Webology (ISSN: 1735-188X)
Volume 18, Number 5, 2021

Free Space Optical Communication System -A Comprehensive Review

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Abstract— In this paper the complete comprehensive analysis of free space optical communication system has been done. The free space optical communication system is a modernized technology where superficial environment acts as transmission medium between transmitter & receiver and for successful transmission of optical signals both the source and the destination should be in LOS. The outer environment, which acts as a channel, can be any outer space, it can be vacuum or modestly air. The FSO system provides attractive bandwidth enhancement with unlicensed bands optical communication spectrum. The transmission & reception in FSO system is mostly rely on the outer channel i.e. the external environment because the presence of external elements like rain (light, medium, heavy), fog, snow, etc. The reliability of the FSO link is immensely dependent on outer or superficial weather conditions that attenuate the optical signal strength travelling in free space. The strength of optical signals gets weakened with the rising or surging of bad weather conditions. For numerous sources wavelength multiplexers can be used which combines the various wavelength optical signals into single source and similarly at destination wavelength de-multiplexers can be used which separates the combined wavelength optical signals. The other aspects which affects the transmission system may encompass the type of light source with particular wavelength of decided band spectrum, modulation formats, amount of data to be send, type of photodetector used etc. The amount of data to be transmitted on particular wavelength is to be either in Mbps or Gbps. The study essentially focuses on the various weather conditions which acts like an obstacle in the FSO system. The weather conditions and amount of data combined are the main consideration for deciding the travelling distance of optical signals from transmitter to receiver. By optimization the FSO system, it maximizes the distance between source and destination by reducing the Bit Error Rate (BER) in output signal. The final conclusion of FSO system can be checked by Q-Factor i.e. the quality of signals and by analyzing the Eye diagrams using Eye analyzer.

Keywords— Free space optical (FSO), Line of sight (LOS), Quality factor (Q-Factor), Megabits per second (Mbps), Giga bits per second (Gbps).

I-INTRODUCTION

The Free space (vacuum or air) optical communication or optical wireless system is a light communicate technology that uses light waves propagating in outer space for transmission of data for telecommunications or for computer networking[1][2]. Here the "free space" means it can be air, it can be outer space, it can be vacuum or somewhat similar media. This dissimilar with using wires such as optical fiber cable or any other optical link[3]. The technology is beneficial where the physical links are impractical due to high costs of equipments or other considerations[4]. The FSO network can be used as information connections among the networks like local area networks (LAN), wide area networks (WAN) and wireless local loops (WLL). The FSO system provides the various networks with unrestricted spectrum, simple placement of network, free external different radio signals interference and high data rate transmission in Gbps[5]. The FSO system promises low power consuming equipment's, light weight equipment's and tools, small sizes of parts of system, transfer of high data rate and low budgets. The reliability of FSO link is badly affected by the different types of weather conditions often known as external environmental turbulence that damages the link performance very badly which leads to poor Q-Factor and BER[6][7][8][9]. These types of external conditions include light rainfall, heavy rainfall, snowfall, dense fog, dark smog and in summer the hot climate[3][10][11][12][13]. In addition to weather conditions the small scale earthquakes, transmitter & receiver misalignments and the high speed wind may also lead to light beam vibrations, which is also termed as pointing error impairment[10][14].

II-REVIEW OF LITERATURE

The FSO technology is easily installable. Now this accent makes it applicable for interlocking the various LAN segments to connect two buildings apart, offices, campuses etc.[15]. The FSO systems have the capability to drive at higher power levels of transmitter for longer distance. The overall FSO system design should be drive at low power consumption as this reduces the maintenance costs[15]. The FSO systems should have the capacity to drive over extensive range of weather temperatures and outer environmental conditions and the performance of FSO system shows the results according to the conditions which are applicable[16]. The FSO system can be used as a backup link as temporary or permanent solution if failure of transmission and reception of signals occurs through fiber link. The FSO link can be used to communicate between the two buildings, two offices, in educational campuses, across river areas, mountain areas. It can also be used between two ships in the ocean or sea[17]. Since the FSO technology is a well-protected system it can join huge areas securely with network preparation and positioning time. Therefore, the protected network is appropriate for many military applications[18].

The figure 1 is a basic model of FSO communication system that is divided in three sections which includes transmitter, medium and receiver. All the components used in FSO system completely covers the three sections shown in the figure 1.

