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Review Article

Free Space Optics: Current Applications and Future Challenges

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FSO is a communication system where free space acts as medium between transceivers and they should be in LOS for successful transmission of optical signal. Medium can be air, outer space, or vacuum. This system can be used for communication purpose in hours and in lesser economy. There are many advantages of FSO like high bandwidth and no spectrum license. The transmission in FSO is dependent on the medium because the presence of foreign elements like rain, fog, and haze, physical obstruction, scattering, and atmospheric turbulence are some of these factors. Different studies on weather conditions and techniques employed to mitigate their effect are discussed in this paper.

1. Introduction

FSO (free space optics) is an optical communication technology in which data is transmitted by propagation of light in free space allowing optical connectivity. There is no requirement of the optical fiber cable. Working of FSO is similar to OFC (optical fiber cable) networks but the only difference is that the optical beams are sent through free air instead of OFC cores that is glass fiber. FSO system consists of an optical transceiver at both ends to provide full duplex (bidirectional) capability. FSO communication is not a new technology. It has been in existence from 8th century but now is more evolved. FSO is a LOS (line of sight) technology, where data, voice, and video communication is achieved with maximum 10 Gbps of data rate by full duplex (bidirectional) connectivity [1].

An effective FSO system should have the following characteristics [1]:

(a) FSO systems should have the ability to operate at higher power levels for longer distance.

(b) For high speed FSO systems, high speed modulation is important.

(c) An overall system design should have small footprint and low power consumption because of its maintenance.

(d) FSO system should have the ability to operate over wide temperature range and the performance degradation would be less for outdoor systems.

(e) Mean time between failures (MTBF) of system should be more than 10 years.

2. Applications

FSO communication link is currently in use for many services at many places. These are described below in detail:

(a) Outdoor wireless access: it can be used by wireless service providers for communication and it requires no license to use the FSO as it is required in case of microwave bands.

(b) Storage Area Network (SAN): FSO links can be used to form a SAN. It is a network which is known to provide access to consolidated, block level data storage [2].

(c) Last-mile access: to lay cables of users in the last mile is very costly for service providers as the cost of digging to lay fiber is so high and it would make sense to lay as much fiber as possible. FSO can be used to solve such problem by implementing it in the last mile along with other networks. It is a high speed link. It is also used to bypass local-loop systems of other kinds of networks [3].

(d) Enterprise connectivity: FSO systems are easily installable. This feature makes it applicable for interconnecting LAN segments to connect two buildings or other property [3].

(e) Fiber backup: FSO can also be applicable in providing a backup link in case of failure of transmission through fiber link [3].

(f) Metro-network extensions: it can be used in extending the fiber rings of an existing metropolitan area. FSO system can be deployed in lesser time and connection of the new networks and core infrastructure is easily done. It can also be used to complete SONET rings [3].

(g) Backhaul: it can be helpful in carrying the traffic of cellular telephone from antenna towers back to the PSTN with high speed and high data rate. The speed of transmission would increase [3].

(h) Service acceleration: it can also be used to provide instant service to customers when their fiber infrastructure is being deployed in the mean time [3].

(i) Bridging WAN Access: FSO is beneficial in WAN where it supports high speed data services for mobile users and small satellite terminals and acts as a backbone for high speed trunking network [4].

(j) It can be used to communicate between point-to-point links, for example, two buildings, two ships, and point-to-multipoint links, for example, from aircraft to ground or satellite to ground, for short and long reach communication [5].

(k) Military access: as it is a secure and undetectable system it can connect large areas safely with minimal planning and deployment time and is hence suitable for military applications [6].

3. Merits

(a) Free space optics is a flexible network that delivers better speed than broadband [1].

(b) Installation is very easy and it takes less than 30 minutes to install at normal locations [1].

(c) It has very low initial investment [3].

(d) It is a straight forward deployment system. There is no need for spectrum license or frequency coordination between users as it is required in radio and microwave systems previously [7].

(e) It is a secure system because of line of sight operation and so no security system upgradation is needed [7].

(f) High data rate can be obtained which is comparable to the optical fiber cable's data rate but error rate is very low and the extremely narrow laser beam enables having unlimited number of FSO links which can be installed in a specific area [7].

(g) There is immunity to radio frequency interference [7].

(h) Electromagnetic and radio-magnetic interference cannot affect the transmission in FSO link [8].

(i) FSO offers dense spatial reuse [8].

