quad \text{with } \phi \equiv \frac{\Theta_n}{\Lambda_n} - \frac{\Lambda_n w_0^2}{\rho_0^2} ; \quad (12)$$

and the global coherence parameter is:

$$\xi = \xi_s + \frac{2w_0^2}{\rho_0^2} ; \quad (13)$$

where ξ_s is the beam coherence parameter of the laser source, and the coherence length of a spherical wave is:

$$\rho_0 = \left[0.55C_n^2\left(\frac{2\pi}{\lambda}\right)^2 L\right]^{-3/5} . \quad (14)$$

The aperture-averaging factor is given by:

$$A_G = \frac{\sigma_I^2(D)}{\sigma_I^2(0)} = \frac{16}{\pi} \int_0^1 x dx \exp\left[-\frac{D^2 x^2}{\rho_0^2} \left(2 + \frac{\rho_0^2}{w_0^2 \Lambda_n^2} - \frac{\rho_0^2 \phi^2}{w_L^2}\right)\right] \left[\cos^{-1}(x) - x\sqrt{1-x^2}\right] ; \quad (15)$$

where $x = \rho/D$, and ρ represents the separation distance between two points.

2.3.3 Geometric Loss and Pointing Errors

A statistical misalignment-induced fading model is considered here, to describe the stochastic characteristics of pointing errors. Assuming the horizontal and vertical displacements from the reference axis are independent and identically Gaussian distributed with variance σ_{pe}^2 , the PDF of pointing error loss is given by:

$$f_{h_p}(h_p) = \frac{\chi^2}{A_0^{\chi^2}} h_p^{\chi^2-1} , \quad \text{with } 0 \leq h_p \leq A_0 ; \quad (16)$$

where the ratio between the equivalent beam radius at the receiver and the pointing error displacement (jitter) standard deviation is:

$$\chi = \frac{w_{zeq}}{2\sigma_{pe}} , \quad \text{with } w_{zeq} = w_L \sqrt{\frac{\sqrt{\pi}\text{erf}(v_p)}{2v\exp(-v_p^2)}} ; \quad (17)$$

and the fraction of collected power is:

$$A_0 = [\text{erf}(v_p)]^2 , \quad \text{with } v = \frac{\sqrt{\pi}D}{2\sqrt{2}w_L} . \quad (18)$$

3. Outage Analysis

For OOK-modulated binary input signals, the instantaneous capacity associated with channel state h is given by:

$$C(SNR(h)) = \sum_{x=0}^1 P_X(x) \int_{-\infty}^{+\infty} f(y|x, h) \log_2 \left[\frac{f(y|x, h)}{\sum_{m=0,1} f(y|x=m, h)P_X(m)} \right] dy ; \quad (19)$$

where $P_X(x)$ denotes the likelihood that the bit is either zero ($x = 0$) or one ($x=1$), with $P_X(x = 0) = P_X(x = 1) = 0.5$, and $f(y|x, h)$ is given by [13]:

$$f(y|x, h) = \begin{cases} \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp \left[-\frac{y^2}{2\sigma_0^2} \right] , & x = 0 \\ \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp \left[-\frac{(y - 2P_{FSO}\gamma h)^2}{2\sigma_0^2} \right] , & x = 1 . \end{cases} \quad (20)$$

When the instantaneous SNR drops below a given threshold, the time-varying channel capacity will not be adequate to provide a maximum data rate, mainly because the optical slow-fading channel is random and stays constant over a lengthy block of data bits. These deep fades circumstances, which may persist up to 100 milliseconds, could result in the losses of up to 10^9 consecutive bits at a data rate of 10 Gbps, thereby resulting in complete system annihilation. The probability of outage which represents the likelihood that the instantaneous channel capacity C falls below a transmission rate R_0 , is a suitable performance metric for the capacity, as given by the relation [15]:

$$P_{out} = \text{Prob}(C(SNR(h)) < R_0) . \quad (21)$$

Considering $C(\cdot)$ is monotonically increasing with the SNR, P_{out} can be equivalently determined by taking the cumulative density function of h evaluated at h_0 [15]:

$$P_{out} = \int_0^{h_0} f_h(h)dh , \quad \text{where } h_0 = \sqrt{\frac{C^{-1}(R_0)\sigma_0^2}{2\gamma^2 P_{FSO}^2}} . \quad (22)$$

4. Numerical Results and Discussion

In this section, FSO system is considered subject to turbulence and various visibilities under clear weather, haze moderate and heavy rain. Table 1 contains the typical values for the channel parameters and the system setup. In this study, different link distances are considered including 2.0 km for short, 3.5 km for moderate, 5.0 km for long, and 8.0 km for extensive link distances. Before observing and optimizing probability of outage relationship with transmitted optical power, bit rates variations are analyzed by focusing a range of consumed power under clear weather and haze.

In Fig. 3(a), a series of transmit optical power values of $P_{FSO} = \{0, 10, 20, 30, 35\}$ dBm are chosen to observe the probability of outage P_{out} for achievable bit rates R_0 ranging from 0 to 1 bits/channel use, where a propagation link distance of $L = 5.0$ km and receiver aperture diameter of $D = 40$ mm under the clear weather condition are considered here. It is evident that, between 0 to 35 dBm, as the power level is reduced the system is susceptible to system outage. On the contrary, power transmission stepwise rises when the channel performs from 0 to 10 dBm, 10 to 20 dBm, 20 to 30 dBm and 30 to 35 dBm. This implies that, in this case 35 dBm is an important link design parameter for maximizing the transmission rate with low outage probability. Next, Fig. 3(b) presents probability of outage against the achievable bit rate under the clear weather at $L = 8.0$ km, $D = 40$ mm

and for $P_{FSO} = \{0, 10, 20, 30, 35\}$ dBm. It is observed that, $P_{FSO} = \{0, 10, 20\}$ dBm starts transmitting bit rate from 0 to 1 bits/channel use. On the other hand, 30 dBm begins to transmit from 0.1 dBm and 35 dBm from 0.65 bits/channel use with lower probability of outage. Similarly, power transmission 20 dBm, 10 dBm and 0 dBm close to facing system outages.