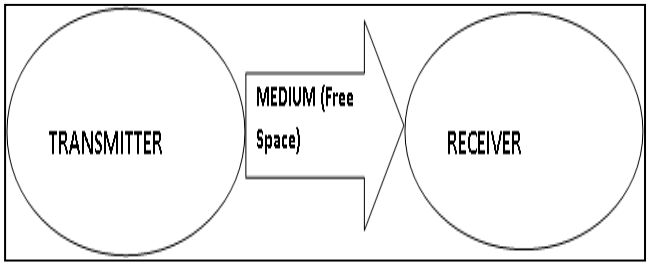

Figure 1: Basic FSO communication model

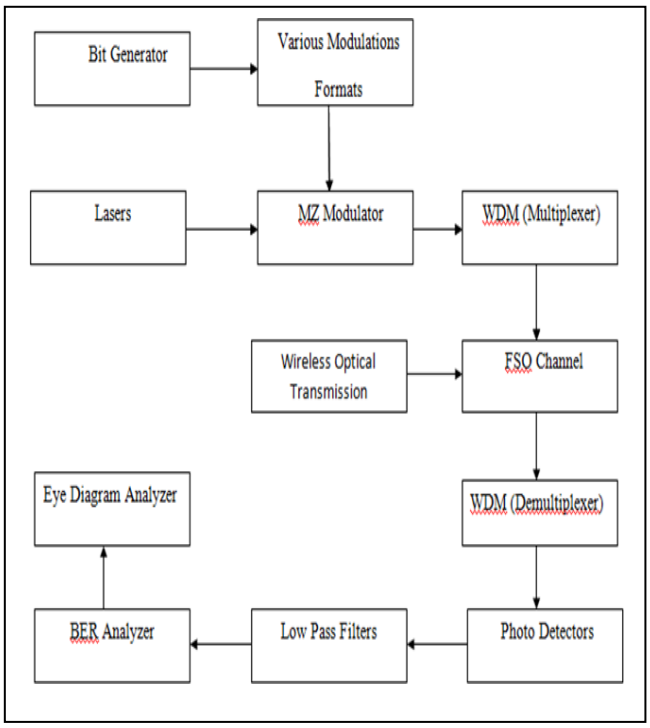

Figure 2. Block Diagram of FSO communication system (Transmitter, Medium, and Receiver)

The figure 2 explains the complete block diagram of FSO communication system with components attach in the different sections of block diagram. The transmitter section comprises of Pseudo random bit sequence generator (PRBS) which generates the data in form of bits either in Mbps of Gbps, different modulation formats, lasers which sends the optical signal and Mach Zehnder modulator which combines the modulation formats and laser wavelength. The combined multiple signals from modulator consist of data can be multiplexed using wavelength division multiplexer (WD-M) for transmission.

The medium in FSO signal transmission is free space provided the transmitter and the receiver must be in line of sight (LOS).

The receiver section includes wavelength division demultiplexer (WD-DM) which demultiplexes the received optical signals consists of data. Further, these signals pass through the photodiode (PIN) which converts the signal and electrical signals are obtained. These signals further pass through low pass filter (LPF) preferably Bessel Low pass filter and at last the signals can be checked and analyzed by quality factor of signal. The minimum the error in the signal, the better is the overall communication. The Eye diagram visually clarifies the successful transmission.

The block diagram in figure 3 explains the working principle of FSO transmission from transmitter to receiver and the medium ought to be in line of sight between source and destination. The free space optical (FSO) system transmits eye-safe optical beams of certain optical communication band from telescopic transmitter using low power laser beams. The transmission rays of light in FSO systems are done by LEDs or lasers focused on extremely sensitive photo detector receivers through free space transmission medium[19]. These photo detector receivers are telescopic receiver lenses that able to collect the photons to convert them and further transmit the data in form of bits containing the different messages in form of audio signal, video signals, images, EM signals or secret data etc. The

available FSO systems offer higher data rate measurements in the range from Mbps to Gbps and with this amount the complete wireless or free space optical (FSO) communication systems can function over longer distances say in kilometers depends upon weather conditions. The appropriate line of sight (LOS) between the starting point and the ending point [20] and with required transmitting power that is not harmful to human beings, the optical transmission and reception is possible.

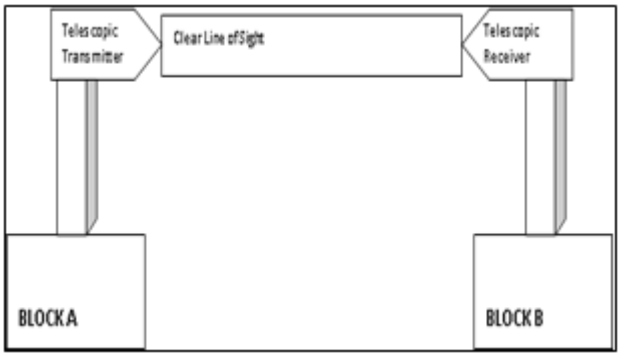

Figure 3. Block Diagram of Working Principle of FSO system.

III- REVIEW OF PREVIOUS YEARS RESEARCH WORK

Barsimantov and Nikulin (2011) proposed that free space optical transmission is a noticeable technology that offers high data rates of transmission and resistance to congestion of data. The lab view software is analyzed for the various parameters, used for setup FSO transmission system. The various proposed parameters, external factors, connection range, bit rates etc. used in the received signal power. The recital of FSO system is analyzed using FSO transmission equipment. The three adaptive system of algorithms, which includes gradient optimization, step optimization and step division optimization were tested using the above set up[1].

Gregory and Badri-Hoeher (2011) proposed that the data communication in external environmental conditions is the main challenging problem that has to be resolved to create a transmission system to be fit for business usage. The objective of the FSO system is mainly to approach the carrier period. The model like Common Fog model and Common Rain Model has been set up to investigate system impact as they are based on computable quantities. These measurements are taken at some distance of maritime pathway. It investigated that the relationship between FSO connection and different external environment parameters showed that changes like the production of fog in cold weather could be handled by checking the dew point temperature without the necessity of other necessary material[11]

Wang et al. (2012) proposed the rapid synchronization method so that reduction in handshake bandwidth requirement is demonstrated. The system is designed for terrestrial FSO system whose media is external environment. The experimental set up is FPGA based full duplex point to point system consist of terminals (transmitter and receiver). The auto power control loop prevents the output power drift due to change in temperature and signal amplifier is used to transform the current of PIN to voltage. It explained the hardware structure of FSO system, the rapid synchronization method is generated using sampling clock. Further, the multi-phase sampling has been done which is practical in data sampling method[21].