(j) Low power usage per transmitted bit is merit of FSO system [8].

(k) There is relatively high bandwidth [8].

(l) It has flexible rollouts [9].

(m) Transmission of optical beam is done in air. Hence, transmission is having speed of light [10].

These merits indicate the significance of FSO system over different communication systems. Comparison of different systems based on various parameters is mentioned in Table 1.

4. Limitations

The advantages of free space optics are easy to come. But as the medium of the transmission is air for FSO and the light passes through it, some environmental challenges are unavoidable. Troposphere regions are the region where most of the atmospheric phenomenon occurred [11]. The effect of these limitations over the atmosphere is shown in Figure 1. Some of these limitations are briefly described below:

(a) Physical obstructions: flying birds, trees, and tall buildings can temporarily block a single beam, when it appears in line of sight (LOS) of transmission of FSO system [1].

(b) Scintillation: there would be temperature variations among different air packets due to the heat rising from the earth and the man-made drives like heating ducts. These temperature variations can cause fluctuations in amplitude of the signal which causes "image dancing" at the FSO receiving end. The effect of scintillation is addressed by Light Pointe's unique multibeam system [1].

(c) Geometric losses: geometric losses which can be called optical beam attenuation are induced due to the spreading of beam and reduced the power level of signal as it travelled from transmitted end to receiver end [7].

(d) Absorption: absorption is caused by the water molecules which are suspended in the terrestrial atmosphere. The photons power would be absorbed by these particles. The power density of the optical beam is decreased and the availability of the transmission in a FSO system is directly affected by absorption. Carbon dioxide can also cause the absorption of signal [9].

(e) Atmospheric turbulence: the atmospheric disturbance happens due to weather and environment structure. It is caused by wind and convection which mixed the air parcels at different temperatures. This causes fluctuations in the density of air and it leads to the change in the air refractive index. The scale size

Table 1: Comparison of FSO with different communication system.

Parameters	FSO	Optical fiber	Microwave radio	Coaxial cable
Installation	Moderate	Difficult	Difficult	Moderate
Data rate	Gbps	Independent	Mbps	Mbps
Security	Good	Very good	Poor	Good
Connectivity	P2P, P2MP short and long reach	P2P, P2MP short and long reach	P2P short reach	Multidrop short reach
Maintenance	Low	Low	Low	Moderate
Spectrum license	Not required	Required	Required	Required

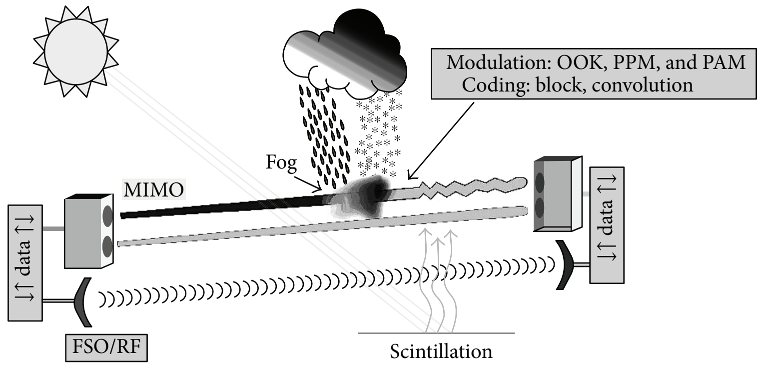

Figure 1: Atmospheric effects on FSO system [1].

of turbulence cell can create different type of effects given below and which would be dominant:

(i) If size of turbulence cell is of larger diameter than optical beam then beam wander would be the dominant effect. Beam wander is explained as the displacement of the optical beam spot rapidly.

(ii) If size of turbulence cell is of smaller diameter than optical beam then the intensity fluctuation or scintillation of the optical beam is a dominant one.

Turbulence can lead to degradation of the optical beam of transmission. Change in the refractive index causes refraction of beam at different angle and spreading of optical beam takes place [11].

(f) Atmospheric attenuation: atmospheric attenuation is the resultant of fog and haze normally. It also depends upon dust and rain. It is supposed that atmospheric attenuation is wavelength dependent but this is not true. Haze is wavelength dependent. Attenuation at 1550 nm is less than other wavelengths in haze weather condition [11]. Attenuation in fog weather condition is wavelength independent.

