

Error Performance of Relay-Assisted Free-Space Optical Communication Links Over Atmospheric Turbulence Channels



Rahat Ara, It Ee Lee, Zabih Ghassemlooy, Gwo Chin Chung,
and Wai Leong Pang

Abstract Free-space optical (FSO) communication has regained substantial research interests in the recent decade and is well reckoned as a viable alternative which is highly complementary/integrable with existing radio frequency (RF) solutions, such as the 5G wireless networks. Unpredictable weather conditions severely impair the link availability and performance of the FSO system. The presence of atmospheric loss and turbulence-induced optical scintillation within the communication channel causes attenuation and random fluctuation of the received optical signals, thereby limiting the link distance and impairing the error performance. Multi-hop relaying technique can be adopted in the FSO system for improving the channel gain and mitigating the turbulence-induced channel fading. In this paper, we examine the bit error rate (BER) performances of FSO systems operating in the single-input single-output (SISO) and multi-hop relay-based configurations. The BER analysis is carried out using MATLAB simulation, whereby weather-dependent parameters and turbulence strength values for different weather scenarios such as clear air, light fog, and haze are considered here. Next, the aperture-averaging phenomenon caused by the receiver aperture dimension is jointly investigated with the relay-assisted multi-hop relaying technique. From our study, it is evident that the SISO FSO configuration is vulnerable to system outage, which can be effectively mitigated with the introduction of relay terminals. Our findings conclude that the relay-assisted multi-hop FSO system with aperture averaging is a feasible approach toward reducing the BER performance with minimum power requirement.

Keywords Free-space optical (FSO) communication · Optical relaying · Atmospheric turbulence · Bit error rate (BER)

R. Ara · I. E. Lee (✉) · G. C. Chung · W. L. Pang
Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Malaysia
e-mail: ielee@mmu.edu.my

Z. Ghassemlooy
Department of Mathematics, Physics and Electrical Engineering, Northumbria University,
Newcastle Upon Tyne NE1 8ST, UK

1 Introduction

Atmospheric loss and turbulence effects are responsible for the inferior performance of free-space optical (FSO) communication systems at the time of sending data using optical lasers. In this overall procedure, initially the information as a form of electrical signal generated from the source is modulated and then converted to optical form by driver circuit [1]. Atmospheric channel through which the optical beam passes faces a lot of challenges as a form of atmospheric attenuation. In the receiver part, optical signal data are converted to electrical form through a photodetector [2] again which can be amplified or processed. Although having some limitations, today FSO is a time-demanding technology for some of its excellent features. However, in recent times, this less costly, cableless, low-powered with no licensing and tariff, extensive linked, and radio frequency interference immunizing technology with various interfaces support is encouraging service providers to make their investment [3]. Despite the major advantages of FSO, its widespread use for long-range links has been hampered in different weather conditions by its disappointing performance due to turbulence effects like scintillation, absorption, scattering, attenuation, etc.

Different turbulence reducing techniques have been examined in several literatures including channel modeling, modulation schemes, relaying and diversity techniques, hybrid systems, etc. To the best of our knowledge [4], for FSO communications, equipping the serial relays with buffers targeted an outage analysis by not addressing the limitations of determining the overall ergodic capacity of this optical system. In an article [5], a simulation was performed considering wavelength division multiplexing (WDM) serial relay aided FSO model for improving path loss and fading effects only for haze and rain. In a study [6], a grouping optimization technique has been proposed for FSO decode forward (DF) multi-hop systems, where laser links were blocked as the relay nodes were not properly optimized in their location path. In a paper [7], asymptotic outage probability was analyzed and lessened through the selection of a weighted relay considering an optimal weight factor.