Chow et al. (2013) proposed the result of light signal various noises to the recital of the optical wireless channel. It also demonstrated the light transmission to lessen the light signal noise so that there is no filtering of optical signal. The Generator with arbitrary waveform generated the PRBS with NRZ. The shining light from the lamp is intentionally located near the receiver of system which worsened the optical signal quality from the communication connection. It demonstrated the study of various coding for light signal communication to lessen the hidden noises. The given coding improves the signal quality and hence provides the synchronization, so it is beneficial for transmission of signal[19].

Khalighi and Uysal (2014) proposed the outdoor terrestrial wireless connection that operates in infrared bands. The FSO transmission systems are used for high rate data transmission between the source and destination over distance that goes for few kilometers also. Using optical communication software the FSO connection can be exaggerated due to various factors such as harsh turbulence in connections related to strong winds with dry climate and strong dwindling in dense fog. These above factors can result in regular connection failures. It explained FSO system that must be measured as an important component for various complex connections. The optimum bandwidth for the FSO communication systems can be used in many applications and therefore it is a powerful alternative as corresponding to the existing radio wireless systems[22].

Zhu and Cheng (2015) proposed the FSO communication with a solo relay assist situation. The new system exploits the FSO channel which is linked to the connection distance. It is shown that the logically and numerically the error rates of new design can provide advanced multiplicity. Using mathematical analysis the intensity of FSO system is calculated with the help of channel modeling. With the new helpful transmission schemes the traditional IADF scheme and improved adaptive decode a forward IADF designs are introduced to minimize the error rates and to increase the connection area. It explained the supportive scheme for single dispatch assisted FSO system. It is verified that IADF can supplied the enhanced performance for practical communication power area[23].

Kaushal and Kaddoum (2015) proposed the various impairments that poses a serious challenge to FSO transmission system. The Adaptive Optics system is used to diminish the effect of outer atmospheric disorder in the path of transmission. It demonstrated that an incredible growth in internet traffic has been done in the recent years, due to optical communication. A huge blaze up in information area is driving the information business to higher data rates[24].

Mignani et al. (2016) proposed the performance of Raman spectroscopy has been checked, and evaluated using optical filters. The Raman Spectroscopy setup is used to relate the monochromatic light to a molecule that exchanges the energy. The light scattered with an unaltered wavelength, of a small portion of the order of 10–6 of optical signal. It demonstrated a good prospective for the non-destructive and quick estimation of honey created in the constituency of Calabria[25].

Sharma et al. (2016) proposed an indoor FSO communication with fixed transmitter and moving receiver for a specified area that provides the good performance with improved SNR for significant changes in performance of key parameters[26].

Jain and Mehra (2017) evaluated the connection which is dependent on outer different weather conditions which dulls the signal power and its strength. The results are obtained from the experimental set up by using Optisystem software, and got the results in wavelength bands such as

short band, long band and conventional band. The performance of FSO system connection has been evaluated for three optical bands such as short band, long band and conventional band. It has also been observed experimentally that for low diminishing condition three bands can be used simultaneously for multiplexing operations[6].

Wang et al. (2017) proposed the spread communication system linked with optical fiber cable and can replicate the communication at random areas. With the help of above method, the performance tests for the two optical terminals can be checked. The communication system comprises of a double channel telescope system with a void space and a shielded optical fiber cable segment. With above simulations the system can generate the data at a rate of 155 Mbps. It evaluated dynamic tentative results that showed the absolute simulation correctness of the optical signal communication is 4.7 percent and the maximum bit error is less than 6.5 percent. The above mentioned percentages can be ignored when the system is compared to the normal connection redundancy[27].

Li et al. (2018) proposed that evaluation is done for designed procedure permits that the user with constructive channel conditions. The mathematical model with the help of math work software suggests the system description, system model, and channel model for cooperative communication. It suggested the novel cooperative transmission system that is evaluated by taking into account the non-broadcast characteristics of FSO[28].

Huang et al. (2018) proposed the FSO communication system of a high speed of data to be transferred. This study provides the transmit of sky scraping speed signal mixed with different wavelengths that are modulated with dissimilar signals. The experimental set up of the projected multiplexing based FSO communication the system that transmits the fusion signals. The TOBPF, used as a device cannot challenge the manipulation of adjoining channels completely as in FSO transmission system the neighboring channels can traverse the TOBPF with negligible remaining parts. It studied that the multiplexing based FSO transmission system that transmits the high speed fusion signals in which different signals that are mixed using one beam optical communication system. The performance of the projected transmission system with over 100 m free space connection is checked by using bit error rates and eye diagrams of experimental set up[29].

Mahajan et al.(2019) evaluated the result of transmitters and receivers used to check the performance of projected, FSO communication system, and further the system is evaluated under different weather conditions. The optisystem, software information is generated by the production of data rate in terms of Gbps that is encoded, and optical signal is matched with the help of Mach Zehnder Modulator (MZM) using conventional Band wavelength. It demonstrated the proposed FSO interface that evaluated Q-factor, Bit Error Rate and the eye diagrams. One transmitter and one receiver is used in the set up for taking data rate[7].

Li et al. (2019) proposed the recital of two spread systems over the free space optical connection and radio frequency connection. The source node communicates with the spread point over the FSO connection with heterodyne detection and supports frequent users during non-orthogonal multiple access techniques. The FSO RF double hop spread experimental set up is done that showed the relationship of NOMA and OMA in the double bound system[30].