Table 1 Parameters of the FSO system and atmospheric channel

System Parameters		
Description	Symbol	Value
Laser wavelength	λ	1550 nm
Photodetector responsivity	γ	0.5 A/W
Noise variance	σ_0^2	10^{-14} A ²
Beam radius at 1 km	w_L	$\cong 2.5$ m
Receiver aperture diameter	D	{20, 40, 80, 100} mm
Link distance	L	{2.0, 3.5, 5.0, 8.0} km
Achievable bit rate	R_0	{0.2, 0.5, 0.8, 1.0} bpcu
Separation distance of two points	ρ	5 mm
Standard variance jitter	σ_{pe}^2	$\cong 30$ cm
Weather-Dependent Parameters		
Weather Condition	V (km)	C_n^2 (m ^{-2/3})
Clear air	10.27	5.0×10^{-14}
Haze	3.50	1.7×10^{-14}
Moderate rain (12.5 mm/h)	2.80	5.0×10^{-15}
Heavy rain (25 mm/h)	1.90	4.0×10^{-15}

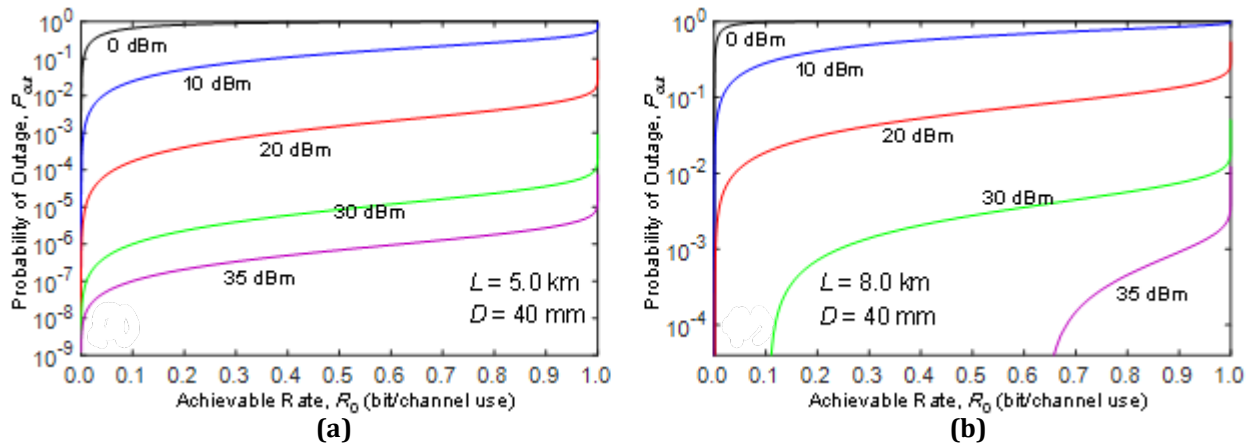


Fig. 3 Outage probability of the FSO system at varying achievable bit rate R_0 , for $D = 40$ mm and $P_{FSO} = \{0, 10, 20, 30, 35\}$ dBm, under the clear weather condition, at link distances of (a) $L = 5.0$ km, and (b) $L = 8.0$ km

The relationship between the probability of outage and achievable bit rates are illustrated in Fig. 4(a) from 0 to 1.0 bits/channel use for $P_{FSO} = \{0, 10, 15, 20, 22\}$ dBm, taking into account the haze weather condition at $L = 2.0$ km and $D = 40$ mm. From the numerical results, it is observed that the increase in power level from 0 to 22 dBm can minimize system outage with $P_{out} < 10^{-9}$. The system performance can be optimized with the selection of transmitted optical power in excess of 20 dBm. In addition, the tradeoff between the probability of outage and the maximum transmission rates for $P_{FSO} = 5$ dBm is examined in Fig. 4(b), for selected receiver diameters of $D = \{20, 40, 80\}$ mm at $L = 2.0$ km under the haze scenario. It is observed that a desirable power requirement of $P_{FSO} = 5$ dBm can achieve better outage mitigation by utilizing a relatively larger $D = 80$ mm, in comparison to

the case of $D = 20$ mm with $P_{out} \sim 1$ (i.e., complete system annihilation). The optimization of FSO channel capacity can be achieved in a good range through proper selection of the receiver aperture dimension D .