The objective of this research work is to optimize the performance of relay-assisted FSO communication systems under different weather conditions. The analysis and performance testing method used here is simulation study, which is carried out using MATLAB by considering turbulence effects, atmospheric losses, and channel effect. In terms of quantifying performance, bit error rate (BER) is analyzed. On top of that, performance enhancement is justified by a relay-assisted FSO system. The overall performance of the proposed system has been analyzed in terms of the relay node optimization for BER vs. consumed optical power considering clear weather, haze, fog, and rainy conditions at a 12 km link distance, and the effects of changing aperture diameter were observed for clear weather and light fog conditions at 8 and 3 km link distances. In all cases, as the number of relays increases, consumed optical power gradually requires less with an average BER of 10^{-9} or less and yields impressive results when aperture diameters are changed with relays. It is pretty evident, among the observations, that the performance can be optimized for triple-hop FSO communication links under clear weather at 12 km link distance, for an

aperture dimension $D = 150$ mm, where consumed power is reduced to -20 dB and an overall enhancement 38 dB as compared to the SISO transmission link at $D = 20$ mm.

The rest of the paper of our relay-based study is arranged followed by Sect. 2, where a system model is introduced considering scintillation, atmospheric loss, pointing errors as well as FSO transmission schemes with the assistance of relay-based multi-hop channels. Parameters for simulation, particularly BER quantization, are derived in Sect. 3. In Sect. 4, the MATLAB simulation results for BER analysis under different weather conditions for SISO and relay-assisted transmission links are presented and discussed. Finally, our conclusions are given in Sect. 5.

2 System Description

2.1 System Model

Figure 1 illustrates the general layout for an FSO communication system operating in the single-input single-output (SISO) configuration and intensity modulation with direct detection (IM/DD) scheme. Assuming non-return-to-zero on-off keying (NRZ-OOK) modulation [8], the transmitted data (at the source) are modulated onto the instantaneous laser beam intensity and propagated along the atmospheric turbulent channel with beam extinction and geometric loss. The optical signals are focused onto a photodetector using a receiving lens, thereby producing photocurrents (at the destination) according to the received optical intensities.

At the destination, the received electrical signal y can be modeled by the relation [9–11]:

$$y = h\gamma x + n_0; \quad (1)$$

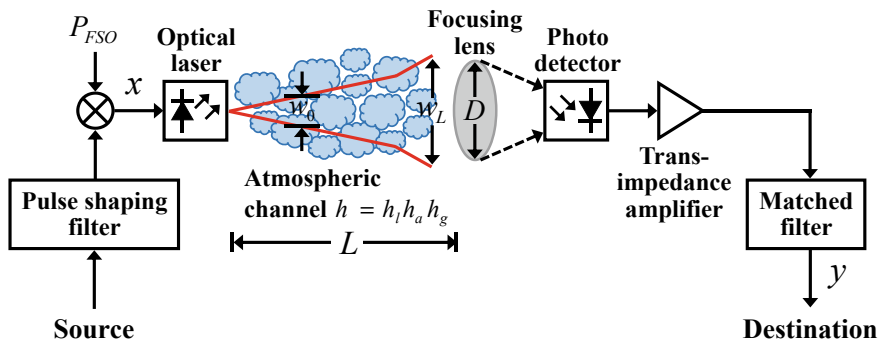


Fig. 1 Block diagram depicting the construction of an FSO communication system with single-input single-output configuration

where $x_o \in \{0, 2P_{\text{FSO}}\}$ denotes the transmitted optical signal, P_{FSO} is the average transmit optical power, h refers to the channel state, and γ is the photodetector responsivity. The n_0 resembles the additive white Gaussian noise (AWGN) having a mean of zero and variance of σ_0^2 .

The channel state h describes the random fluctuations of the optical intensities contributed by propagation path loss, geometric loss, and atmospheric turbulence and is given by [12]

$$h = h_l h_g h_a. \quad (2)$$

The term h_l corresponds to the attenuation factor due to beam extinction, which is caused by scattering and absorption of atmospheric particulates. On the other hand, h_g and h_a account for the beam spreading and optical scintillation effects, respectively.