Sun et al. (2020) proposed that marine wireless optical communication has attracted attention in various seawater actions, because of its superior bandwidth when it is compared to sound and radio frequency technologies. The Omni directional photo detector using optical communication software is an future age of the Internet of Undersea things development on the transmitter side that have enabled the transmission in Gbps in submerged environments. It suggested that the investigation in practical submerged optical communication deployments. The example is the physical layer of undersea communication, which still requires substantial efforts before the system construction[31].

Ji et al. (2020) proposed that FSO channel which accesses the code division multiple access with optical signals. Further the reliability and security of system is investigated for the weak and strong turbulence circumstances. The experimental set up showed that the time multiplicity system is larger than the non-time multiplicity system in light and bulky turbulence environments which indicates that optical code division multiple access- time multiplicity, may improve the physical layer security of FSO system channel. It studied the design and demonstrated an experimental system of FSO system using code division multiple access for optical signals with time multiplicity reception. The bit error rate of the genuine user is measured and the confidentiality capacity of the system is achieved[32].

Al-Gailani et al. (2021) proposed the next generation optical technology for flexible communication from source to destination. The fundamental concepts in FSO system includes the architecture that comprises of light beams with WDM technology and can be used as a future technology in the field of communication. It is also studied that bad weather conditions acts as attenuation in the propagation of signal from one end to another end[33].

TABLE I. COMPARATIVE ANALYSIS OF RADIO FREQUENCY AND FREE SPACE OPTICAL SYSTEMS[31][35].

Types of Systems	**Distance**	**Security**	**Band**
Radio Frequency (RF) system	Suitable for the long distance communication[35]	Lower security condition	Frequency band from few KHz to 1 GHz.
Free Space Optical (FSO) system	Suitable where line of sight (LOS) is not a problem for the transmission link between source and destination and up to only few kilometers depending upon parameters[34][36][37]	Enhanced security conditions	Various optical bands i.e. O-band, E-band, S-band, C-band, L-band etc.

The table I provide the data for radio frequency system and free space optical communication system. The study from the data in the table I concludes that the optical communication whether wired or wireless provides a secure way of transmitting that data without any delay or loss of data in mid-way. The bandwidth of optical communication is also large as compared to radio frequency system.

TABLE II. COMPREHENSIVE ANALYSIS OF PREVIOUS RESEARCH WORK WITH THEIR PUBLICATION YEARS

Journal/Conference and Reference No.	Author	Communication type	Bit Rate used	Wavelength Band used
JOCN[38]	Barsimantov and Nikulin	Free space	1 Gbps	C –Band Distance less than 1 km.
ICSOS[39]	Gregory and Badri-Hoeher	Free space	Less than 200 Mbps	C-band Distance Up to 10 km
ICCECT[21]	Wang et al.	Free space	100 Mbps	C-band
Optical Society of America[40]	Lin et al.	Visible light Communication	500 Mbps	Not Given
IEEE Photonics [41]	Chow et al.	Optical Wireless	2.5 Mbps	Not Given
IEEE Photonics [42]	Ijaz et al.	Free Space	Not Given	C-Band with less than 500 m to 50 m
IEEE Communications[22]	Khalighi and Uysal	Free Space	10 Gbps	C-Band with Distance few 100 m
ICECS[20]	Srikanth et al.	Free Space	2.5 Gbps	C-Band with Distance up to 2 km
IJARCCE[43]	Gursale et al.	Free Space	100 Mbps to 2.5 Gbps	C-Band and Distance only in few meters
IEEE Photonics Journal[44]	Zou and Xu	Free space	Not Given	Distance 100 m to 1 km
ICCE[6]	Jain and Mehra	Free Space	Varies and up to 10 Gbps	C-band and L-Band Distance less than 500 m
IEEE Communications Surveys[45]	Kaushal and Kaddoum	Free Space	1-3 Gbps	C-Band
IEEE Photonics [29]	Huang et al.	Free Space	Variable in Gbps with WDM	Distance 100m
IEEE Communications[28]	Li et al.	Free Space	Not Given	C-Band and Distance Up to 2 km
JOCN[30]	Li et al.	Free Space/RF Links	Not Given	Not Given

ICSPIN[7]	Mahajan et al.	Free Space	Variable in Gbps	C-Band Distance Up to 1 km
IEEE Photonics[32]	Ji et al.	Free Space	Up to 10 Gbps	C-Band with distance merely 1.8 m
IEEE Access[33]	Al-Gailani et al.	Free Space	1-1.2 Gbps	C-Band with distance 1.2 km

The study in table II shows that in free space the system cannot work for longer distance on increasing the data rate between transmitter and receiver. The research work by authors focused mainly on C- Band for the optical communication system.

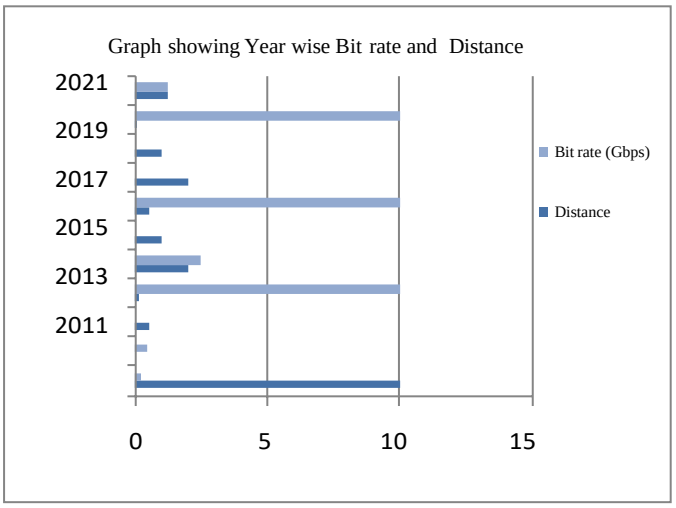

Figure 4. Graphical representation of distance (km) and bit rate (Gbps) in last decade.