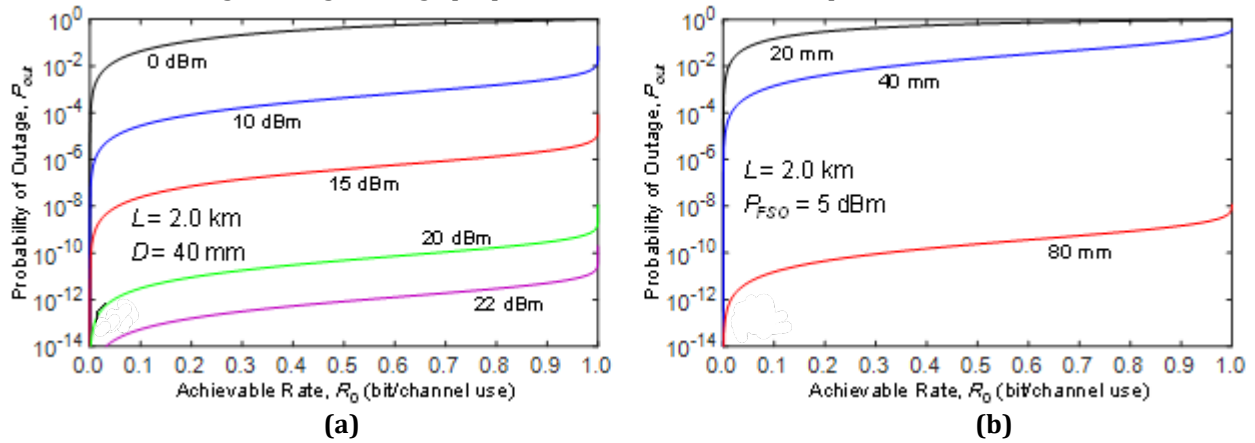


Fig. 4 Outage probability of the FSO system in terms of achievable bit rate R_0 , at $L = 2.0$ km under the haze condition. The transmit power requirements and aperture-averaging effects are shown here, using the simulation settings: (a) $D = 40$ mm and $P_{FSO} = \{0, 10, 15, 20, 22\}$ dBm; and (b) $P_{FSO} = 5$ dBm and $D = \{20, 40, 80\}$ mm

Parameters for Fig. 5: $L = 2.0, 3.5,$ and 5.0 km, $D = 40$ mm, visibility $V = 3.50$ km and turbulence strength $C_n^2 = 1.7 \times 10^{-14} \text{ m}^{-2/3}$. In addition, $R_0 = 0.2$ (Fig. 5(a)), 0.5 (Fig. 5(b)) and 1.0 (Fig. 5(c)) bits/channel. When the link distance (2.0 km, 3.5 km and 5.0 km) increases, the power requirement gets higher. In order to achieve $P_{out} = 10^{-9}$ for clear weather, optical power requires >20 dBm for 3.5 km link distance where the data rate 0.2 and 0.5 bits/channel, $P_{FSO} >25$ dBm for 1.0 bits/channel. Power needed >30 dBm for 5.0 km and 8.0 km link distances.

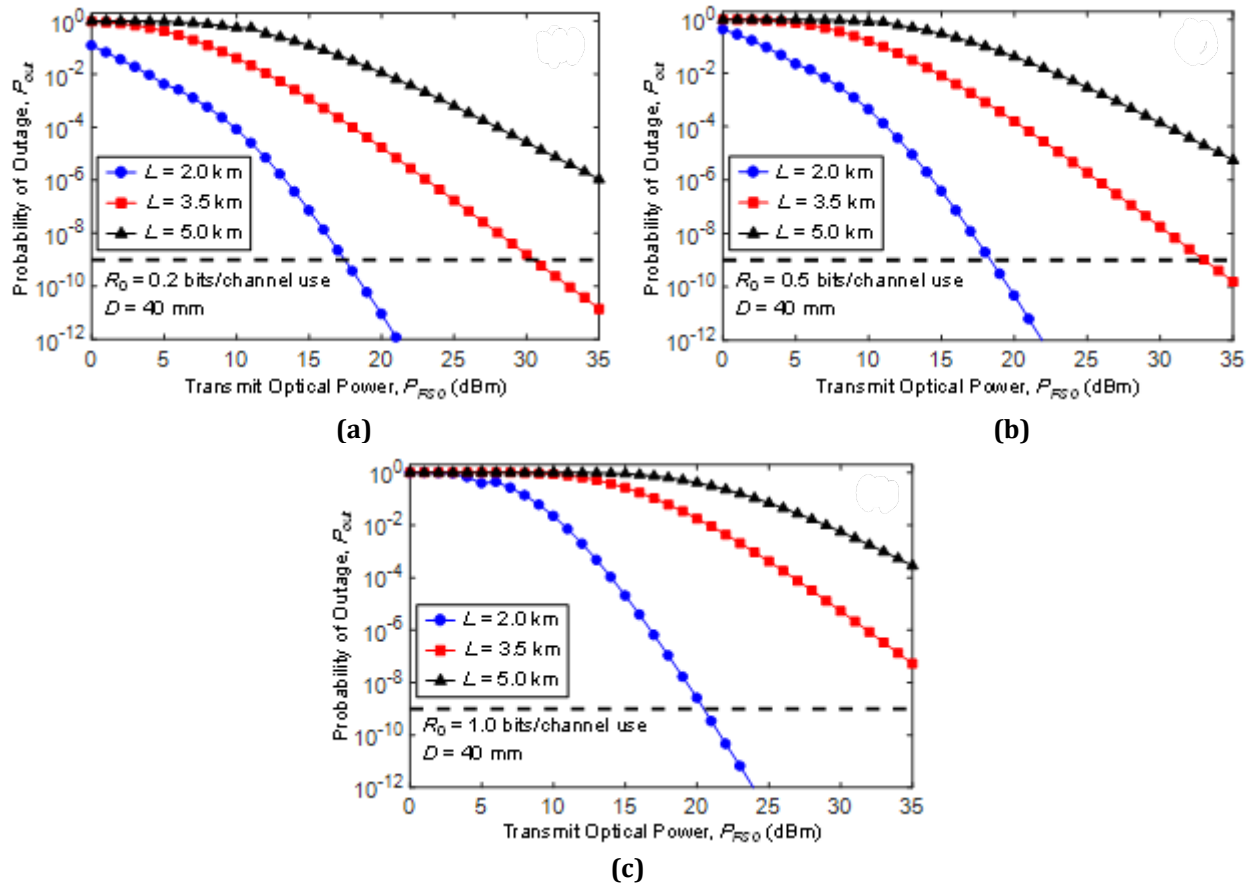


Fig. 5 Outage performance of the FSO system with varying transmit optical power, for $L = \{2.0, 3.5, 5.0\}$ km and $D = 40$ mm, under the haze scenario, at achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, (b) $R_0 = 0.5$ bits/channel use, and (c) $R_0 = 1.0$ bits/channel use

Probability of outage vs. transmitted optical power under moderate rain for Fig. 6. Parameters for figures (a), (b) and (c): $L = 2.0, 3.5,$ and 5.0 km, $D = 40$ mm, visibility $V = 2.80$ km and turbulence strength $C_n^2 = 5.0 \times 10^{-15}$ m^{-2/3}. In addition, $R_0 = 0.2$ (Fig. 6 (a)), 0.5 (Fig. 6(b)) and 1.0 (Fig. 6 (c)) bits/channel use. $P_{out} = 10^{-9}$ can be established for 2.0 km link distance where optical power is needed >15 dBm for $R_0 = 0.2$ and $R_0 = 0.5$ bits/channel use and more than 15 dBm for $R_0 = 1.0$. Moreover, for 3.5 km and 5.0 km link distances, optical power is consumed > 20 and 35 dBm with outage 1.