Considering OOK-modulated signal propagating through a non-ergodic slow-fading channel, the electrical signal-to-noise ratio (SNR) at the receiver is [13, 14]

$$\Gamma = \frac{2P_{\text{FSO}}^2 \gamma^2 h^2}{\sigma_0^2}. \quad (3)$$

Figure 2 illustrates the configuration of a relay-assisted multi-hop FSO communication system, where the modulated light beam is transmitted from the optical transmitter (source) to the optical receiver (destination) via intermediate optical terminals known as relays. An amplify-and-forward relaying scheme is considered [15, 16]. With the placement of relay nodes R_i (where $i = 1, 2, \dots, (N - 1)$) separated by equal distance [19], the modulated signal propagates through N channels/hops before arriving at the destination. The end-to-end SNR of the channel-dependent N -hop FSO propagation link is given by

$$\Gamma_{\text{eq}} = \left[\prod_{i=1}^N \left(1 + \frac{1}{\Gamma_i} \right) - 1 \right]^{-1}; \quad (4)$$

where Γ_i denotes the SNR of the n th hop and is given by

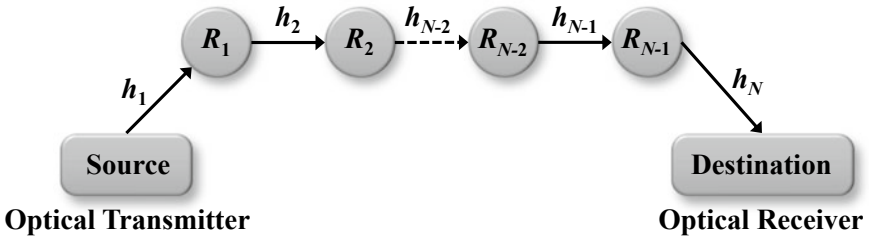


Fig. 2 Configuration of a relay-assisted N -hop FSO communication system

$$\Gamma_i = \frac{2P_{\text{FSO}}^2 \gamma^2 h_i^2}{\sigma_{0,i}^2}. \quad (5)$$

2.2 Channel Model

Atmospheric Loss. It is mainly contributed by scattering and absorption, which is well modeled by the Beers–Lambert law [9, 17] given by

$$h_l = e^{-\sigma L}; \quad (6)$$

where σ is an attenuation coefficient affected by the wavelength and weather parameters and L denotes the link distance.

Applying the visibility data for different weather scenarios, the attenuation coefficient σ can be predicted using the following relations [8]. For clear and foggy weather,

$$\sigma = \frac{3.91}{V} \left(\frac{\lambda}{550} \right)^{-q}; \quad (7)$$

and for rainfall conditions:

$$\sigma = \frac{2.9}{V}; \quad (8)$$

where λ is the laser wavelength, V resembles the link visibility, and q represents a parameter dependent on the visibility and particle size distribution.

Turbulence-Induced Optical Scintillation. The log-normal distribution is applied in our analysis to model the randomly fading optical irradiance signals caused by weak-to-moderate turbulences. The probability density function (pdf) of the irradiance intensity in the turbulence channel is given by

$$f_{h_a}(h_a) = \frac{1}{h_a \sigma_I(D) \sqrt{2\pi}} \exp \left\{ -\frac{[\ln(h_a) + \frac{1}{2}\sigma_I^2(D)]^2}{2\sigma_I^2(D)} \right\}. \quad (9)$$

For an optical receiver with an aperture dimension D , the scintillation index can be determined from the relation:

$$\sigma_I^2(D) = A_g \times \sigma_I^2(0); \quad (10)$$

where A_G denotes the aperture-averaging factor and $\sigma_I^2(0)$ is the point-received (with $D \sim 0$) scintillation index given by

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

The Rytov variance for a plane wave is

$$\sigma_R^2 = 1.23C_n^2(2\pi/\lambda)^{7/6}L^{11/6}; \quad (12)$$

where C_n^2 is a parameter relevant to the index of refraction structure, which quantifies the atmospheric turbulence strength. This indicator is taken as constant for a horizontal path FSO link. At the receiver, the optical beam parameters are defined as

$$\Theta_L = 1 + \frac{L}{F_L} \text{ and } \Lambda_L = \frac{\lambda L}{\pi w_L^2}; \quad (13)$$

The corresponding beam width at link distance L is

$$w_L = w_0\sqrt{\Theta_n + \zeta\Lambda_n^2}; \quad (14)$$

where w_0 is the transmitter beam width. The resultant phase front radius of curvature is given by

$$F_L = \frac{L(\Theta_n^2 + \zeta\Lambda_n^2)}{\varphi\Lambda_n - \zeta\Lambda_n^2 - \Theta_n^2}, \text{ with } \varphi \equiv \frac{\Theta_n}{\Lambda_n} - \frac{\Lambda_n w_0^2}{\rho_0^2}. \quad (15)$$

