International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 6 Issue 4, May-June 2022 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

A Detailed Discussion of Free Space Optical Communication Systems: A Review

Shivam Vats, Arvind Kumar, Amit Chaudhary, Richa Tejpal

Department of Electronics & Communication Engineering, UIET, Panjab University, Chandigarh, India

ABSTRACT

Free space optical communication (FSOC) is a potential technique for high-speed, secure data transmission. It has the capacity to serve a huge number of people and deliver a large amount of bandwidth. FSOC is utilized in locations where optical fiber is difficult to deploy and saves time while also being license-free. FSO networks have a wide range of possible applications, from house to satellite. FSO networks, on the other hand, have not gained traction due to a lack of availability and dependability. In order to take use of the features of wireless optical channels, researchers have concentrated on challenges in the physical layer. However, recent technical advancements with positive outcomes have made it feasible to investigate the benefits of high bandwidth. In FSO networks, several researchers have begun to focus on network and higher layer issues. In this review article, FSO systems are elaborated and discussed its history technologies in FSO, comparison to RF, advantages, disadvantages, and applications. Further, discussion on the utmost important performance limiting factor such as atmospheric turbulence is done and moreover beam divergence, scattering, dispersion in FSO, absorption, line of sight misalignment etc are also explained. Fog, haze, rain and their intensities such as low, medium and heavy ranges affect the FSO performance prominently. Different studies are reported in the literature to increase speed, capacity, and performance and also to perform better under the effects of different atmospheric turbulences using different modulations, multiple transmitters, optical amplifiers, wavelength windows, large antenna sizes, relay communication etc. However, FSO systems still need improvement in speed, capacity and performance.

How to cite this paper: Shivam Vats | Arvind Kumar | Amit Chaudhary | Richa Tejpal "A Detailed Discussion of Free Space Optical Communication Systems: A Review" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-6 | Issue-4, June 2022, pp.452-465, URL: www.ijtsrd.com/papers/ijtsrd50065.pdf

IJTSRD50065

1. Development of Optical Communication Channels

The growing expansion of computers and laptops for usage in offices, warehouses, enterprises, manufacturing, and retail has put indoor communications under strain [1]. To complete company operations, many computers are controlled in the same indoor space. A cluster of numerous computers needs centralized communication capable of serving the nodes and providing dependable connections. Various ways have been used to enhance the efficiency of systems in order to fulfill the demands of users, such as encryption, large capacity systems (multichannel systems), appropriate amplifications, and modulations [2]. However, it is commonly believed and stated that wired connections have been used extensively and conspicuously to cater to consumers. End consumers can be linked at high data rates through wired media, however this comes with a hefty cost because of the actual cables [3]. Furthermore, there are certain concerns with the use of cables, such as network expansion challenges, the need for extra space, installation time, and trenching manpower [4]. Aside from the numerous disadvantages of using wired connections, there are certain advantages, such as the fact that wired media can provide security and seamless connectivity [5].

Different cables, such as optical fibers, twisted pair cables, and coaxial cables, can be used to communicate across a wired media. Using the aforementioned transmission channels has a variety of advantages and disadvantages. Table 1.1 provides a comparison of several wired media. Twisted pair cables come in two types: shielded and unshielded, each with its own set of advantages and disadvantages. The main advantages of these cables are their ease of installation and low cost [6]. However, EMI has a significant impact on these (electromagnetic interference). After that, coaxial cables are used to deal with EMI concerns and may be used over extended distances. These cables have less EMI than twisted pair cables, but their deployment is more expensive. Optical fiber communication has emerged as the final solution to the problems of low bit rates, short distances, and high operational costs [7]. The complete internal reflection principle governs the operation of fiber optical cables. It can span long distances; however it suffers from expensive initial implementation costs for optical fiber lines [8].

The cost of trenching and the time it takes to establish wireless media has decreased dramatically as a result of their implementation. Wireless has emerged as the best option for overcoming the problems associated with wired transmission. It is defined as a method of transmitting signals without the need of cables, utilizing just air as the medium in the terrestrial link. Radio frequency (RF) is a widely utilized option in RF communication [9-11].