(g) Scattering: scattering phenomena happen when the optical beam and scatterer collide. It is wavelength dependent phenomenon where energy of optical beam is not changed. But only directional redistribution of optical energy happens which leads to the reduction in the intensity of beam for longer distance. Atmospheric attenuation is divided into three types [12]:

(1) Rayleigh scattering which is known as molecule scattering.

(2) Mie scattering which is known as aerosol scattering.

(3) Nonselective scattering which is known as geometric scattering.

The type of scattering depends upon the physical size of the scatterer [1]:

(i) When it is smaller than the size of wavelength, Rayleigh scattering.

(ii) When the size of the scatterer is comparable to the wavelength, Mie scattering.

(iii) When it is much larger than the size of wavelength, nonselective scattering.

Atmospheric Weather Conditions. Atmosphere is the medium of transmission for a FSO link. Attenuation caused by it depends upon several conditions. Weather conditions are the main cause of attenuation. The region in which a link is being established has some specific weather conditions so that the preceding knowledge of attenuation can be gained; for example, fog and heavy snow are the two primary weather conditions in temperate regions. In tropical regions, heavy rain and haze are two main weather conditions and have major effect on the availability of FSO link in that region [13]. Some of the weather conditions are described below.

(a) Fog. Fog substantially attenuates visible radiation. Optical beam of light is absorbed, scattered, and reflected by the hindrance caused by fog. Scattering caused by fog, also known as *Mie scattering* [1], is largely a matter of boosting the transmitted power.

(b) Rain. Rain attenuation exists due to rain fall and is a *nonselective scattering*. This type of attenuation is wavelength independent [11]. Rain has the ability to produce the fluctuation effects in laser delivery. The visibility of FSO system depends upon the quantity of the rain. In case of heavy rain, water droplets have solid composed and it can either modify the optical beam characteristics or restrict the passage of beam as optical beam is absorbed, scattered, and reflected [8].

(c) Haze. Haze particles can stay longer time in the air and lead to the atmospheric attenuation. So, attenuation values depend upon the visibility level at that time. There are two ways to gather information about attenuation for checking the performance of FSO system: first, by installing system temporary at the site and check its performance and, second, by using Kim and Kruse model [11].

(d) Smoke. It is generated by the combustion of different substances like carbon, glycerol, and household emission. It affects the visibility of transmission medium [14].

(e) Sandstorms. Sandstorms are the well-known problem in outdoor link communication. These can be characterized by two ways: first, the size of the wind particles which depends on the soil texture and, second, necessary wind speed in order to blow the particles up during a minimum period of time [15].

(f) Clouds. Cloud layers are main part of earth atmosphere. The formation of clouds is done by the condensation or deposition of water above earth's surface. It can completely block the fractions of optical beam transmitted from earth to the space. The attenuation caused by clouds is difficult to calculate because of the diversity and inhomogeneity of the cloud particles [16].

(g) Snow. Snow has larger particles which causes the geometric scattering. The snow particles have impact similar to *Rayleigh scattering* [17].

5. Different Studies Based on Attenuation Effect

Different studies are going on different weather condition to design new models based on the effectiveness of the system. The main focuses of these studies are fog, haze, rain, and snow weather conditions. Based on these studies results, measures can be taken in practical system.

In a study authors followed theoretical and experimental research to study the effect of fog and smoke. Experimental results validated the laboratory-based empirical model that 830, 940, and 1550 nm are most durable wavelength windows. Empirical model is used to compare the experimental result for the continuous attenuation spectrum of fog and smoke conditions and results show that the disambiguation is decreasing linearly [14]. In another study, author studies whether fog is wavelength dependent or not. A fog-like environment is developed in a chamber for experimenting. It is verified that attenuation caused by fog is wavelength dependent parameter. FSO link employed with 830 nm and 1550 nm in parallel in the same chamber and power is measured at the receiving end for both the cases: with fog and without fog. Fog particles lead to Mie scattering so Mie theory is applicable to measure the scattering. One model from the three famous models, that is, empirical, Kim, and Ferdinandov, can be used to calculate the attenuation due to fog [18].