The graph in figure 4 represents the decade publication of research work and the distance travel by the light source for the particular bit rate. The graph in figure 4 with given data in table II clearly indicates that if the distance is of few meters then more data rate in form of bits per sec would be travelled to the receiver. On the contrary, if the distance travelled by the system is larger i.e. in kilometers then lower data rate in form of bits per sec would be travelled up to the receiver. The other factors which lower the data rate are atmospheric turbulence i.e. the external environmental conditions.

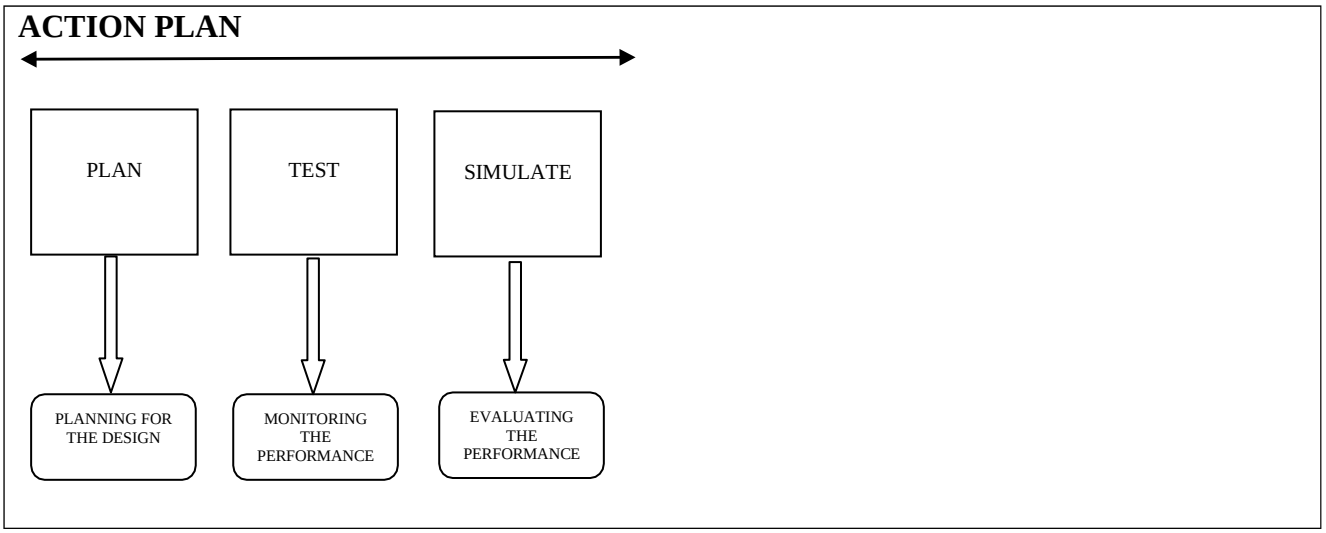

Figure 5: Action plan to evaluate the optical signal from transmitter to receiver.

The action plan in figure 5 helps the researcher to understand the particulars about the certain problem. Accordingly, to the problem, the required planning is done for appropriate designing. The designed model is then monitored for the various parameters used as an input to the design and at last, the performance of the designed system is evaluated to get the improved results.

A. Applications

The FSO systems can easily installable in almost any type of areas provided there should be proper Line of Sight (LOS) between the starting point and the ending point (destination)[35][46]. This accent makes it appropriate for joining various LAN segments to attach two buildings apart, campuses, offices etc.[17]. The FSO links usually used by the various wireless service agencies regarding broadcast or communication purposes and it is license free to use the free space system as it is obligatory in event of microwave bands[22]. The FSO set ups are used to arrange a Storage Area Network (SAN) which delivers an access to the merged block level data storages. The FSO link can also be pertinent in providing an alternate set up in case of catastrophe of transmission through fiber optic link and is advantageous in WAN links also where it supports high speed data facilities[4]. The FSO set up can be installed in slighter time and assembly of the new networks can be easily done. Further it provides an immediate service to clients when their fiber structure and network is being installed which needs some specific time to complete the system[37]. The FSO technology is best suited for transporting the traffic of cellular mobiles from antenna pillars to other system like PSTN with well-maintained speed and required data rate. The speed of transmission of data would rise by using the new technique[29]. The FSO system is a safe and sound network with another advantage i.e. undetectable system. Therefore, it can be used for communicating secret messages also. It can link huge areas with smaller time and the deployment time is also less. For all these features it is perfect for use in defense related applications[18].

B. Merits

The Installation is easy and it takes within few hours to install at normal locations in contrast to optical fiber cables which needs longer process and more man power to install[47]. The speed of optical signal transmitted is extremely fast as compare to radio frequency signals. The FSO system is a straight headlong positioning system i.e. Line of Sight (LOS)[48][49]. The FSO also free from spectrum license among the various users on using multiplexer[46]. The FSO system is a secure system for transmission

and reception of data from optical signals, so no security system updation is needed[22]. The error rate in FSO system is very low as because of secure system. The FSO system is invulnerable to radio frequency interference. Due to the low power usage, heat produce during transmission is almost negligible in FSO system..