Table 1.1 Comparison of several wired communication mediums [7]

Parameters	Twisted pair cable	Coaxial cable	Optical fiber
Speed	10 Mbps to 1000 Mbps	10 Mbps to 100 Mbps	100 Mbps to 100 Gbps
Maximum length	100 m	500 m	10 km
Installation	Easy	Very easy	Difficult
Electromagnetic Interference	Most vulnerable	Less vulnerable	Not effected by EMI
Bandwidth	1-155 Mbps	10 Mbps	2 Gbps
Overall cost	Least expensive	Inexpensive	Expensive
Attenuation	High	Lower	Lowest

Radio frequency needs an operation which is performed on the frequencies that are fixed by the government. Frequency range of the radio spectrum is 3 kHz to 300 GHz. Due to wireless operation and other advantages, radio frequency based transmission is also popular [5] [6]. It has potential to cater many users simultaneously. However, there is a major reason that creates issues in this technology is low reach and less secure transmission. It provides less strength to the signal over large distances, thus more error occurs. In order to cope with issues of RF communication, a promising way-out is suggested by researchers and it is termed as free space optical (FSO) communications [12-15].

1.1. Free Space Optical (FSO) Communication

FSO communication is the wireless transmission of data from one end to another using optical light signals in telecommunication. Free space can be empty space with or without air in free space optical communication. FSO is extensively employed in locations where trenching and fiber deployment are time-consuming, and it is the best way to reduce system costs. FSO has been identified as a promising technology for both indoor and outdoor communications, and it will be widely employed in next-generation broadband services [16]. Two major forms of FSO communications are short range distance applications and long reach distance applications. Short-range communication is utilized in terrestrial communications on Earth, whereas long-range communication is used in space where there is no air. Indoor wireless communication, such as infrared communication, is referred to as infrared communication, whereas exterior signal transmission is referred to as FSO transmission [17].

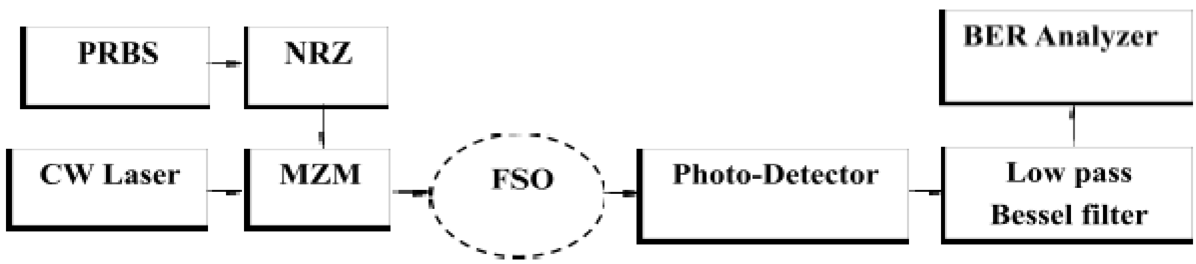

Figure 1.1 Block diagram free space optical communication system

FSO allows for optical spectrum license-free communication, or in other words, transmission without the need for a license [18]. It is said that it is license-free, however it has one fundamental flaw that degrades the system's performance: weather conditions. Turbulence in the atmosphere is caused by changes in the environment's temperature or pressure. Due to these meteorological instabilities, the medium's refractive index changes [19]. Because of the existence of air turbulence, there have been more mistakes and a lower signal to noise ratio. FSO technology is also becoming a popular approach for signal transmission and inspection systems that can display data quickly while still providing secure transfer. These systems may operate with a variety of systems to provide a well-developed, robust sensor communication network [20].

1.2. History of FSO

Signals have been conveyed through optical transmission for thousands of years. The Greeks used polished shields to reflect sunlight as battle signals on the battlefield. In 1880, Charles Sumner and Alexander Graham Bell utilized a picture phone for the first time to transmit voice and a beam of light [21]. On the 3rd of June, Bell made the first wireless transmission between two stations separated by 213 meters. However, after many years of Bell's experimentation, optical telegraphy was the first to employ wireless communication. When World War I broke out, Morse transmitters, sometimes known as blinkgrets, were used for the first time on the occurrence of communication breakdown due to wire cuts. The employed transmitter had a range of 4 km and 8 km during the day and night, respectively [22]. At the end of the battle, light reliance communication through phones was realized. Carl Zeiss Jena developed optical communication equipment that was used by the German army in Atlantic Wall bunkers and anti-aircraft combat units during World War 2. In the 1960s, the LASER was found, ushering in a revolution in free space optical communication. This contributed in the increase of military department expansion in particular. In today's fiber optic line networks, lasers are used in wireless communication, which is a crucial step toward achieving autonomy from permanent and costly line repair [23-25].