The normalized components are given by

$$\Theta_n = 1 - \frac{L}{F_0} \text{ and } \Lambda_n = \frac{\lambda L}{\pi w_0^2}; \quad (16)$$

where F_0 is the transmitter phase front radius of curvature. The global coherence parameter is

$$\zeta = \zeta_s + \frac{2w_0^2}{\rho_0^2}; \quad (17)$$

where ζ_s is the beam coherence and the coherence length of a spherical wave is given by

$$\rho_0 = \left[0.55C_n^2\left(\frac{2\pi}{\lambda}\right)^2 L\right]^{-3/5}. \quad (18)$$

The aperture-averaging factor is given by

$$A_G = \frac{\sigma_I^2(0)}{\sigma_I^2(0)} = \frac{16}{\pi} \int_0^1 x dx \exp \left\{ \frac{-D^2 x^2}{\rho_0^2} \left(2 + \frac{\rho_0^2}{w_0^2 \Lambda_n^2} - \frac{\rho_0^2 \varphi^2}{w_L^2} \right) \right\} \times \left[\cos^{-1}(x) - x \sqrt{1-x^2} \right]; \quad (19)$$

where D is the receiver aperture diameter and $x = \rho/D$ with ρ being the separation distance between two points.

Geometric Loss. It is a fixed loss for a given FSO link caused by the spreading of the laser beam when propagating in free space. This inherent beam divergence increases with link distance and is independent of weather conditions. Assuming the optical transmitter has an ideal Gaussian beam profile and is well aligned with the receiver, the geometric loss for a fixed point-to-point link can be approximated as [8]

$$h_g = \left[\operatorname{erf} \left(\frac{\sqrt{\pi} a}{\sqrt{2} w_L} \right) \right]^2; \quad (20)$$

where $w_L \approx \phi \times L$ is the beam width at a link distance L , ϕ is the beam divergence angle, and $a = D/2$.

3 Performance Analysis

Considering OOK modulation for the system under study, the BER can be expressed as [6, 18]

$$P_e = P_X(0)P_X(e|0) + P_X(1)P_X(e|1); \quad (21)$$

where $P_X(0)$ and $P_X(1)$ resemble the probabilities of transmitting “0” and “1” bits, respectively, and $P_X(e|0)$ and $P_X(e|1)$ are the corresponding conditional probabilities for bit “0” and “1”. The bit error probabilities conditioned to the channel state h are given by

$$P_X(e|0, h) = P_X(e|1, h) = Q(\sqrt{\Gamma}); \quad (22)$$

where $Q(\cdot)$ is the Gaussian-Q function defined by

$$Q(y) = \frac{1}{\sqrt{2\pi}} \int_y^\infty \exp\left(\frac{-t^2}{2}\right) dt. \quad (23)$$

Assuming symmetry with $P_X(0) = P_X(1) = 0.5$ and $P_X(e|0) = P_X(e|1)$, the average BER can be determined from the following relation:

$$P_e = \int_0^{\infty} f_h(h) Q(\sqrt{\Gamma}) dh. \quad (24)$$

4 Numerical Results and Discussion

In Fig. 3, we examine the average BER P_e as a function of the transmit optical power P_{FSO} for the conventional SISO single-hop FSO system (i.e., Relay (0)) and the relay-assisted multi-hop FSO link configurations (i.e., Relay (N)), where $N = \{1, 2, 3\}$ denotes the number of relay nodes. Different weather conditions including the clear, haze, and light fog are considered, for a link distance $L = 12$ km and receiver aperture diameter $D = 40$ mm. The system parameters and weather-related settings are summarized in Table 1. A maximum BER threshold of 10^{-9} (i.e., only one erroneous bit out of 10^9 received bits is tolerated) is required for establishing seamless wireless communication and hence is chosen as our reference BER. For telecommunications applications, the specified maximum BER ranges from 10^{-9} to 10^{-12} .

