Proposing two Novel Hybrid RF/FSO Systems to Reduce the Damaging Effects of Foggy Channels

Negin Nikbakht-Sardari[1], Mohammad Ghiamy[2], Mohammad E. Akbari[1], Asghar Charmin[1]
[1]Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
[2]Department of Electrical Engineering, Ardabil Branch, Islamic Azad University, Ardabil, Iran
Email: mo.ghiamy@iau.ac.ir(Corresponding author)
Receive Date: 27 January 2025 Revise Date: 15 February 2025 Accept Date: 15 March 2025

Abstract

In recent years, much research has been done on optical wireless communication systems. In this regard, we proposed two novel hybrid RF-FSO systems in foggy channels. In the first scheme, one RF-FSO link (path 1) is paralleled with an RF link (path 2). In the second scheme, an FSO link (path 1) and a hybrid RF-FSO link (path 2) are paralleled. The FSO links are modeled by a new distribution that proposed for foggy channels. Also, the RF links are modeled by Rayleigh distribution. To obtain the system outage probability, we derive the closed-form equations using the Intensity Modulation with Direct Detection (IM/DD) technique.

Keywords: Free Space Optical (FSO) Communication; Hybrid RF/FSO Systems; Foggy channel; Haze channel; Outage Probability

1. Introduction

In recent years, the use of Optical Wireless Communication (OWC) systems has been growing due to its advantages. High bandwidth and data transmission security, easy and low-cost implementation, and no need to obtain a license are some of the advantages of this system [1]. On the other hand, recent studies have shown that the FSO system can be a promising solution to increase the data transmission rate in the fifth and sixth generation (5 and 6G) of mobile communications [2], [3]. Despite all these advantages, there are challenges to using this system that are related to the free space channel. In the other hand, the FSO links performance is highly dependent on the free space channel conditions and link distance [4], [5], [6], [7]. The dust, heavy snowfall, raindrops, fog, and haze attenuate the power of the light beam. Fog molecules cause the highest amount of scattering in the transmitted light beam. This phenomenon decreases the visibility and as a result, increases the Outage Probability. Even dense fog can cause disconnection, completely [8], [9], [10], [11]. One suggested way to reduce the mentioned effects is to use the RF system as a backup in two parallel and series architectures. In other words, the complementary characteristics of the RF and FSO systems make the whole system's performance appropriate in different channel conditions [12], [13], [14], [15].

In [16], a dual-hop hybrid relay-based FSO/RF communication system is presented. In this scheme, an access point connects users to the base station via a hybrid parallel FSO/RF link. The RF and FSO channels are modeled by Rayleigh and Gamma-Gamma distributions, respectively. Also, in the FSO system, the effect of atmospheric turbulence and pointing error has been studied. According to the paper, the parallel FSO/RF system and the use of an access point will increase the capacity, reliability, and systems data rate.

In [17], the hybrid FSO/RF system is introduced as a promising solution for a reliable wireless backhaul system for the fifth-generation technology standard for cellular networks. Performance analysis of the hybrid FSO/RF single threshold system has been carried out based on switching technique for both terrestrial and satellite communication scenarios in the presence of atmospheric turbulence and pointing error.

A multi-hop hybrid RF-FSO system in [18] based on Amplify-and-Forward (AF) relays is introduced (similar to [19], [20], [21]). Also, the RF and FSO channels are modeled by Rayleigh and Gamma-Gamma distributions, respectively. Partial relay selection based on channel state information (CSI) is used to select active relays for transmission.

In [22], a hybrid RF-FSO\FSO-RF scheme is presented that the data will be transmitted from RF-FSO or FSO-RF paths. In other words, the FSO-RF path supports the RF-FSO path. Also, the Intensity Modulation with Direct Detection (IM/DD) and heterodyne detection techniques are used in FSO links. furthermore, this paper proposed an algorithm for computing Extended Generalized Bivariate Meijer-G Function (EGBMGF) for the first time.

In [23] and [24], studies have been done on the effect of fog in weakening the light beam. Also, a new distribution is presented to study the foggy channel behavior in FSO systems. Paper [24] suggests that to reduce the effect of fog, use optical AF relays in the FSO link, which shortens the length of the optical links. Also, a parallel hybrid system based on a hard switch is presented, which selects the appropriate link for data transmission using the channel state information (CSI).

Paper [25] proposed two novel adaptive hard switching relay based hybrid system to improve the performance of FSO system. In this schemes, the two threshold SNR strategy is used. In these presented architectures, the FSO and RF links have been modeled by Gamma-Gamma and Rayleigh distribution, respectively. Also, the performance of proposed systems are presented in the different atmospheric and pointing error conditions.

In this article, according to [25], the effects caused by fog in the two introduced systems will be presented.

In the first scheme (dual threshold SNR hybrid RF-FSO/RF), the main RF-FSO path is supported by the RF link in the foggy channel. In the foggy channel, if the received SNR from the RF-FSO path is less than the lower threshold SNR, data transfer is done through the RF link.