1.3. Comparison of FSO and RF technologies

In most cases, RF communication is inextricably linked to wireless technology. Broadcasting of signals other than RF carriers, such as communication based on optical, can provide better results. Free space optical huge bandwidth and simplicity of access can provide a lot of promise in wireless communication to internet back ends, which can provide a last-mile solution. This factor may influence the availability of services such as less interruption, run songs and data interchange, movies on demand, film conferencing, job allocation capability, and real-time health imaging transmission [26]. Secure channels with a lower chance of interception, which may be created by restricted divergence and laser beams in the midst of a free space optical link. Minor free space laser beams have the capability of penetrating impediments [27]. For example, suppose a bit rate of several Gbps is delivered across a free space connection with a 0.1 mrad (milliradian) divergence of the laser beam that may easily pass through dense fog until the link length reaches a kilometer. Despite the tremendous advantages of FSO, it does come with certain limitations. Because FSO bonds employ line of sight (LOS) communication between the receiver and transmitter, they are susceptible to air disturbances or turbulence. Disturbances from clouds, rain, haze, fog, and snow also impair it, causing a drop in performance and perhaps connection loss. The FSO linkages have a limited range due to the excessive surrounding noise. The key distinctions between RF and FSO technologies are shown in Table 1.1.

Table 1.2 Comparison of RF & FSO links [6]

Parameters	RF Link	FSO link
Data Rate	Less than 100 Mbps	100 Mbps to Gbps
Channel Security	Low	High
Source of Signal Degradation	Multipath fading, rain and user interference	Atmospheric Disturbances, rain, fog, haze, snow
Component Dimensions	Large	Small
Network Architecture	Non Scalable	Scalable

It should be noted that free space optical communication cannot be used without a radio link. However, free space communication and radio frequency signal transmission can both be used at the same time. Hybrid FSO/RF can be used to take use of the benefits of both free space optical and radio frequency communication technologies at the same time. It is also believed that when wired media and radio frequency are unavailable, FSO may serve as a backup for communication, and that the overall rate of data used in such a system is superior to that of an RF system [28]. The radio frequency-based network has bandwidth constraints while delivering different types of communications, such as high-definition video. As a result, with hybrid wireless communication, a combination of FSO and RF networks may provide high capability and availability [29-30].

1.4. Technologies and its usage in FSO

Optical light pulse trains are produced by two sorts of sources: light emitting diodes and lasers. Because light emitting diodes are non-coherent, they are unable to provide long-distance communication via a free space optical link. Lasers, on the other hand, may cover greater distances due to their directionality and coherent nature. Signal transmission and information sharing in spacecraft, ships, and other vehicles are examples of free space optical communication applications. The performance of the FSO system is influenced by meteorological instabilities such as fog, haze, rainfall, high temperatures, mist, and dust. The utilization of a coherent and highly directed light source is required for high-speed data transfer. MOSTCOM demonstrated a wireless communication link called Arto-link M1-10G that uses lasers to transmit data at a rate of 10 Gbps. This was done for a 2.5-kilometer-long connection [31-33].

1.5. Advantages of FSO
When a new communication technology is developed, all of its benefits and drawbacks should be taken into account. The first and most important benefit of FSO communication is its cheap cost. In the case of FSO, no optical fiber cable installation or safety upgrade is necessary. The system is simple to upgrade and requires no licensing [34] [35]. Another benefit of FSO is its fast transmission speed. The high speed is achieved because wave transmission over air is substantially quicker than optical fiber cables [36]. Between wireless stations, signal transmission takes place via a LOS route. Another advantage of FSO communication is that it is immune to EMI [37]. The radio frequency obstacle to information is reduced in a free space optical communication system. As a result, the information transfer is good and there are no disruptions. FSO has numerous benefits as given below:
- Less Bit error rates and deployment of FSO is easy
- FSO can be used in full duplex mode
- Transparent protocol
- Security of FSO is high due to narrow beams