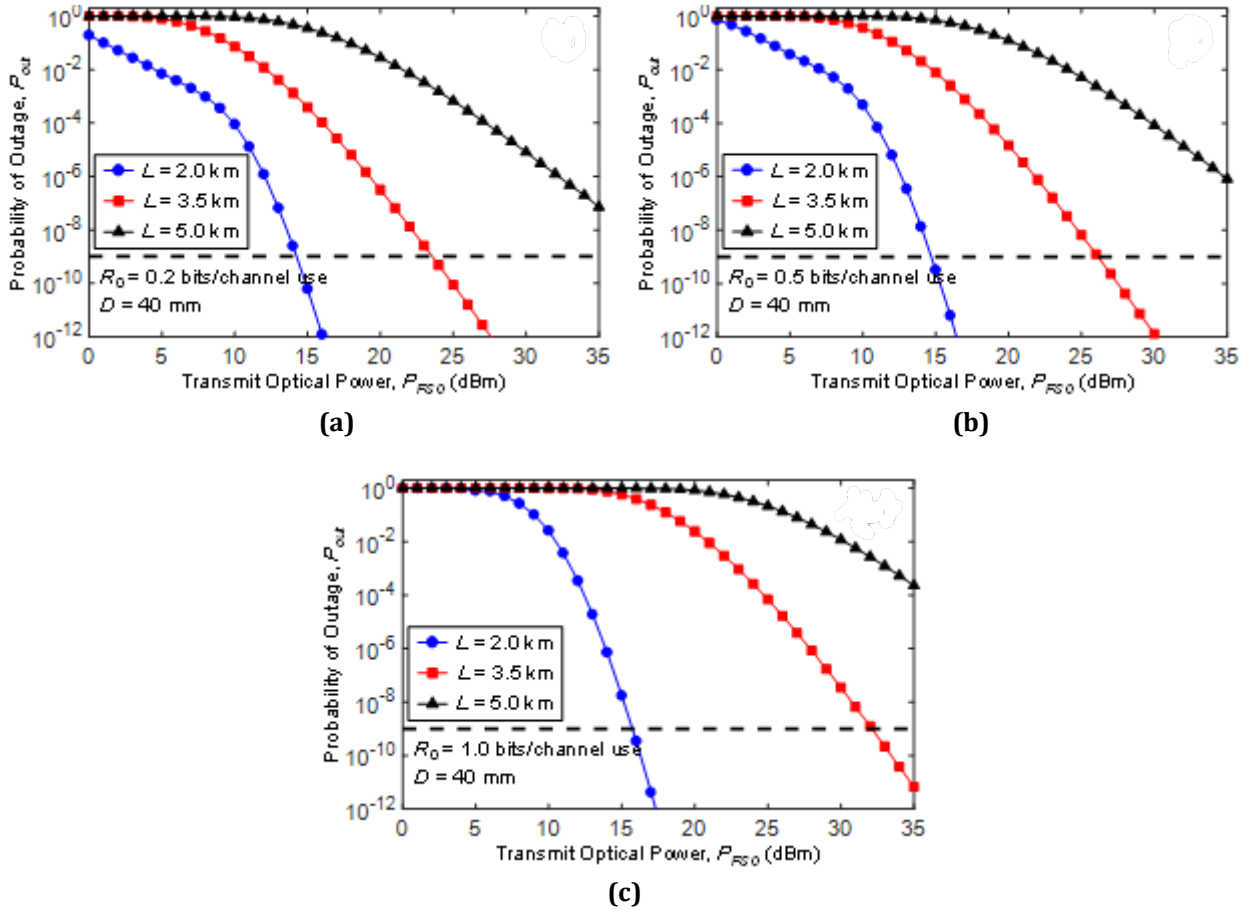


Fig. 6 Outage performance of the FSO system versus transmit optical power, for $L = \{2.0, 3.5, 5.0\}$ km and $D = 40$ mm, under the moderate rain condition, at achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, (b) $R_0 = 0.5$ bits/channel use, and (c) $R_0 = 1.0$ bits/channel use

Probability of outage vs. transmitted optical power under heavy rain for Fig. 7. Parameters for figures (a), (b) and (c): $L = 2.0, 3.5,$ and 5.0 km, $D = 40$ mm, visibility $V = 1.90$ km and turbulence strength $C_n^2 = 4.0 \times 10^{-15}$ m^{-2/3}. Additionally, $R_0 = 0.2$ (Fig. 7(a)), 0.5 (Fig. 7(b)) and 1.0 (Fig. 7(c)) bits/channel. At $L = 2.0$ km, $P_{FSO} = 17.5, 18, 19$ dBm for $0.2, 0.5$ and 1.0 bits/channel. For 3.5 km power requires more than 25 dBm for data rate $0.2, 0.5$ and 1.0 bits/channel and for 5 km system performance deteriorates for all data rates.