Under the clear weather scenario with a visibility $V = 10.27$ km and turbulence strength value $C_n^2 = 5 \times 10^{-14} \text{ m}^{-2/3}$ (in Fig. 3), the conventional SISO FSO system can achieve a desirable error performance of $P_e < 10^{-9}$ at $P_{\text{FSO}} =$

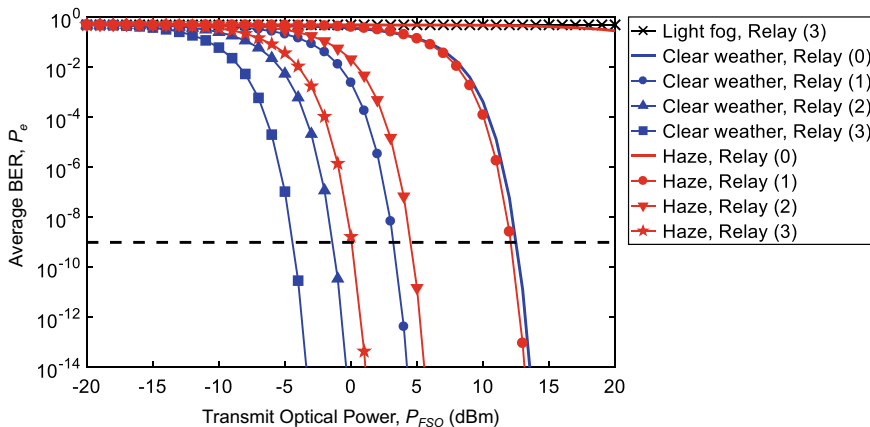


Fig. 3 Error performance comparison between the conventional SISO FSO system (Relay (0)) and the relay-assisted multi-hop FSO link configurations (Relay (N), where $N = \{1, 2, 3\}$), for $L = 12$ km and $D = 40$ mm, under the clear weather, haze, and light fog conditions

Table 1 FSO system parameters and simulation settings

<i>System parameters</i>		
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	$\cong 2.5 \text{ m}$
Link distance	L	{3.0, 8.0, 12.0} km
Receiver aperture diameter	D	{20, 40, 80 150} mm
Separation distance between two points	ρ	5 mm
<i>Weather-dependent parameters</i>		
Weather condition	V(km)	$C_n^2(\text{m}^{-2/3})$
Clear air	10.27	5.0×10^{-14}
Haze	3.50	1.7×10^{-14}
Light fog	0.77	3.0×10^{-15}
Moderate rain (12.5 mm/h)	2.80	5.0×10^{-15}
Heavy rain (25 mm/h)	1.90	4.0×10^{-15}

15 dBm. On the other hand, the single-hop FSO link undergoes complete system outage under the haze and light fog conditions with relatively lower link visibilities of 3.50 km and 0.77 km, respectively, as evident from the poor error performance with P_e approaching 1. This is mainly contributed by the atmospheric loss due to the presence of numerous gaseous molecules within the earth's atmosphere, which severely attenuates the optical intensity of the propagating laser beam.

For the relay-assisted FSO link configuration (see Fig. 3), it is observed that a significant reduction in P_{FSO} requirement in excess of 9 dB can be achieved by a dual-hop system (Relay (1)) while maintaining the average BER at 10^{-9} , under the clear weather condition. The P_{FSO} requirement can be improved by up to 16.5 dB for a quadruple-hop FSO system (Relay (3)), as compared to the conventional single-hop system. In addition, the average BER can be significantly improved using a dual-hop system under the haze condition, whereby $P_e < 10^{-9}$ can be achieved at $P_{\text{FSO}} = 12 \text{ dBm}$, as compared to the conventional SISO FSO system with $P_e \sim 1$. A further reduction in P_{FSO} requirement of 12 dB can be made possible using a quadruple-hop FSO system albeit the presence of haze. However, the multi-hop FSO configuration is unable to mitigate the system outage under the visibility-limiting light fog condition, particularly for long-distance FSO transmission with $L > 5 \text{ km}$.