1.6. Disadvantages of FSO
When all of the pros and downsides are considered, a number of drawbacks emerge. Ecological turbulence and several air variables might aggravate the FSO framework [38]. Rain, brown haze, and snowfall are the fundamental calculations that obstruct the optical correspondence from afar. When the transmission path is long, this is the main issue. The main source of impedance is the mugginess that can be seen all throughout due to brown haze, rain, and snowfall. The presence of stickiness in exhaust clouds, rain, and snowfall encourages introspection, scrambling, and sign absorption [39]. Because of the retention, the signal control is reduced, whereas dispersing produces signal spreading in a variety of ways with the same signal control. Another issue with the FSO structure is physical hindrance. Due to earthquakes, the physical impedance can be flashing, such as birds, building sways, and cranes. Scintillation occurs as a result of the earth's high temperature and manmade materials, posing a challenge in signal transmission. Some other disadvantages of FSO are as follows:
- Beam dispersion
- Scintillation
- Interferences caused by background light sources

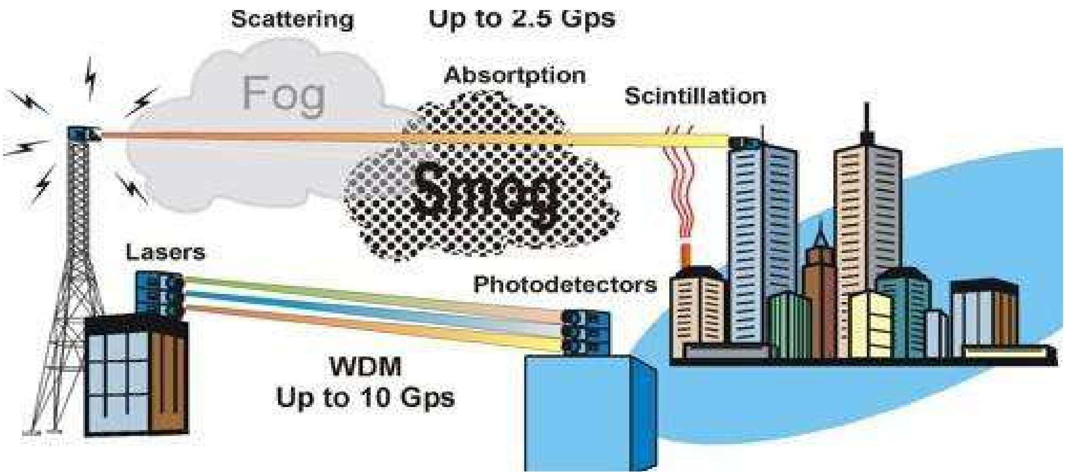

Figure 1.2 Turbulences in Free space optical communication [4]

After outlining the benefits and drawbacks, the outcomes show that the benefits outweigh the drawbacks. As a result, FSO may be a dependable and cost-effective wireless communication solution.

1.7. Applications and security in FSO
Wireless communication based on optical technology offers various advantages, but it is also important to consider FSO's security and wide range of applications. FSO has been installed on ships to allow them to

communicate with one another, as well as in aero planes for information sharing. It is a last-mile technology that is commonly employed in institutions and private locations these days [40]. This transmission allows institutions to interact with a variety of buildings without the need for trenching or other infrastructure. It is a type of terrestrial communication that can communicate across small distances. Universities, health departments, organizations, cities, businesses, and house-to-house correspondence are some of the other sectors where FSO is used. FSO offices to maintain a safe and secure environment [41]. Signal interception is the true health concern in FSO. For data transmission, FSO uses a narrow signal rather than a larger signal. Signals may readily be intercepted, and narrow signals do not change throughout transmission.

Interferences alter the broadcast signal for a variety of reasons before it is received. Another risk of using FSO is that it might prevent the signal from being sent. This restriction can be lifted by differentiating the signal before it reaches the receiver. In FSO correspondence, the side bands are missing, resulting in a loss of intensity in side projections and the posterior of the signals [42]. Because the signal's power is similar to that of the side bands, the signal's power is reduced, and it can be intercepted by others. The extra applications of free space optical are described as follows:

- Network deployment on the temporary basis
- In order to provide several Gbps links between different buildings or campuses such as in LAN-to-LAN connection
- For the elimination of the rights of ways by bypassing the buildings
- To establish communication between inter as well as intra chip
- To provide high speed communication and act as backup to optical fiber networks
- Potential alternative to the wireless communication

1.8. Effects of atmospheric variations in FSO

Because of the various gases present in the environment, the information signal can be absorbed, scattered, and dispersed to varied extents at various wavelengths. The different phenomena are explained below:

1.8.1. Absorption

Absorption is a phenomenon in which visible light is soaked or absorbed by atmospheric gases, resulting in dark bands in the light spectrum. The wavelengths that are either absorbed or scattered by the gas molecules are indicated by these black bands. Because different gases absorb and scatter light at different wavelengths, the position of the black bands varies depending on which gases are used. The similar phenomenon applies to light waves in the infrared and ultraviolet bands, with the exception that these bands are absorbed more by the gases in the air. Figure 1.3 shows the degree of absorption of various wavelengths by various gases.