C. Limitations

In FSO system the obstructions may come like flying birds, towers, trees, buildings etc. can temporarily block the optical signal and network. The FSO system is highly affected by different weather conditions like aerosols, dust, sandstorm, thunder storm, fog, rainfall, snow etc.[6][7]. Due to these bad or sometimes severe weather conditions, the attenuation like absorption, scattering etc. affects to the optical transmission [50][51][52][53][54].

CONCLUSION

The marvelous progress and advancement in the free space communication field delivers the large bandwidth and huge capacity to furnish the existing and upcoming requirements. The study in field of free space optical (FSO) system shows that impact of weather conditions creates the attenuation which limits the performance of communication system. The effect of attenuation can be minimized by varying the numerous parameters used in the FSO communication system for the successful transmission from the source and reception at the destination.

REFERENCES

[1] O. Barsimantov and V. V. Nikulin, “Adaptive Optimization of a Free Space Laser Communication System Under Dynamic Link Attenuation,” J. Opt. Commun. Netw., vol. 3, no. 3, p. 215, Mar. 2011, doi: 10.1364/JOCN.3.000215.

[2] S. Dubey, S. Kumar, and R. Mishra, “Simulation and performance evaluation of free space optic transmission system,” 2014 Int. Conf. Comput. Sustain. Glob. Dev. INDIACom 2014, pp. 850–855, 2014, doi: 10.1109/IndiaCom.2014.6828083.

[3] A. Malik and P. Singh, “Free Space Optics: Current Applications and Future Challenges,” Int. J. Opt., vol. 2015, pp. 1–7, 2015, doi: 10.1155/2015/945483.

[4] V. Sharma and Sushank, “High speed CO-OFDM-FSO transmission system,” Optik (Stuttg)., vol. 125, no. 6, pp. 1761–1763, Mar. 2014, doi: 10.1016/j.ijleo.2013.10.010.

[5] G. Soni and V. K. Banga, “Performance analysis of Free Space Optics link at different data rates,” in 2014 International Conference on Contemporary Computing and Informatics (IC3I), Nov. 2014, pp. 1251–1255, doi: 10.1109/IC3I.2014.7019625.

[6] D. Jain and R. Mehra, “Performance analysis of Free Space Optical communication system for S, C and L band,” 2017 Int. Conf. Comput. Commun. Electron. COMPTELIX 2017, pp. 183–189, 2017, doi: 10.1109/COMPTELIX.2017.8003961.

[7] S. Mahajan, D. Prakesh, and H. Singh, “Performance Analysis of Free Space Optical System under Different Weather Conditions,” 2019 6th Int. Conf. Signal Process. Integr. Networks, SPIN 2019, pp. 220–224, 2019, doi: 10.1109/SPIN.2019.8711687.

[8] X. Li, X. Zhao, P. Zhang, and S. Tong, “BER performance of FSO communication system with differential signaling over correlated atmospheric turbulence fading,” China Commun., vol. 17, no. 4, pp. 51–65, 2020, doi: 10.23919/JCC.2020.04.006.

[9] M. S. Awan, E. Leitgeb, R. Nebuloni, F. Nadeem, and M. S. Khan, “Optical wireless ground- link attenuation statistics of fog and snow conditions,” in 2009 IFIP International Conference on Wireless and Optical Communications Networks, Apr. 2009, pp. 1–5, doi: 10.1109/WOCN.2009.5010571.

[10] H. AlQuwaiee, I. S. Ansari, and M.-S. Alouini, “On the Performance of Free-Space Optical Communication Systems Over Double Generalized Gamma Channel,” IEEE J. Sel. Areas Commun., vol. 33, no. 9, pp. 1829–1840, Sep. 2015, doi: 10.1109/JSAC.2015.2432529.

[11] M. Gregory and S. Badri-Hoeher, “Characterization of maritime RF/FSO channel,” 2011 Int. Conf. Sp. Opt. Syst. Appl. ICSOS’11, no. 1, pp. 21–27, 2011, doi: 10.1109/ICSOS.2011.5783672.

[12] I. I. Kim, B. McArthur, and E. J. Korevaar, “<title>Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications</title>,” Feb. 2001, pp. 26–37, doi: 10.1117/12.417512.

[13] N. Kumar and A. K. Rana, “Impact of various parameters on the performance of free space optics communication system,” Optik (Stuttg)., vol. 124, no. 22, pp. 5774–5776, Nov. 2013, doi: 10.1016/j.ijleo.2013.04.062.

[14] A. A. Farid and S. Hranilovic, “Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors,” J. Light. Technol., vol. 25, no. 7, pp. 1702–1710, Jul. 2007, doi: 10.1109/JLT.2007.899174.

[15] H. A. Willebrand and B. S. Ghuman, “Fiber optics without fiber,” IEEE Spectr., vol. 38, no. 8, pp. 40–45, Aug. 2001, doi: 10.1109/6.938713.

[16] S. Jiang et al., “Performance Analysis of Space-Diversity Free-Space Optical Links Over Exponentiated Weibull Channels,” IEEE Photonics Technol. Lett., vol. 27, no. 21, pp. 2250–2252, Nov. 2015, doi: 10.1109/LPT.2015.2458321.