In Fig. 8, outage probability performances are observed for hazy weather in terms of transmit optical power for $L = 5.0$ km where turbulence strength $C_n^2 = 1.7 \times 10^{-14}$ m^{-2/3} and visibility $V = 3.50$ km. In Fig. 8(a), achievable rate $R_0 = 0.2$ bits/channel use and in Fig. 8(b) $R_0 = 0.8$ bits/channel are considered for $D = \{20, 40, 80, 100\}$ mm. It is evident that, for both data rates, a relatively larger aperture diameter of 100 mm can minimize power level less than 20 dBm whereas for $D = 20$ mm consumed power level exceeds more than 35 dBm considering reference value of outage 10^{-9} . However, by applying $D = 20$ mm, more than 20 dBm power level can be conserved than $D = 100$ mm. On the contrary, data rate 0.2 bits/channel use can reduce power consumption up to a certain range than 0.8 bits/channel use.

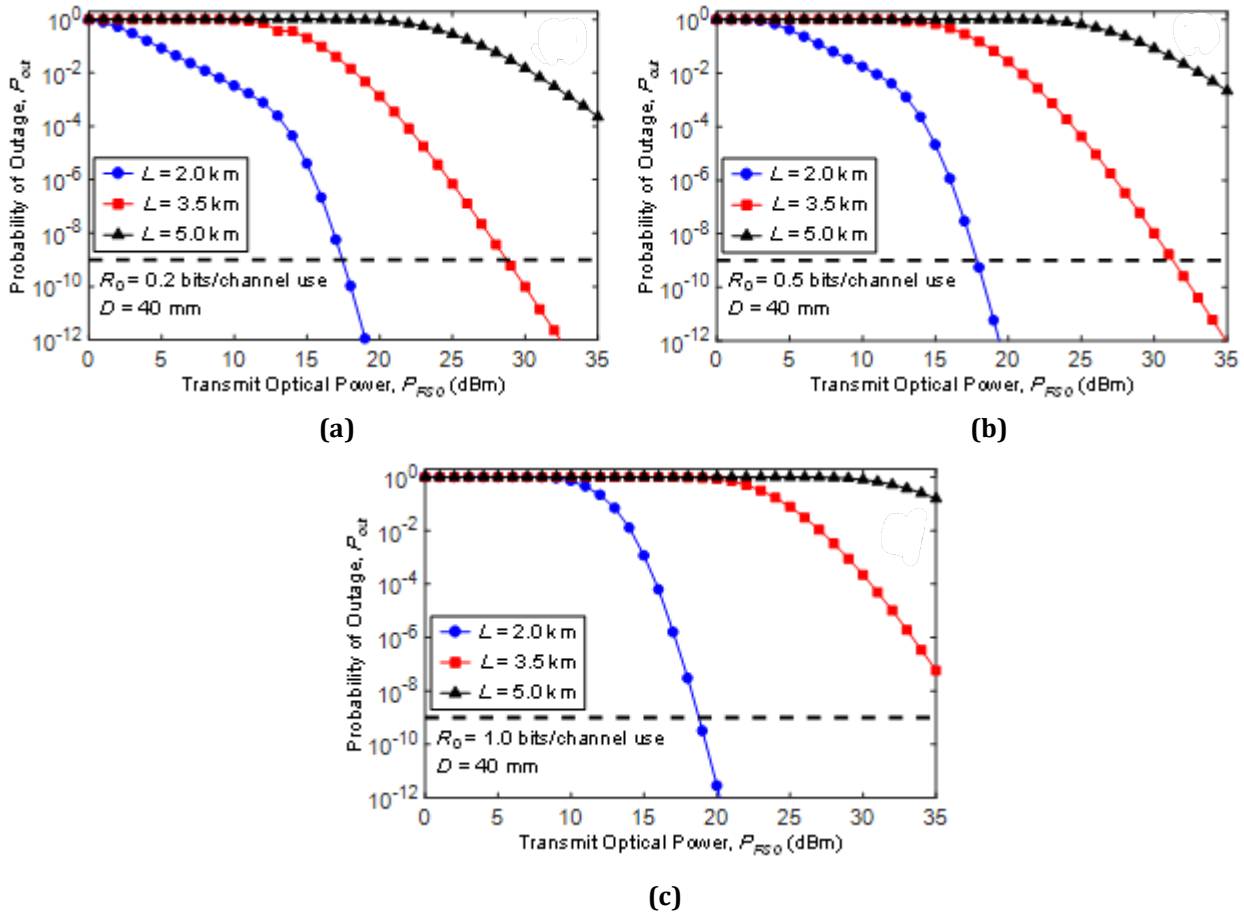


Fig. 7 Outage performance of the FSO system versus transmit optical power, for $L = \{2.0, 3.5, 5.0\}$ km and $D = 40$ mm, under the heavy rain condition, at achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, (b) $R_0 = 0.5$ bits/channel use, and (c) $R_0 = 1.0$ bits/channel use