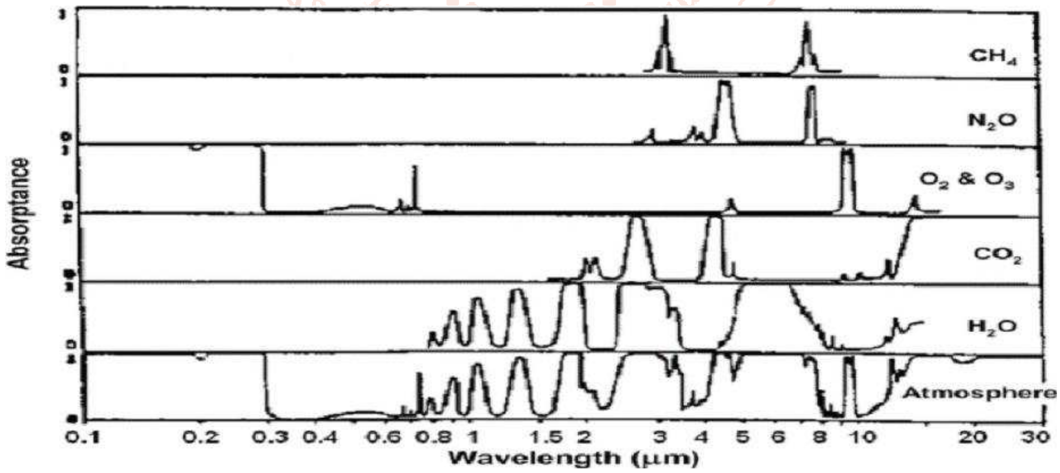

Figure 1.3 Absorption of EMR by Atmospheric Gases [5]

Visible light with wavelengths ranging from 0.4 um to 0.7 um is absorbed extremely inefficiently by oxygen and ozone gases. FSO employs infrared rays with wavelengths ranging from 0.7 to 1.5 microns, which are readily absorbed by water molecules. Almost all gases can absorb the upper infrared band at different wavelengths. Ultraviolet light with wavelengths less than 0.3 microns is absorbed heavily by oxygen and ozone gases. The atmosphere's transmittance in the visible and infrared bands of light is seen in Figure 1.4. It demonstrates that water is the most significant impediment to signal transmission. The absorption of visible and infrared radiation in the atmosphere is mostly due to O2, H2O, O3, and CO2. The three dotted lines indicate the wavelengths utilized in FSO technology, which are 0.80, 0.85, and 1.55 microns, and these wavelengths give great atmospheric transmittance [43-45].