Similarly, in the second scheme, the main path for data transmission is the FSO link. If, due to fog, the received SNR is less than the lower threshold, the backup path (RF/FSO) will send the data. If the received SNR from path 1 exceeds the upper threshold, data is sent again through the FSO link.

The main contribution of this work is proposing a double threshold SNR for the relay-based hard switching system that guarantees the optical link quality in the foggy channel. To the best of our knowledge, this is the first work that the two relay-based schemes proposed using dual threshold SNR for the reduction of the FSO link performance in foggy conditions.

2. Channel model

The presence of water molecules in the fog causes scattering phenomena in the free space channel and attenuating the light signal power. In recent years, there have been studies about the attenuation caused by fog on the optical signal, and the results of two of them are given in Tables 1 and 2.

Table 1. the k and Ω parameters in different foggy channel [24]

fog densities	parameters	values
Light fog	k Ω	2.32 13.12
Moderate fog	k Ω	5.49 12.06
Think fog	k Ω	6.00 23.00
Dense fog	k Ω	36.05 11.91

Table 2. The visibility parameters and optical signal attenuation in different fog density [4]

Channel condition	attenuation $(dB/Km) \cong$	Visibility $(m) \cong$
Very clean air	0.47	23000
	0.19	50000
Clean Air	0.6	18100
	0.54	20000
Light fog	18.3	770
Moderate fog	28.9	500
Think fog	75	200
dense fog	315	50

In this paper, we assumed that the Intensity modulation/Direct Detection (IM/DD) technique and OOK modulation have been used in the FSO system. On the other hand, the intensity of received signal fluctuations is due to the atmospheric losses, pointing errors and the additive noise. Therefore, the received signal is modeled as [24]

$$y = RIx + n \tag{1}$$

That R and I are the receive responsivity (A/W), and channel state, respectively. Also, x is the signel intensity and n is the additive white Gaussian noise (AWGN) with variance σ_n^2. The destructive effect of atmospheric turbulence is inversely proportional to the concentration of channel fog. Therefore, in the considered model, the fog atmospheric loss and pointing error are considered and can be expressed as $I = I_P I_l$, where I_P and I_l are the channel states due to the pointing errors and fog atmospheric loss, respectively. For equal-probability symbols, the received electrical SNR is as

$$\gamma = \frac{2P_t^2 R^2 I^2}{\sigma_n^2} \tag{2}$$

Where P_t is the average optical transmitted power.

The statistical behavior of the foggy channel can be expressed by [26]

$$f_{I_l}(I_l) = \frac{z^k}{\Gamma(k)}\left[ln\left(\frac{1}{I_l}\right)\right]^{k-1} I_l^{\,z-1} \quad 0 < I_l \leq 1 \qquad (3)$$

Where $z = 4.343/\Omega L$ and $\Gamma(k)$ is the Gamma Gamma function. Also, L is the FSO link distance in Km. k and Ω represent the shape and scale parameters of the signal attenuation in the different fog densities tath proposed in Table 1.

Parameter $k\Omega$ is the determined average value of signal attenuation due to fog (dB/km). Table 2 shows the visibility parameters and optical signal attenuation in different fog density. The information presented in this table will be used to analyze the numerical results. According to [4] and Tables 1 and 2, the system performance will depend on the link length and fog density.

3. Conclusion

In this paper, we proposed the two novel hybrids hard switching based scheme in the foggy channel using two threshold SNR. In these schemes, we assumed that there is a backup path for the main data transmission path to transmit the desired data in case of bad fog conditions.

Acknowledgments

The authors would like to thank Dr. Amin Tahami, for his helpful responses to the questions of the first author.

References

[1] 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.

[2] H. B. Jeon *et al.*, "Free-Space Optical Communications for 6G Wireless Networks: Challenges, Opportunities, and Prototype Validation," *IEEE Commun. Mag.*, vol. 61, no. 4, pp. 116–121, 2023, doi: 10.1109/MCOM.001.2200220.

[3] R. Harada, N. Shibata, S. Kaneko, T. Imai, J. ichi Kani, and T. Yoshida, "Adaptive Beam Divergence for Expanding Range of Link Distance in FSO with Moving Nodes toward 6G," *IEEE Photonics Technol. Lett.*, vol. 34, no. 20, pp. 1061–1064, 2022, doi: 10.1109/LPT.2022.3199789.

[4] Z. Ghassemlooy, W. O. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*, 2nd Editio. CRC press, 2019.

[5] B. B. Yousif, E. E. Elsayed, and M. M. Alzalabani, "Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system," *Opt. Commun.*, vol. 436, pp. 197–208, 2019, doi: 10.1016/j.optcom.2018.12.034.

[6] B. B. Yousif, E. E. Elsayed, and M. M. Alzalabani, "Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system," *Opt. Commun.*, vol. 436, pp. 197–208, 2019, doi: 10.1016/J.OPTCOM.2018.12.034.

[7] A. Tahami, A. Dargahi, K. Abedi, and A. Chaman-Motlagh, "Two novel hybrid architectures for improving the system performance in long length FSO links," *Opt. Commun.*, vol. 451, 2019, doi: 10.1016/j.optcom.2019.06.046.