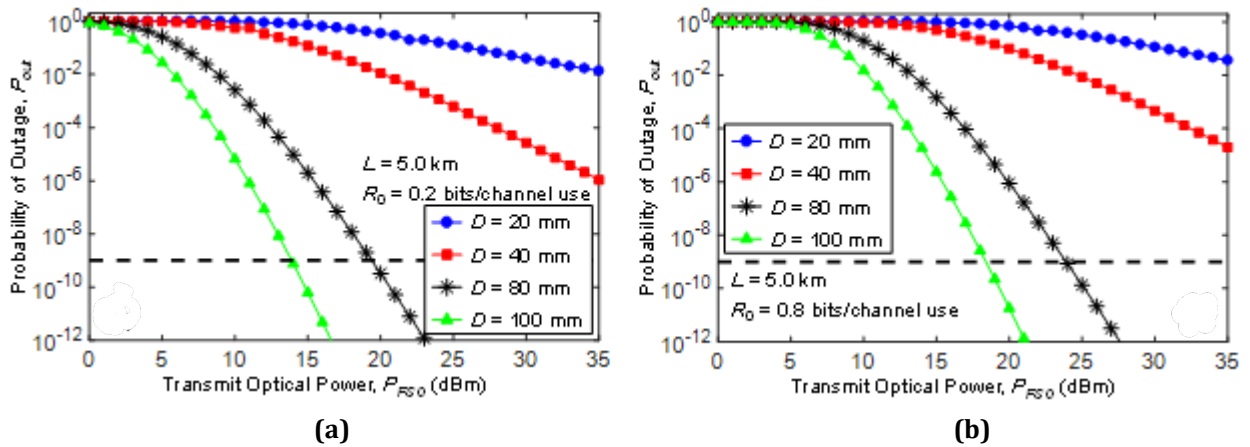


Fig. 8 Outage probability as a function of transmit optical power for the FSO system, under the aperture-averaging effect with receiver aperture dimensions $D = \{20, 40, 80, 100\}$ mm. The haze weather condition is observed at $L = 5.0$ km, with achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, and (b) $R_0 = 0.8$ bits/channel use

In Fig. 9, probability of outage versus optical power consumption is considered for both 0.2 bits/channel use and 0.8 bits/channel use, where aperture diameters $D = \{20, 40, 80, 100\}$ mm are considered for moderate rain at 5.0 km link distances. In both conditions, aperture diameter 100 mm performs better than 20 mm. For data rate 0.2 power consumption becomes almost 17.5 dBm for 100 mm and for bit rate 0.8 optical power requirement is almost 22 dBm at the same diameter.

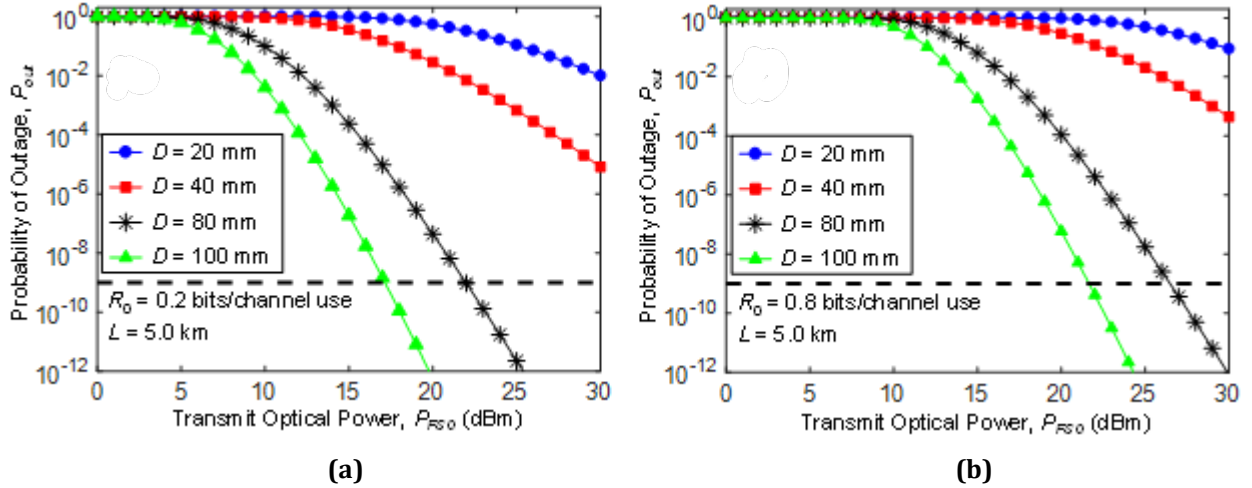


Fig. 9 Outage probability versus transmit optical power for the FSO system, with $D = \{20, 40, 80, 100\}$ mm. The moderate rain scenario at $L = 5.0$ km is considered, for achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, and (b) $R_0 = 0.8$ bits/channel use

Fig. 10 illustrates probability of outage and transmitted optical power performance for different aperture diameters of the bit rates 0.2 bits/channel use in Fig. 10(a) and 0.8 bits/channel use in Fig. 10(b), under heavy rain for 5 km link distance with $D = \{20, 40, 80, 100\}$ mm. It is noted that, in the low visibility condition of $C_n^2 = 4.0 \times 10^{-15} \text{ m}^{-2/3}$ and $V = 1.90$ km, more than 25 dBm excess power is required for $D = 20$ mm rather than $D = 100$ mm. In addition, data rate of 0.2 bits/channel use can be operated at $P_{FSO} = 26$ dBm for $D = 100$ mm which is minimum power consumption while maximum power level reached for $D = 20$ at 0.8 bits/channel use.

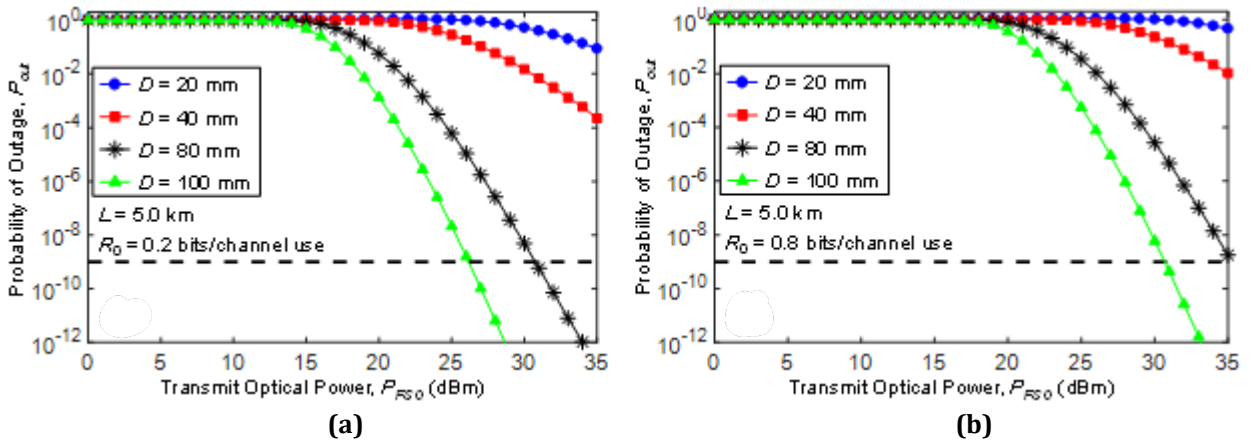


Fig. 10 Outage performance of the FSO system in terms of transmit optical power, with $D = \{20, 40, 80, 100\}$ mm. The heavy rain condition at $L = 5.0$ km is considered, for achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, and (b) $R_0 = 0.8$ bits/channel use