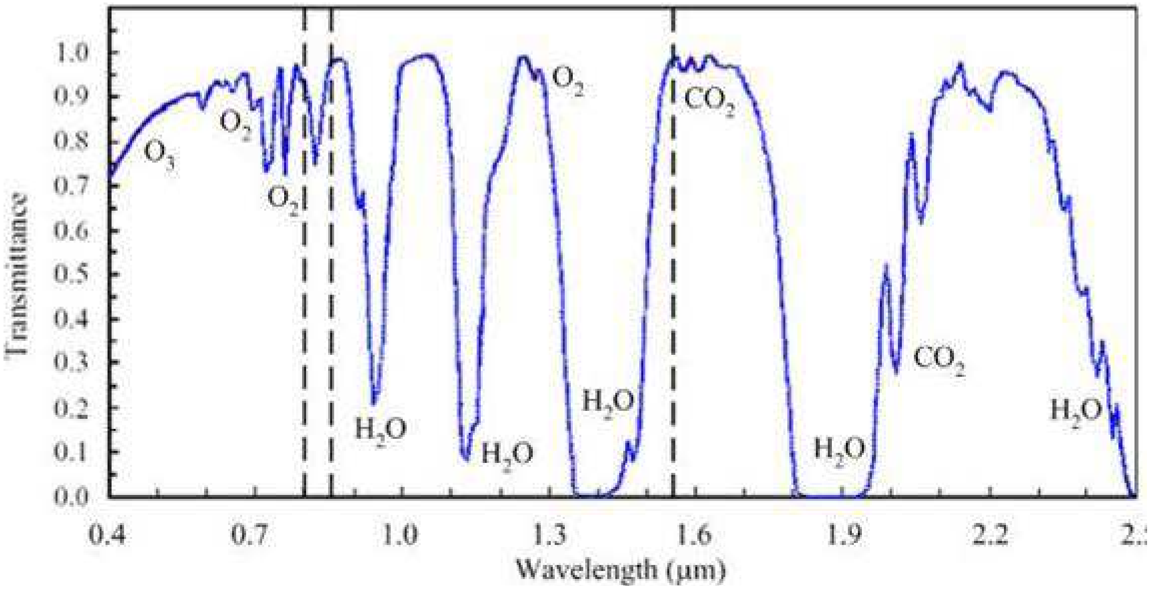

Figure1.4 Visible and Infrared Atmospheric Transmittance [6]

1.8.2. Scattering

The atmosphere causes signal scattering, which is another process that occurs when signals are delivered. The size of the molecules of gases and particles in the atmosphere that cause the signal to scatter is equal to or less than the wavelength of the light wave. Fog, haze, and aerosols have particle sizes in the range of the wavelengths employed in FSO technology; hence they are a major source of concern in this technology. There are three forms of scattering: Raman scattering, Rayleigh scattering, and Mie scattering. Raman scattering occurs when light is scattered by gas molecules and particles with sizes ranging from 10% to 150% of the wavelength of the light wave. When light waves collide with these particles, the light's energy rises or decreases. The light released by Raman Scattering differs from incoming light because the frequency of light is determined by its energy. The light emitted as a result of Raman scattering has a different frequency than the transmitted light waves. Only the Raman scattering is considered when a strong laser is employed; otherwise, it might be insignificant. Rayleigh scattering is caused by gases and particles in the atmosphere that are less than 10% of the wavelength of light waves. The energy of the light wave is not changed as a result of Rayleigh scattering, and the frequency of the emitted light is the same as the frequency of the incident light waves. Raman scattering produces less dispersed light than Rayleigh scattering, and Raman scattering is 10^6 to 10^8 times less intense than Rayleigh scattering [46-48]. The intensity ofRayleigh scattering can be calculated as:

$$I_S = \frac{8\pi^4 \alpha^2}{\lambda^4 r^2}\left(1 + \cos^2\theta\right) I_0 \qquad (1)$$

Scattering intensity I0 is the intensity of incident light α is the particle's polarization ability λ is incident light wavelength r is the scattering center θ is the angle of scattered light. From the above equation for calculation of Rayleigh scattering, it is clear that Rayleigh scattering is inversely proportional to the fourth power of the light radiation's wavelength. Hence, shorter the wavelength of the light higher is the Rayleigh scattering and longer is the wavelength, lesser is the Rayleigh scattering. Mie scattering is caused by the particles having size approximately equal to the wavelength of the light waves [49].

The scattered light is distributed differently owing to the enormous size of the scattering particles in Mie scattering than it is in Rayleigh scattering. As seen in Figure 1.5, Rayleigh scattering and Mie scattering are not the same.

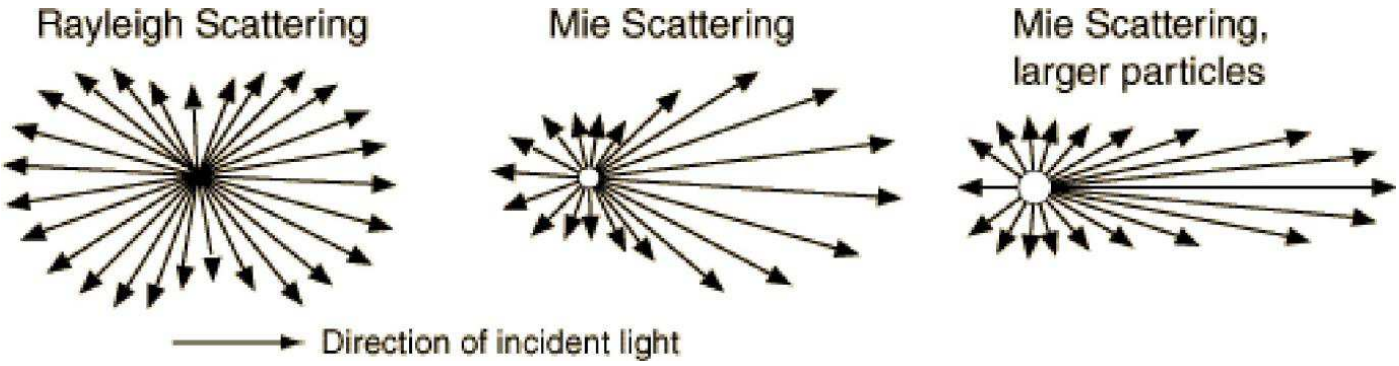

Figure 1.5 Comparisons of Rayleigh and Mie Scattering [7]