[8] M. A. Esmail, H. Fathallah, and M. S. Alouini, "An Experimental Study of FSO Link Performance in Desert Environment," *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1888–1891, 2016, doi: 10.1109/LCOMM.2016.2586043.

[9] Z. Rahman, S. M. Zafaruddin, and V. K. Chaubey, "Performance of Opportunistic Receiver Beam Selection in Multiaperture OWC Systems over Foggy Channels," *IEEE Syst. J.*, vol. 14, no. 3, pp. 4036–4046, 2020, doi: 10.1109/JSYST.2019.2962580.

[10] Z. Rahman, S. M. Zafaruddin, and V. K. Chaubey, "Multihop Optical Wireless Communication Over F-Turbulence Channels and Generalized Pointing Errors With Fog-Induced Fading," *IEEE Photonics J.*, vol. 14, no. 5, 2022, doi: 10.1109/JPHOT.2022.3200247.

[11] Y. Chang, Z. Liu, H. Yao, S. Gao, K. Dong, and S. Liu, "Performance Analysis of Multi-Hop FSOC over Gamma-Gamma Turbulence and Random Fog with Generalized Pointing Errors," *Photonics*, vol. 10, no. 11, 2023, doi: 10.3390/photonics10111240.

[12] M. A. Amirabadi and V. T. Vakili, "On the performance of a multi-user multi-hop hybrid FSO / RF communication system," *Opt. Commun.*, vol. 444, no. March, pp. 172–183, 2019, doi: 10.1016/j.optcom.2019.03.070.

[13] E. Balti, M. Guizani, B. Hamdaoui, and Y. Maalej, "Partial Relay Selection For Hybrid RF/FSO Systems with Hardware Impairments," no. D, 2019, [Online]. Available: http://arxiv.org/abs/1901.05097

[14] M. A. Amirabadi and V. Tabataba Vakili, "A novel hybrid FSO / RF communication system with receive diversity," *Optik (Stuttg).*, vol. 184, no. December 2017, pp. 293–298, 2019, doi: 10.1016/j.ijleo.2019.03.037.

[15] M. A. Amirabadi and V. Tabataba Vakili, "A novel hybrid FSO / RF communication system with receive diversity," *Optik (Stuttg).*, vol. 184, pp. 293–298, 2019, doi: 10.1016/j.ijleo.2019.03.037.

[16] M. A. Amirabadi and V. T. Vakili, "Performance analysis of a novel hybrid FSO/RF communication system," *IET Optoelectron.*, 2020, doi: 10.1049/iet-opt.2018.5172.

[17] N. Vishwakarma and S. R, "Performance analysis of hybrid FSO/RF communication over generalized fading models," *Opt. Commun.*, 2021, doi: 10.1016/j.optcom.2021.126796.

[18] M. I. Petkovic, I. S. Ansari, G. T. Djordjevic, and K. A. Qaraqe, "Error rate and ergodic capacity of RF-FSO system with partial relay selection in the presence of pointing errors," *Opt. Commun.*, vol. 438, pp. 118–125, 2019, doi: 10.1016/j.optcom.2019.01.028.

[19] C. Abou-Rjeily, "All-active and selective FSO relaying: Do we need inter-relay cooperation?," *J. Light. Technol.*, vol. 32, no. 10, pp. 1899–1906, 2014, doi: 10.1109/JLT.2014.2315853.

[20] C. Abou-Rjeily, "Performance Analysis of FSO Communications with Diversity Methods: Add More Relays or More Apertures?," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1890–1902, 2015, doi: 10.1109/JSAC.2015.2432526.

[21] C. Abou-Rjeily and Z. Noun, "Impact of Inter-Relay Co-Operation on the Performance of FSO Systems with Any Number of Relays," *IEEE Trans. Wirel. Commun.*, 2016, doi: 10.1109/TWC.2016.2529630.

[22] A. Tahami, A. Dargahi, K. Abedi, and A. Chaman-Motlagh, "A new relay based architecture in hybrid RF/FSO system," *Phys. Commun.*, vol. 36, 2019, doi: 10.1016/j.phycom.2019.100818.

[23] M. A. Esmail, H. Fathallah, and M. S. Alouini, "Outdoor FSO Communications under Fog: Attenuation Modeling and Performance Evaluation," *IEEE Photonics J.*, vol. 8, no. 4, 2016, doi: 10.1109/JPHOT.2016.2592705.

[24] 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, pp. 1–13, 2017, doi: 10.1109/JPHOT.2017.2672641.

[25] N. Nikbakht-Sardari, M. Ghiamy, M. E. Akbari, and A. Charmin, "Novel adaptive hard-switching based hybrid RF-FSO system architecture using two threshold values in the presence of atmospheric turbulence and pointing error," *Results Eng.*, vol. 17, no. October 2022, p. 100813, 2023, doi: 10.1016/j.rineng.2022.100813.

[26] M. A. Esmail, H. Fathallah, and M. S. Alouini, "Channel modeling and performance evaluation of FSO communication systems in fog," in *2016 23rd International Conference on Telecommunications, ICT 2016*, 2016. doi: 10.1109/ICT.2016.7500472.