For a clear weather scenario, the tradeoff between probability of outage and optical power consumption is considered for different aperture diameters $D = \{20, 40, 80, 100\}$ mm at 5 km (Fig. 11(a) and Fig. 11(b)). Considering the data rate of 0.2 bits/channel use and 0.8 bits/channel use, respectively, in both cases, power consumption becomes less for a diameter of 100 mm and becomes maximal for a diameter of 20 mm. For data rate 0.2 bits/channel use, power consumption is 6.5 dBm at 100 mm diameter where outage nearly 10^{-2} , and for 0.8 bits/channel, 11 dBm at the same diameter for outage of 1.

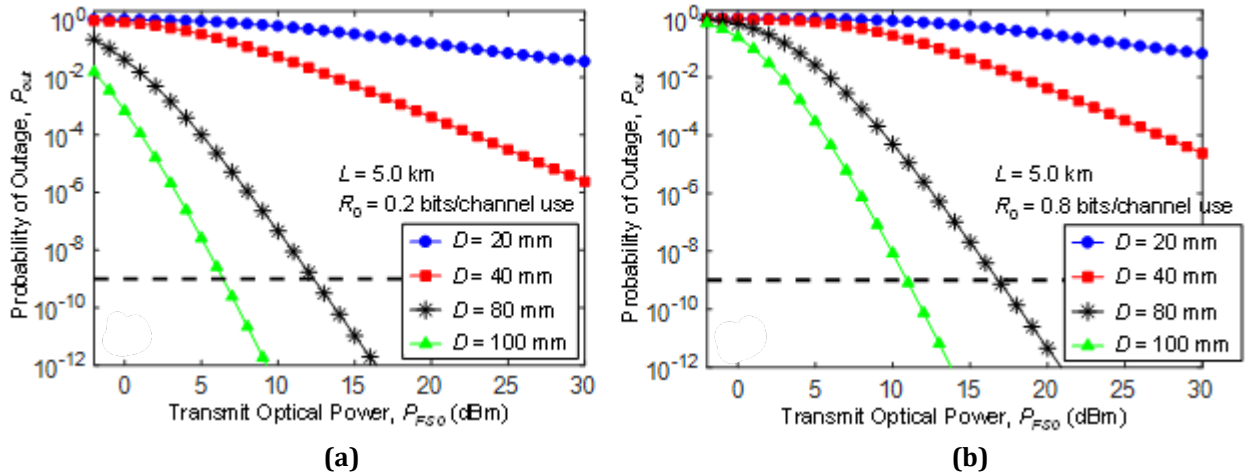


Fig. 11 Outage probability versus transmit optical power for the FSO system, under the aperture-averaging effect with $D = \{20, 40, 80, 100\}$ mm. The clear weather scenario at $L = 5.0$ km is considered, for achievable bit rates of (a) $R_0 = 0.2$ bits/channel use, and (b) $R_0 = 0.8$ bits/channel use

5. Conclusions

In summary, we have made an analytical investigation of the probability of an outage, a number of bit rates, and transmitted optical power in clear air, as well as turbulence-induced low-visible (haze, moderate rain and heavy rain) free space optical channels. Initially, outage analysis is performed in the range of 0 to 1 bit/channel, where few power selection run for the system under clear weather and haze. This implies that, the system will experience an outage when the power level drops with smaller aperture diameters. Furthermore, It is evident that the probability of outage 10^{-2} achieves the lowest power transmission under clear weather which is nearly 6 dBm at $L = 5$ km for $D = 100$ mm and $R_0 = 0.2$ bits per channel. In contrast, with outage 1, the least amount of power is consumed in hazy weather conditions at $L = 5$ km, $R_0 = 0.2$ bits per channel, and $D = 100$ mm as compared to moderate and heavy rain resulting in optimized power with desired outage.

Acknowledgement

This research work is supported by the Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FRGS/1/2020/TK0/MMU/03/8) and Multimedia University, Malaysia.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** It Ee Lee, Zabih Ghassemloo; **data collection:** It Ee Lee, Rahat Ara; **analysis and interpretation of results:** It Ee Lee, Gwo Chin Chung; **draft manuscript preparation:** Rahat Ara, It Ee Lee, Muhammad Sheraz, Teong Chee Chuah. All authors reviewed the results and approved the final version of the manuscript.

References

- [1] S. hil, S. Agarwal, Y. Singhal, and P. Bhardwaj, "An Overview of Free Space Optical Communication," *Int. J. Eng. Trends Technol.*, vol. 55, no. 3, pp. 120–125, 2018.
- [2] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surv. Tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014, doi:10.1109/COMST.2014.2329501.
- [3] A. Malik and P. Singh, "Free Space Optics: Current Applications and Future Challenges," *Int. J. Opt.*, vol. 2015, no. c, pp. 1–7, 2015, doi:10.1155/2015/945483.
- [4] B. Jaksic, J. Todorovic, N. Arsic, A. Petrovic, and V. Maksimovic, "Performance of the FSO System Modeled with Gamma-Chi-square Distribution and DPSK and BPSK Modulation Scheme," *2024 13th Mediterr. Conf. Embed. Comput. MECO 2024*, no. June, pp. 11–14, 2024, doi:10.1109/MECO62516.2024.10577944.