Next, Fig. 4. presents the error performance of the conventional SISO FSO system and the relay-assisted multi-hop FSO link configurations, under the moderate and heavy rain conditions, with $L = 12 \text{ km}$ and $D = 40 \text{ mm}$. It is evident that the

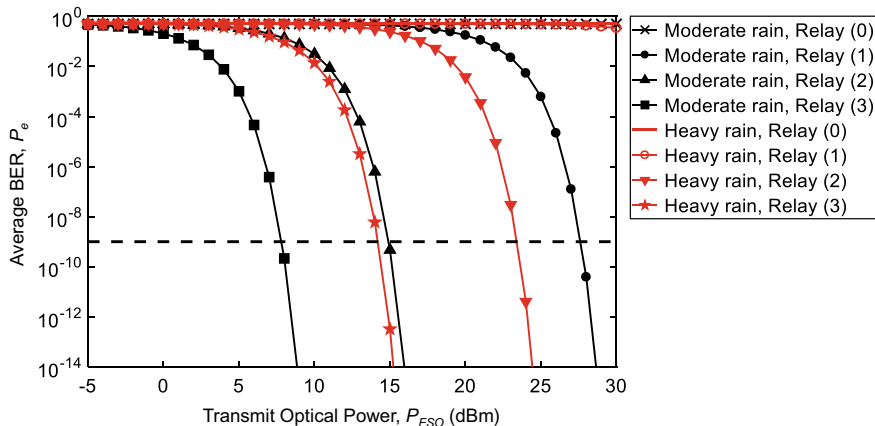


Fig. 4 Error performance comparison between the conventional SISO FSO system (Relay (0)) and the relay-assisted multi-hop FSO link configurations (Relay (N), where $N = \{1, 2, 3\}$), for $L = 12$ km and $D = 40$ mm, under the moderate and heavy rain conditions

conventional SISO FSO link undergoes complete system outage in the presence of moderate and heavy rain, which can be effectively mitigated with the multi-hop FSO implementation. By adopting a triple-hop FSO system through the placement of two relay nodes between the optical transmitter (source) and receiver (destination), a desirable error performance of $P_e < 10^{-9}$ can be achieved at $P_{\text{FSO}} = 25$ dBm during heavy rain, which is also attainable with a much lower P_{FSO} of 15 dBm under the moderate rain scenario. For a quadruple-hop FSO system, the P_{FSO} requirement can be further minimized by more than 7 dB while maintaining $P_e = 10^{-9}$, under both the moderate and heavy rain conditions.

Figure 5 illustrates the changes in the BER performance, P_e with respect to the transmit optical power, P_{FSO} for the conventional SISO FSO system and relay-assisted triple-hop FSO system, during clear weather at $L = 8$ km. In particular, we examine the aperture-averaging effects with increasing receiver aperture diameter settings of $D = \{20, 40, 80, 150\}$ mm, which potentially mitigates the undesirable turbulence-induced signal fading. With the adoption of receiver apertures with larger values of D , the error performance of the FSO link is significantly improved, in which a P_{FSO} reduction of more than 25 dB is observed at $P_e = 10^{-9}$ by using $D = 150$ mm, in comparison with $D = 20$ mm, for the conventional SISO FSO system. It is observed that the P_{FSO} requirement can be further reduced by 10 dB while maintaining $P_e = 10^{-9}$, for a triple-hop FSO system with $D = 150$ mm, thus resulting in an astounding overall P_{FSO} improvement of ~ 38 dB.

Figure 6 depicts the BER characteristics as a function of the transmit optical power requirements due to the changing aperture-averaging effects with $D = \{20, 40, 80, 150\}$ mm. Both cases of the conventional SISO FSO system and relay-assisted dual-hop FSO system are studied for the low-visibility light fog scenario at $L = 3$ km. Our results show that the conventional single-hop FSO link is highly susceptible to