[17] R. K. Z. Sahbudin, M. Kamarulzaman, S. Hitam, M. Mokhtar, and S. B. A. Anas, “Performance of SAC OCDMA-FSO communication systems,” Opt. - Int. J. Light Electron Opt., vol. 124, no. 17, pp. 2868–2870, Sep. 2013, doi: 10.1016/j.ijleo.2012.08.067.

[18] G. Shaulov, J. Patel, B. Whitlock, P. Mena, and R. Scarmozzino, “Simulation-Assisted Design of Free Space Optical Transmission Systems,” in MILCOM 2005 - 2005 IEEE Military Communications Conference, pp. 1–5, doi: 10.1109/MILCOM.2005.1605797.

[19] C. W. Chow, C. H. Yeh, Y. F. Liu, and P. Y. Huang, “Mitigation of optical background noise in light-emitting diode (LED) optical wireless communication systems,” IEEE Photonics J., vol. 5, no. 1, p. 7900307, 2013, doi: 10.1109/JPHOT.2013.2238618.

[20] S. Srikanth, P. Sriram, and D. S. Kumar, “Performance analysis of OFDM employing free space optical communication system,” in 2015 2nd International Conference on Electronics and Communication Systems (ICECS), Feb. 2015, pp. 70–74, doi: 10.1109/ECS.2015.7125002.

[21] H. Wang, J. Guo, T. Wang, Q. Zhang, and J. Shao, “Physical Layer Design for Free Space Optical Communication,” in 2012 International Conference on Control Engineering and Communication Technology, Dec. 2012, pp. 978–981, doi: 10.1109/ICCECT.2012.106.

[22] 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.

[23] B. Zhu, J. Cheng, and L. Wu, “A distance-dependent free-space optical cooperative communication system,” IEEE Commun. Lett., vol. 19, no. 6, pp. 969–972, 2015, doi: 10.1109/LCOMM.2015.2420612.

[24] and C. E. H. Kaushal, G. Kaddoum, “Free Space Optical Communication : Challenges and Mitigation Techniques,” pp. 1–28, 2015.

[25] A. Grazia Mignani, L. Ciaccheri, A. A. Mencaglia, R. Di Sanzo, S. Carabetta, and M. Russo, “Dispersive Raman Spectroscopy for the Nondestructive and Rapid Assessment of the Quality of Southern Italian Honey Types,” J. Light. Technol., vol. 34, no. 19, pp. 4479–4485, Oct. 2016, doi: 10.1109/JLT.2016.2539550.

[26] R. Sharma, M. Aggarwal, and S. Ahuja, “Performance analysis of indoor FSO communication systems under receiver mobility,” Proc. - 2016 Int. Conf. Micro-Electronics Telecommun. Eng. ICMETE 2016, pp. 652–657, 2016, doi: 10.1109/ICMETE.2016.61.

[27] J. Wang, G. Wang, R. Bai, B. Li, and Y. Zhou, “Ground Simulation Method for Arbitrary Distance Optical Transmission of a Free-Space Laser Communication System Based on an Optical Fiber Nanoprobe,” J. Opt. Commun. Netw., vol. 9, no. 12, p. 1136, Dec. 2017, doi: 10.1364/JOCN.9.001136.

[28] R. Li, J. Zhang, and A. Dang, “Cooperative System in Free-Space Optical Communications for Simultaneous Multiuser Transmission,” IEEE Commun. Lett., vol. 22, no. 10, pp. 2036–2039, 2018, doi: 10.1109/LCOMM.2018.2865734.

[29] X.-H. Huang et al., “WDM Free-Space Optical Communication System of High-Speed Hybrid Signals,” IEEE Photonics J., vol. 10, no. 6, pp. 1–7, Dec. 2018, doi: 10.1109/JPHOT.2018.2881701.

[30] R. Li, T. Chen, L. Fan, and A. Dang, “Performance Analysis of a Multiuser Dual-Hop Amplify-and-Forward Relay System With FSO/RF Links,” J. Opt. Commun. Netw., vol. 11, no. 7, p. 362, Jul. 2019, doi: 10.1364/JOCN.11.000362.

[31] X. Sun et al., “A Review on Practical Considerations and Solutions in Underwater Wireless Optical Communication,” J. Light. Technol., vol. 38, no. 2, pp. 421–431, 2020, doi: 10.1109/JLT.2019.2960131.

[32] J. Ji, B. Wu, J. Zhang, M. Xu, and K. Wang, “Design and Investigation of 10 Gb/s FSO Wiretap Channel Using OCDMA Time-Diversity Reception,” IEEE Photonics J., vol. 12, no. 3, p. 1, 2020, doi: 10.1109/JPHOT.2020.2985747.

[33] S. A. Al-Gailani et al., “A Survey of Free Space Optics (FSO) Communication Systems, Links, and Networks,” IEEE Access, vol. 9, pp. 7353–7373, 2021, doi: 10.1109/ACCESS.2020.3048049.

[34] X. Liu, “Free-space optics optimization models for building sway and atmospheric interference using variable wavelength,” IEEE Trans. Commun., vol. 57, no. 2, pp. 492–498, Feb. 2009, doi: 10.1109/TCOMM.2009.02.070089.

[35] G. Aldabbagh, S. T. Bakhsh, N. Akkari, S. Tahir, S. Khan, and J. Cioffi, “Distributed dynamic load balancing in a heterogeneous network using LTE and TV white spaces,” Wirel. Networks,

vol. 21, no. 7, pp. 2413–2424, Oct. 2015, doi: 10.1007/s11276-015-0921-4.