- [5] K. Mtshiza, N. Pillay, and E. O. Olurotimi, "Free Space Optical Communication Link Performance Based on Various Transmission Schemes Over Gamma-Gamma Distribution Channel," *Int. Conf. Electr. Comput. Energy Technol. ICECET 2023*, no. November, pp. 1–6, 2023, doi:10.1109/ICECET58911.2023.10389300.
- [6] T. Xu, S. Song, Y. Yang, S. Xiao, Y. Liu, and L. Guo, "Intelligent Relay Selection with Predicted Link States for Relay-Assisted Free Space Optical Network," *2021 IEEE 9th Int. Conf. Information, Commun. Networks, ICICN 2021*, pp. 225–229, 2021, doi:10.1109/ICICN52636.2021.9673855.
- [7] D. H. Kwon and S. K. Han, "CSI Extraction using Double Cross-Gain Modulation of Optical Amplifiers for Pre-compensated Free Space Optical," *2023 IEEE Int. Conf. Sp. Opt. Syst. Appl. ICSOS 2023*, pp. 198–200, 2023, doi:10.1109/ICSOS59710.2023.10491214.
- [8] Y. Huang *et al.*, "Free-space optics communications employing elliptical-Aperture multimode diversity reception under anisotropic turbulence," *J. Light. Technol.*, vol. 40, no. 5, pp. 1502–1508, 2022, doi:10.1109/JLT.2021.3130250.
- [9] H. Khanna, M. Aggarwal, and S. Ahuja, "Outage analysis of a variable-gain amplify and forward relayed mixed RF-FSO system," *2016 IEEE Annu. India Conf. INDICON 2016*, pp. 1–6, 2017, doi:10.1109/INDICON.2016.7839140.
- [10] R. Rani *et al.*, "Outage probability analysis of RF/FSO System Over Nakagami-m Fading and Fisher-Snedecor Distribution with Pointing Error," *2022 Int. Conf. Adv. Comput. Commun. Mater. ICACCM 2022*, pp. 1–5, 2022, doi:10.1109/ICACCM56405.2022.10009180.
- [11] M. I. Petkovic and Z. Trpovski, "Exact outage probability analysis of the mixed RF/FSO system with variable-gain relays," *IEEE Photonics J.*, vol. 10, no. 6, pp. 1–14, 2018, doi:10.1109/JPHOT.2018.2882611.
- [12] M. Petkovic, J. Anastasov, G. T. Djordjevic, and P. Ivanis, "Impact of correlation on outage performance of FSO system with switch-and-stay diversity receiver," *IEEE Int. Conf. Commun.*, vol. 2015-September, pp. 2756–2761, 2015, doi:10.1109/ICC.2015.7248743.
- [13] M. Siddharth, S. Shah, and R. Swaminathan, "Outage analysis of adaptive combining scheme for hybrid FSO/RF communication," *26th Natl. Conf. Commun. NCC 2020*, pp. 1–6, 2020, doi:10.1109/NCC48643.2020.9056009.
- [14] E. Zedini, H. Soury, and M. S. Alouini, "Outage probability of dual-hop FSO fixed gain relay transmission systems," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, pp. 1–6, 2016, doi:10.1109/PIMRC.2016.7794654.
- [15] M. Feng, J. B. Wang, M. Sheng, L. L. Cao, X. X. Xie, and M. Chen, "Outage performance for parallel relay-assisted free-space optical communications in strong turbulence with pointing errors," *2011 Int. Conf. Wirel. Commun. Signal Process. WCSP 2011*, pp. 1–5, 2011, doi:10.1109/WCSP.2011.6096717.
- [16] N. Zdravkovic, M. I. Petkovic, G. T. Djordjevic, and K. Kansanen, "Outage analysis of mixed FSO/WiMAX link," *IEEE Photonics J.*, vol. 8, no. 1, 2016, doi:10.1109/JPHOT.2016.2516250.
- [17] V. K. Jagadeesh, V. Palliyembil, P. Muthuchidambaranathan, and F. M. Bui, "Channel capacity and outage probability analysis of sub carrier intensity modulated BPSK system over M-distribution free space optical channel," *2nd Int. Conf. Electron. Commun. Syst. ICECS 2015*, no. Icecs, pp. 1051–1054, 2015, doi:10.1109/ECS.2015.7124740.
- [18] S. Mali and J. Ratnam, "Outage Probability of DCO-OFDM based Free-Space Optical Links over the Log-normal fading channel," *2nd Odisha Int. Conf. Electr. Power Eng. Commun. Comput. Technol. ODICON 2022*, pp. 1–6, 2022, doi:10.1109/ODICON54453.2022.10010026.
- [19] H. Kashif and M. N. Khan, "Outage Probability Analysis of Free Space Communication System Using Diversity Combining Techniques," *Comput. Mater. Contin.*, vol. 73, no. 3, pp. 6001–6017, 2022, doi:10.32604/cmc.2022.031291.
- [20] M. A. Esmail, H. Fathallah, and M. S. Alouini, "Outage Probability Analysis of FSO Links over Foggy Channel," *IEEE Photonics J.*, vol. 9, no. 2, 2017, doi:10.1109/JPHOT.2017.2672641.
- [21] R. Ara, I. E. Lee, Z. Ghassemlooy, G. C. Chung, and W. L. Pang, "Error Performance of Relay-Assisted Free-Space Optical Communication," in *Proc. 8th International Congress on Information and Communication Technology (ICICT 2023)*, London, Volume 3 (1st ed., Vol. 3, pp. 25-37). (Lecture Notes in Networks and Systems; Vol. 695). Springer.