In rain based study, a correlation of precipitation rates with rain attenuation is studied on the short wavelength (785 nm). The four-existing-model rain attenuation is utilized to find the result and measured data is compared with calculated results to determine the turbulence model [8]. The effects of rain intensity variation on its attenuation prediction are the focus of another study. The analysis of 7 reduction format models is done to study the FSO link with rain intensity variations. Six of the models have a reduction factor value of unity where one model has 0.7. It reduces the effective path length of FSO link. Rainfall distribution for longer path seems to be more widespread in case of low rain rate and more concentrated in case higher rain rate [19]. In a study, single and multiple transceiver concept is used to study the effect of tropical Malaysian weather on FSO link based on the value of link distance and received power. It is concluded that four-beam FSO system can successfully operate under heavy rain for larger distance depending upon the value of signal to noise ratio (SNR), geometrical and atmospheric losses, and bit error rate (BER) [17].

6. Various Techniques to Enhance System Performance

Various techniques to enhance the system performance are being introduced. Some of these techniques are discussed below in detail and their comparison is done in the following section.

(a) Performance of SAC OCDMA Based FSO System. Spectral Amplitude Coding Optical Code Division Multiple Access technique is used in FSO system by the researchers. This multiplexing scheme has several advantages like flexibility of channel allocation, asynchronously operative ability, privacy enhancement, and network capacity increment. KS (Khazani-Syed) codes are used with SDD (spectral direct decoding) technique. An optical external modulator (OEM) is used to modulate the code sequence with data. The data is an independent unipolar digital signal. Mach-Zehnder Modulator (MZM) is used and combination of modulated code sequences is transmitted through the FSO link and these sequences are separated by an optical splitter at the receiver end. The overlapping chips are discarded to avoid the interference at receiver end and decoder will only filter the nonoverlapping chips. Optical band pass filters serve the purpose of encoders and decoders. A low pass filter

Table 2: Comparison table of various techniques based on system parameters on wavelength of 1550 nm [4, 5, 11, 21].

Technique		Weather condition	Attenuation level (dB/km)	Power level (dBm)	Data rate	Link distance (km)
SAC OCDMA-FSO	SDD	Heavy rain	8.68	0	2.5 Gbps	1.1
		Clear sky	3	0	2.5 Gbps	1.3
OFDM-FSO	OFDM-OSTB-FSO	Clear	0.155	0	2 Gbps	10
					5 Gbps	6
		Mild clear	0.441	0	2 Gbps	9
					5 Gbps	5
		Low haze	1.537	0	2 Gbps	5.4
					5 Gbps	3.4
		Mild haze	4.285	0	2 Gbps	3.2
					5 Gbps	2.2
		Heavy haze	10.115	0	2 Gbps	1.8
					5 Gbps	1.15
		Low fog	15.55	0	2 Gbps	1.35
					5 Gbps	1
		Mild fog	33.961	0	2 Gbps	0.720
					5 Gbps	0.540
		Heavy fog	84.904	0	2 Gbps	0.360
					5 Gbps	0.300
	OFDM-OSSB-FSO	Clear	0.155	0	2 Gbps	10.2
					5 Gbps	6.2
		Mild clear	0.441	0	2 Gbps	8
					5 Gbps	5.2
		Low haze	1.537	0	2 Gbps	5
					5 Gbps	3.6
		Mild haze	4.285	0	2 Gbps	2.8
					5 Gbps	2.5
		Heavy haze	10.115	0	2 Gbps	1.7
					5 Gbps	1.4
		Low fog	15.55	0	2 Gbps	1.26
					5 Gbps	1.2
		Mild fog	33.961	0	2 Gbps	0.740
					5 Gbps	0.590
		Heavy fog	84.904	0	2 Gbps	0.360
					5 Gbps	0.310
WDM-FSO		Very clear	0.065	−10	2.5 Gbps	150
		Clear	0.233	10	2.5 Gbps	150
		Light haze	0.55	20	2.5 Gbps	150
		Heavy haze	2.37	40	155 Mbps	150
		Heavy haze	2.37	30	155 Mbps	55
					622 Mbps	51.52
		Light rain	6.27	30	155 Mbps	22
					622 Mbps	20.8
		Medium rain	9.64	30	155 Mbps	14.7
					622 Mbps	13.9
		Heavy rain	19.28	30	155 Mbps	7.6
					622 Mbps	7.2

(LPF) is used to recover the original data. The performance of this system with SDD technique is analyzed along with FSO system using intensity modulation with direct detection (IM/DD) technique. SDD technique performs better and the link distance is improved by 22.7% [5].