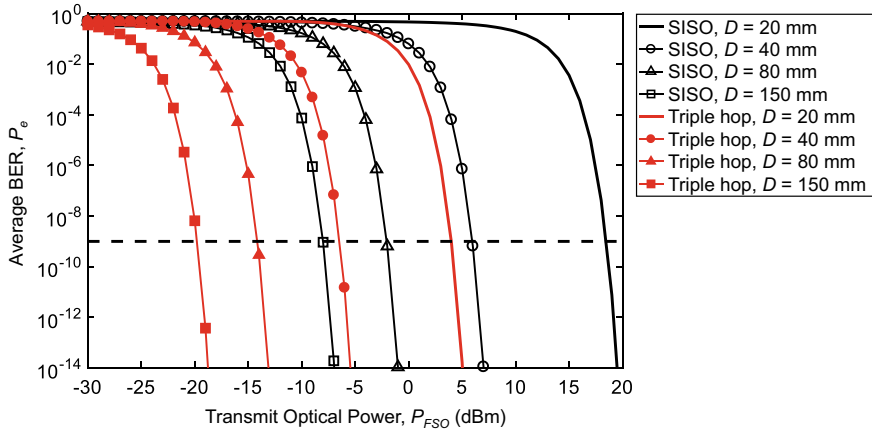


Fig. 5 Average BER versus the transmit optical power for the conventional SISO FSO system and relay-assisted triple-hop FSO system, under the aperture-averaging effect with $D = \{20, 40, 80, 150\}$ mm. The clear weather scenario at $L = 8$ km is considered

system outage, particularly for smaller aperture dimensions $D = \{20, 40\}$ mm. While larger receiver apertures $D = \{80, 150\}$ mm can establish wireless communication with $P_e < 10^{-9}$, the P_{FSO} requirements are impractically high (i.e., > 28 dBm). With the placement of a single relay node for enabling a dual-hop FSO link, the P_{FSO} requirement can be greatly reduced, especially when combined with larger receiver apertures. Comparing the single-hop and dual-hop FSO systems with $D = 150$ mm, it is evident that the latter is capable of establishing better performance of $P_e < 10^{-9}$ with a significantly lower P_{FSO} requirement of < 0 dBm. Therefore, we conclude that the relay-assisted multi-hop FSO system with aperture averaging is a feasible approach toward reducing the error performance with minimum power requirement.

5 Conclusions

In summary, we have proposed a multi-hop FSO system based on optical relaying as a feasible alternative for effectively mitigating the undesirable effects of atmospheric attenuation and turbulence-induced scintillation. Along with relays, aperture-averaging effects are also observed, which in some cases evince better output. SNR, BER, link distance, and optical power were considered under different weather conditions and turbulence effects. According to result analysis, consumed optical power can be reduced by adding multi-hopped relays under clear weather haze, moderate rain, and heavy rain at 12 km link distance with an achievable bit error rate of 10^{-9} or lower than that except light fog condition. Furthermore, it is clear that introducing an aperture-averaging effect with different receiver diameters in clear weather at

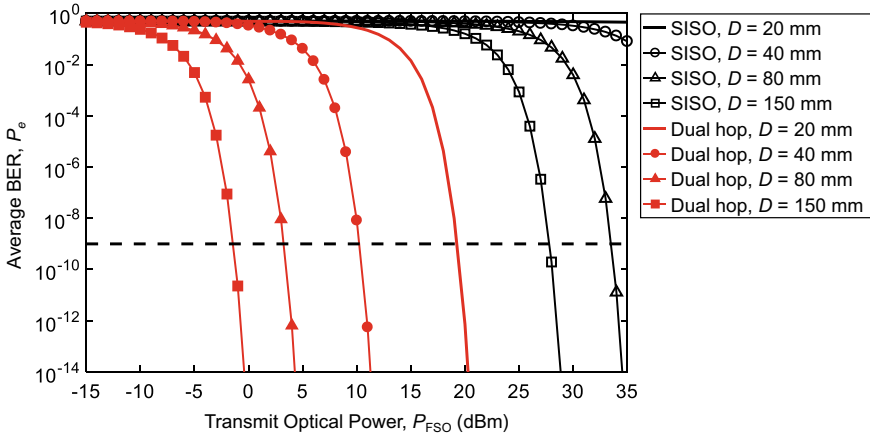


Fig. 6 Average BER versus the transmit optical power for the conventional SISO FSO system and relay-assisted dual-hop FSO system, under the aperture-averaging effect with $D = \{20, 40, 80, 150\}$ mm. The low-visibility light fog scenario at $L = 3$ km is considered

8 km and light fog at 3 km significantly improves the performance of the relay-based multi-hopped channel over SISO FSO system. Observation for light fog at $L > 5$ km applied with a multi-hopped relayed FSO system was unable to get an acceptable system outage, which can leave future work in order for the betterment of long-distance turbulence in a cost-effective way.