[36] Y. Kaymak, S. Fathi-Kazerooni, and R. Rojas-Cessa, "Indirect Diffused Light Free-Space Optical Communications for Vehicular Networks," IEEE Commun. Lett., vol. 23, no. 5, pp. 814–817, 2019, doi: 10.1109/LCOMM.2019.2904031.

[37] C. H. Yeh, Y. R. Xie, C. M. Luo, and C. W. Chow, "Integration of FSO Traffic in Ring-Topology Bidirectional Fiber Access Network with Fault Protection," IEEE Commun. Lett., vol. 24, no. 3, pp. 589–592, 2020, doi: 10.1109/LCOMM.2019.2960221.

[38] O. Barsimantov and V. V. Nikulin, "Adaptive optimization of a free space laser communication system under dynamic link attenuation," J. Opt. Commun. Netw., vol. 3, no. 3, pp. 215–222, 2011, doi: 10.1364/JOCN.3.000215.

[39] M. Gregory and S. Badri-Hoeher, "Characterization of maritime RF/FSO channel," in 2011 International Conference on Space Optical Systems and Applications (ICSOS), May 2011, pp. 21–27, doi: 10.1109/ICSOS.2011.5783672.

[40] W.-Y. Lin et al., "10m/500Mbps WDM visible light communication systems," Opt. Express, vol. 20, no. 9, p. 9919, Apr. 2012, doi: 10.1364/OE.20.009919.

[41] C. W. Chow, C. H. Yeh, Y. F. Liu, and P. Y. Huang, "Mitigation of Optical Background Noise in Light-Emitting Diode (LED) Optical Wireless Communication Systems," IEEE Photonics J., vol. 5, no. 1, pp. 7900307–7900307, Feb. 2013, doi: 10.1109/JPHOT.2013.2238618.

[42] M. Ijaz, Z. Ghassemlooy, J. Perez, V. Brazda, and O. Fiser, "Enhancing the Atmospheric Visibility and Fog Attenuation Using a Controlled FSO Channel," IEEE Photonics Technol. Lett., vol. 25, no. 13, pp. 1262–1265, Jul. 2013, doi: 10.1109/LPT.2013.2264046.

[43] G. V M, P. S S, and K. A B, "Enhancement in Free Space Optical Communication: A Review," IJARCCE, vol. 5, no. 12, pp. 65–71, Dec. 2016, doi: 10.17148/IJARCCE.2016.51213.

[44] D. Zou and Z. Xu, "Information Security Risks Outside the Laser Beam in Terrestrial Free-Space Optical Communication," IEEE Photonics J., vol. 8, no. 5, pp. 1–9, 2016, doi: 10.1109/JPHOT.2016.2607699.

[45] H. Kaushal and G. Kaddoum, "Optical Communication in Space: Challenges and Mitigation Techniques," IEEE Commun. Surv. Tutorials, vol. 19, no. 1, pp. 57–96, 2017, doi: 10.1109/COMST.2016.2603518.

[46] T. Siegel and S. Ping, "Investigations of Free Space Optical Communications Under Real - World Atmospheric Conditions," Wirel. Pers. Commun., vol. 116, no. 1, pp. 475–490, 2021, doi: 10.1007/s11277-020-07724-1.

[47] C. H. Yeh, C. W. Chow, C. S. Gu, B. S. Guo, Y. J. Cheng, and J. H. Chen, "Performance analysis of free space optical communication traffic integrated with passive optical network," Electron. Lett., vol. 54, no. 21, pp. 1228–1229, Oct. 2018, doi: 10.1049/el.2018.5559.

[48] M. Khan and M. Yuksel, "Maintaining a free-space-optical communication link between two autonomous mobiles," in 2014 IEEE Wireless Communications and Networking Conference (WCNC), Apr. 2014, pp. 3154–3159, doi: 10.1109/WCNC.2014.6953020.

[49] G. G. Lema, "Free space optics communication system design using iterative optimization," J.

Opt. Commun., Jul. 2020, doi: 10.1515/joc-2020-0007.

[50] H. A. Fadhil et al., “Optimization of free space optics parameters: An optimum solution for bad weather conditions,” Optik (Stuttg)., vol. 124, no. 19, pp. 3969–3973, Oct. 2013, doi: 10.1016/j.ijleo.2012.11.059.

[51] A. . Rahman, M. . Anuar, S. . Aljunid, and M. . Junita, “Study of rain attenuation consequence in free space optic transmission,” in 2008 6th National Conference on Telecommunication Technologies and 2008 2nd Malaysia Conference on Photonics, Aug. 2008, pp. 64–70, doi: 10.1109/NCTT.2008.4814239.

[52] J. Singh and N. Kumar, “Performance analysis of different modulation format on free space optical communication system,” Optik (Stuttg)., vol. 124, no. 20, pp. 4651–4654, Oct. 2013, doi: 10.1016/j.ijleo.2013.02.014.

[53] S. Vigneshwaran, I. Muthumani, and A. S. Raja, “Investigations on Free space optics communication system,” in 2013 International Conference on Information Communication and Embedded Systems (ICICES), Feb. 2013, pp. 819–824, doi: 10.1109/ICICES.2013.6508300.

[54] S. A. Zabidi, M. R. Islam, W. Al Khateeb, and A. W. Naji, “Investigating of rain attenuation impact on Free Space Optics propagation in tropical region,” in 2011 4th International Conference on Mechatronics (ICOM), May 2011, pp. 1–6, doi: 10.1109/ICOM.2011.5937121.