(b) High Speed, Long Reach OFDM-FSO Transmission Link Incorporating OSSB and OTSB Schemes. By introducing the OFDM scheme, an effort has been made to probe the impact of the environment conditions and to design a high speed and long reach FSO system free from the multipath fading. Different weather conditions like clear, foggy, and hazy channel are used to model different types of condition in system. CW laser diode is used at the line-width of 10 MHz and 1550 nm wavelength. The power to be used by hybrid system is 0 dBm and ideal antenna aperture is 15 cm. The data rate is 5 Gbps and a 4-QAM sequence generator generates the data and OFDM modulator using 512 subcarriers is used. The data is transmitted over FSO link using OTSB/OSSB schemes instead of ODSB scheme which is prone to fading problem. This modulation is done by Dual Electrode Mach-Zehnder Modulator (DEMZM) and a phase shifter. It is concluded that hybrid OFDM-FSO system performs better in diverse channel conditions and upon comparing both OSSB and OTSB schemes OSSB performs better than OTSB at high data rate as it has more immunity against fading due to weather conditions [4].

(c) Optimization of Free Space Optics Parameters Using WDM System. A unidirectional WDM system is designed by the investigators. Different characteristics like data rate, power, link range, number of users, and channel spacing are needed to be optimized according to the weather conditions. The attenuation for different type of rain is 6.27, 9.64, and 19.28 dB/km for light, medium, and heavy rain, respectively. 1550 nm wavelength is best for both rain and haze as there is less attenuation than any other wavelength. The priority for optimization of parameters is required to be done for the better performance of system. Geometric losses are not considered during this work. Optical Amplifier Gain is having the highest priority and the rest of priority decrementing series is laser power, data rate, and aperture size and link length is having the lowest priority. A 622 Mbps of data rate is maximized for all types of rain as concluded from results. For clear weather condition, data rate could be 2.5 Gbps for the distance of 150 km. For critical weather conditions, short link distance and lower data rate can be used to optimize the FSO system for successful transmission [11].

Comparison of these studies is done based on the different parameters like wavelength, power level, data rate, and link distance. Summarization of all parameters with different techniques is done in Table 2.

From Table 2, it can be concluded that the more the attenuation the smaller the link distance. With increase in the data rate, link distance reduces. If power level increases, then link distance improves depending upon the value of power level. Effect of attenuation is lesser if power level is high but power level cannot be increased more than value defined by various organizations that define the principle of laser safety. Such as a human eye can be affected by Laser when eye comes in direct contact with it on a particular wavelength at a particular power like 10 mW power for Class 1 M laser in 1550 nm wavelength permissible by IEC (International Electro technical Commission) standards [20].

7. Conclusion

FSO offers many advantages over existing techniques which can be either optical or radio or microwave. Less cost and time to setup are the main attraction of FSO system. Optical equipment can be used in FSO system with some modification. Merits of FSO communication system and its application area make it a hot technology but there are some problems arising due to the attenuation caused by medium. FSO system poses some problem like attenuation in medium that can affect the performance of transmission as power loss would be there. But extra care and prestudy of the medium can guide what type of parameters to be considered before setting up the system. Many studies are going in this perspective to minimize the effect of attenuation by introducing new system design like WDM based FSO system.

Different models based on these studies are used to study the system performance before installing it at the location. This can lead to the improvement of the system. Different techniques like OFDM-FSO, WDM-FSO based system are new approach to improve the system performance with high speed and longer distance. So new techniques can be designed by combination of these and, by enhancing these techniques, system designing can be improved and the demerits of FSO system can be reduced to a minimum level.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] http://www.laseroptronics.com/index.cfm/id/57-66.htm.

[2] J. Kaufmann, "Free space optical communications: an overview of applications and technologies," in *Proceedings of the Boston IEEE Communications Society Meeting*, 2011.

[3] H. A. Willebrand and B. S. Ghuman, "Fiber optics without fiber," *IEEE Spectrum*, vol. 38, no. 8, pp. 40–45, 2001.

[4] V. Sharma and G. Kaur, "High speed, long reach OFDM-FSO transmission link incorporating OSSB and OTSB schemes," *Optik*, vol. 124, no. 23, pp. 6111–6114, 2013.

[5] R. K. Z. Sahbudin, M. Kamarulzaman, S. Hitam, M. Mokhtar, and S. B. A. Anas, "Performance of SAC OCDMA-FSO communication systems," *Optik*, vol. 124, no. 17, pp. 2868–2870, 2013.