Acknowledgements This research project is supported by the Multimedia University (MMU) Graduate Research Assistant (GRA) Scheme (MMUI/190009) and the Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FRGS/1/2020/ TK0/MMU/03/8).

References

1. Hil S, Agarwal S, Singhal Y, Bhardwaj P (2018) An overview of free space optical communication. *Int J Eng Trends Technol* 55(3):120–125
2. Farhad MM, Islam MR, Islam NN, Ali MM (2013) Performance analysis of turbo coded free space optical communication system over AWGN channel. *Int J Sci Adv Technol* 3(7)
3. Khalighi MA, Uysal M (2014) Survey on free space optical communication: a communication theory perspective. *IEEE Commun Surv Tutor* 16(4):2231–2258
4. Abou-Rjeily C, Fawaz W (2018) Buffer-aided serial relaying for FSO communications: asymptotic analysis and impact of relay placement. *IEEE Trans Wireless Commun* 17(12):8299–8313
5. Dayal N, Singh P, Kaur P (2017) Relay-assisted WDM-FSO system: a better solution for communication under rain and haze weather conditions. *J Telecommun Inf Technol* 2017(4):54–59
6. Zhu B, Cheng J, Alouini MS, Wu L (2015) Relay placement for FSO multihop DF systems with link obstacles and infeasible regions. *IEEE Trans Wireless Commun* 14(9):5240–5250
7. Cui H, Song L, Jiao B (2013) Weighted amplify-and-forward relay selection with outdated channel state information. *IEEE Wirel Commun Lett* 2(6):651–654

8. Lee IE, Ghassemlooy Z, Ng WP, Rajbhandari S (2011) Fundamental analysis of hybrid free space optical and radio frequency communication systems. In: Proceedings of the 12th annual post graduate symposium on the convergence of telecommunications, networking and broadcasting, pp 281–285, Liverpool (2011)
9. Lee IE, Ghassemlooy Z (2019) Analysis of the effects of aperture averaging and beam width on a partially coherent Gaussian beam over free-space optical communication links. In: Majumdar AK, Ghassemlooy Z, Arockia Basil Raj A (eds) Principles and applications of free space optical communications. IET Press, pp 247–303
10. Dabiri MT, Sadough SMS (2018) Performance analysis of all-optical amplify and forward relaying over log-normal FSO channels. *J Opt Commun Netw* 10(2):79–89
11. Fang J, Bi M, Xiao S, Yang G, Liu L, Zhang Y, Hu W (2018) Polar-coded MIMO FSO communication system over gamma-gamma turbulence channel with spatially correlated fading. *J Opt Commun Netw* 10(11):915–923
12. Sharma S, Madhukumar AS, Swaminathan R (2018) Switching-based hybrid FSO/RF transmission for DF relaying system. In: Proceedings of the 2018 IEEE wireless communications and networking conference. IEEE, Barcelona, pp 1–6
13. Farid AA, Hranilovic S (2007) Outage capacity optimization for free-space optical links with pointing errors. *J Lightwave Technol* 25(7):1702–1710
14. Sandalidis HG (2008) Optimization models for misalignment fading mitigation in optical wireless links. *IEEE Commun Lett* 12(5):395–397
15. Sharma PK, Bansal A, Garg P, Tsiftsis T, Barrios R (2017) Relayed FSO communication with aperture averaging receivers and misalignment errors. *IET Commun* 11(1):45–52
16. Hasna MO, Alouini MS (2003) End-to-end outage probability of multihop transmission over lognormal shadowed channels. *Arab J Sci Eng* 28(2C):35–44
17. Vu MQ, Pham TV, Dang NT, Pham AT (2020) Design and performance of relay-assisted satellite free-space optical quantum key distribution systems. *IEEE Access* 8:122498–122510
18. Deka R, Sipani J, Anees S (2022) On the performance of a HAPS assisted AF based dual-hop FSO communication system. In: Proceedings of the 2022 international conference on wireless communications signal processing and networking. IEEE, Chennai, pp 13–18
19. Gao SJ, Li YT, Geng TW (2022) Deep reinforcement learning-based relay selection algorithm in free-space optical cooperative communications. *Appl Sci* 12(10):4881–4894