The light is incident on the particle from the left to the right in Figure 1.5. When there is Rayleigh scattering, the light scattering is very uniform in all directions except at right angles to the incident light, where it is half of the dispersed light in other directions. Light scatters mostly in the direction of incoming light due to Mie scattering. As the particle size grows larger, the incoming light scatters less. As a result, the infrared radiations sent by the FSO system are scattered significantly by fog and clouds, owing to the size of the water drops present in them being almost equivalent to the wavelength of the system. Rain has a smaller impact on the FSO system since the rain drops are larger than the wavelength of the system [50].

1.8.3. Dispersion

The process of dispersion occurs when an electromagnetic signal traveling in a physical medium degrades when distinct wave components of the signal propagate at varying velocities through the medium. Because the practical laser generates a limited range of frequencies rather than a single frequency, the laser signal disperses with time. The dispersion can also affect the ideal laser, i.e. a laser that emits just one frequency. The consequences of dispersion on a rectangular pulse are seen in Figure 1.6. The received signal spreads with lower power peaks than the source signal due to dispersion [51].

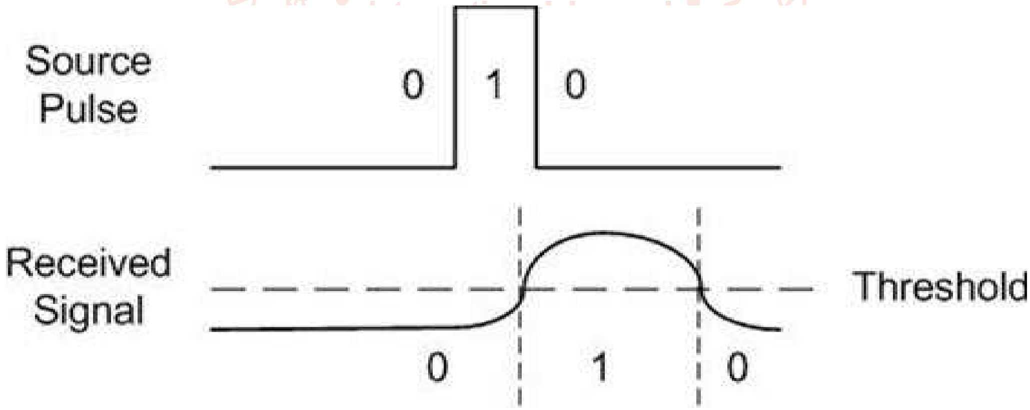

Figure 1.6 Dispersion of Rectangular Pulse [8]

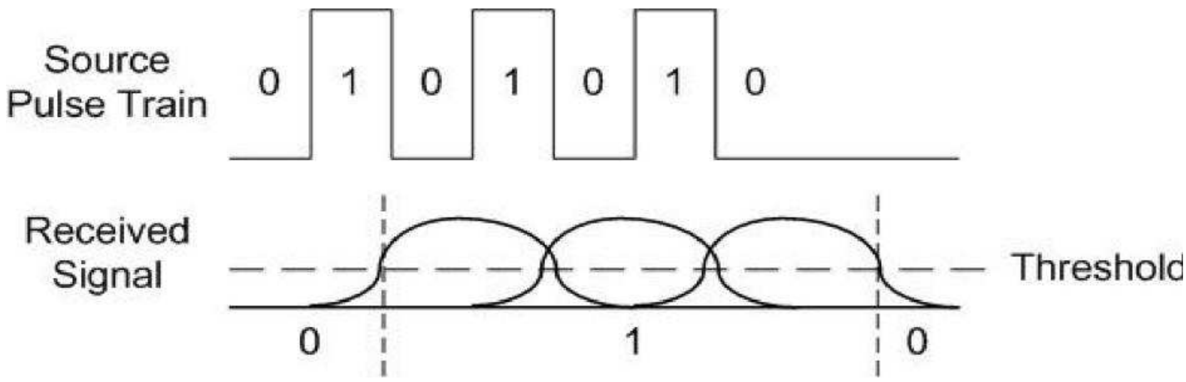

Figure 1.7 Dispersion of a Pulse Train [8]

The threshold should be chosen so that a "1" in the attenuated signal can be distinguished from a "0." The dispersion of the source light that sends the train of pulses to the receiver is seen in Figure 1.7. The signal will be stretched out over time, limiting the data speeds that may be transferred. The received pulse train is overlapped owing to dispersion, and the receiver will incorrectly view it as a protracted high signal since the receiver is unable to separate these overlapped pulses.