[6] G. Shaulov, J. Patel, B. Whitlock, P. Mena, and R. Scarmozzino, "Simulation-assisted design of free space optical transmission systems," in *Proceedings of the Military Communications Conference (MILCOM '05)*, vol. 2, pp. 918–922, Atlantic City, NJ, USA, October 2005.

[7] S. Vigneshwaran, I. Muthumani, and A. S. Raja, "Investigations on free space optics communication system," in *Proceedings of*

the International Conference on Information Communication & Embedded Systems (ICICES '13), pp. 819–824, IEEE, Chennai, India, February 2013.

[8] A. K. Rahman, M. S. Anuar, S. A. Aljunid, and M. N. Junita, "Study of rain attenuation consequence in free space optic transmission," in *Proceedings of the 2nd Malaysia Conference on Photonics Telecommunication Technologies (NCTT-MCP '08)*, pp. 64–70, IEEE, Putrajaya, Malaysia, August 2008.

[9] J. Singh and N. Kumar, "Performance analysis of different modulation format on free space optical communication system," *Optik*, vol. 124, no. 20, pp. 4651–4654, 2013.

[10] N. Kumar and A. K. Rana, "Impact of various parameters on the performance of free space optics communication system," *Optik*, vol. 124, no. 22, pp. 5774–5776, 2013.

[11] H. A. Fadhil, A. Amphawan, H. A. B. Shamsuddin et al., "Optimization of free space optics parameters: an optimum solution for bad weather conditions," *Optik*, vol. 124, no. 19, pp. 3969–3973, 2013.

[12] S. A. Zabidi, W. Al Khateeb, R. Islam, and A. W. Naji, "Investigating of rain attenuation impact on free space optics propagation in tropical region," in *Proceedings of the 4th International Conference on Mechatronics (ICOM '11)*, pp. 1–6, IEEE, Kuala Lumpur, Malaysia, May 2011.

[13] S. A. Al-Gailani, A. B. Mohammad, and R. Q. Shaddad, "Enhancement of free space optical link in heavy rain attenuation using multiple beam concept," *Optik*, vol. 124, no. 21, pp. 4798–4801, 2013.

[14] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, and E. Bentley, "Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions," *Journal of Lightwave Technology*, vol. 31, no. 11, Article ID 6497447, pp. 1720–1726, 2013.

[15] Z. Ghassemlooy, J. Perez, and E. Leitgeb, "On the performance of FSO communications links under sandstorm conditions," in *Proceedings of the 12th International Conference on Telecommunications (ConTEL '13)*, pp. 53–58, IEEE, Zagreb, Croatia, June 2013.

[16] K. Rammprasath and S. Prince, "Analyzing the cloud attenuation on the performance of free space optical communication," in *Proceedings of the 2nd International Conference on Communication and Signal Processing (ICCSP '13)*, pp. 791–794, Melmaruvathur, India, April 2013.

[17] S. A. Al-Gailani, A. B. Mohammad, R. Q. Shaddad, and M. Y. Jamaludin, "Single and multiple transceiver simulation modules for free-space optical channel in tropical malaysian weather," in *Proceedings of the IEEE Business Engineering and Industrial Applications Colloquium (BEIAC '13)*, pp. 613–616, Langkawi, Malaysia, April 2013.

[18] M. Ijaz, Z. Ghassemlooy, S. Rajbhandari, H. Le Minh, J. Perez, and A. Gholami, "Comparison of 830 nm and 1550 nm based free space optical communications link under controlled fog conditions," in *Proceedings of the 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP '12)*, pp. 1–5, IEEE, Poznan, Poland, July 2012.

[19] A. Z. Suriza, I. M. Rafiqul, A. K. Wajdi, and A. W. Naji, "Effects of rain intensity variation on rain attenuation prediction for Free Space Optics (FSO) links," in *Proceedings of the International Conference on Computer and Communication Engineering (ICCCE '12)*, pp. 680–685, IEEE, Kuala Lumpur, Malaysia, July 2012.

[20] S. Bloom, E. Korevaar, J. Schuster, and H. Willebrand, "Understanding the performance of free-space optics," *Journal of Optical Networking*, vol. 2, no. 6, pp. 178–200, 2013.

[21] V. Sharma and G. Kaur, "Modelling of OFDM-ODSB-FSO transmission system under different weather conditions," in *Proceedings of the 3rd International Conference on Advanced Computing & Communication Technologies (ACCT '13)*, pp. 154–157, IEEE, Rohtak, India, April 2013.