1.9. Effects of weather conditions

Because the FSO system transmits data wirelessly across an unguided atmospheric route, the information is strongly influenced by atmospheric and meteorological circumstances. Rain, fog, haze, and snow are examples of diverse weather conditions that have a significant impact on the FSO system. Climate/weather conditions have a significant impact on the performance of the FSO system. The performance of FSO systems can be harmed by these various weather conditions. The information signal traveling through the sky might be scattered by fog, rain, haze, and snow. Scattering causes a portion of the information signals to be deviated from their original route. Fog has the most influence on the FSO system of all the weather situations because fog contains minute water drops whose size is approximately equivalent to the wavelength of infrared wavelengths, causing more signal scattering. Snow and rain also affect the functioning of the FSO system, but their effects are less noticeable. Because these meteorological conditions seldom occur at the same time, they may be investigated independently [52].

1.10. Other limitations of FSO

1.10.1. Directional Precision

Due to the low beam divergence of lasers, there will be a high level of security against eavesdropping. It's tough to concentrate a laser beam to the receiver because of the low beam divergence. With the assistance of the diagram below, the beam pattern for a broadcast signal at the receiver side may be illustrated. The pointing resolution in Figure 1.8 is kept equal to the beam divergence of θ, which indicates that the laser beam can diverge θ with an angle of in either the x or y directions [53].

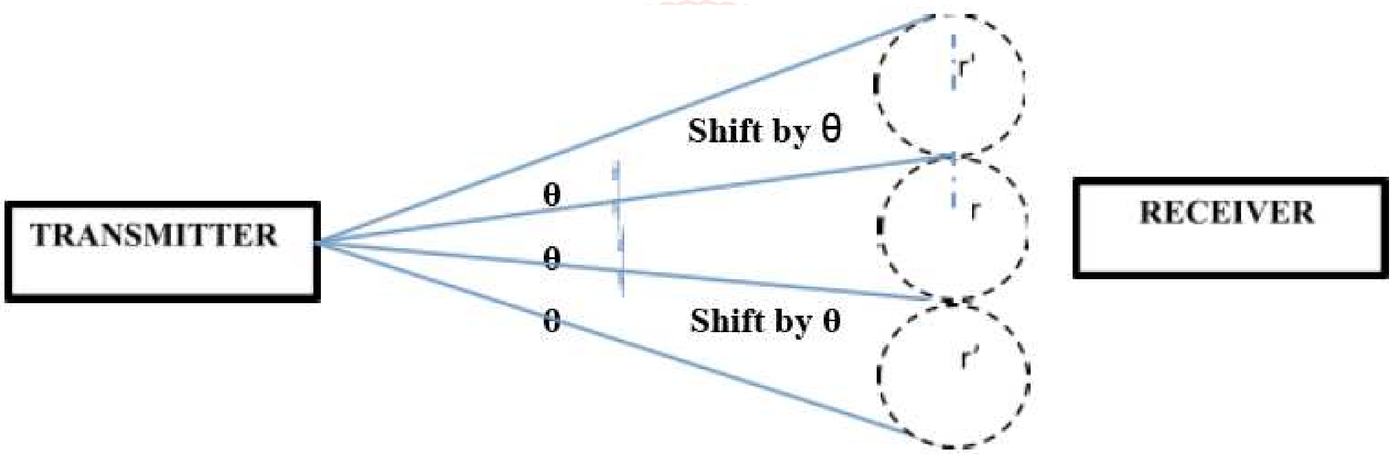

Figure 1.8 Beam Pattern at Receiver with Pointing Resolution θ [11]

Figure 1.8 shows that it appears to offer continuous coverage to the receiver side, but in actuality, gaps appear in the beam pattern when the transmitter's aiming resolution is maintained. Because of the gaps, the laser beam sent by the transmitter will not be properly focused.

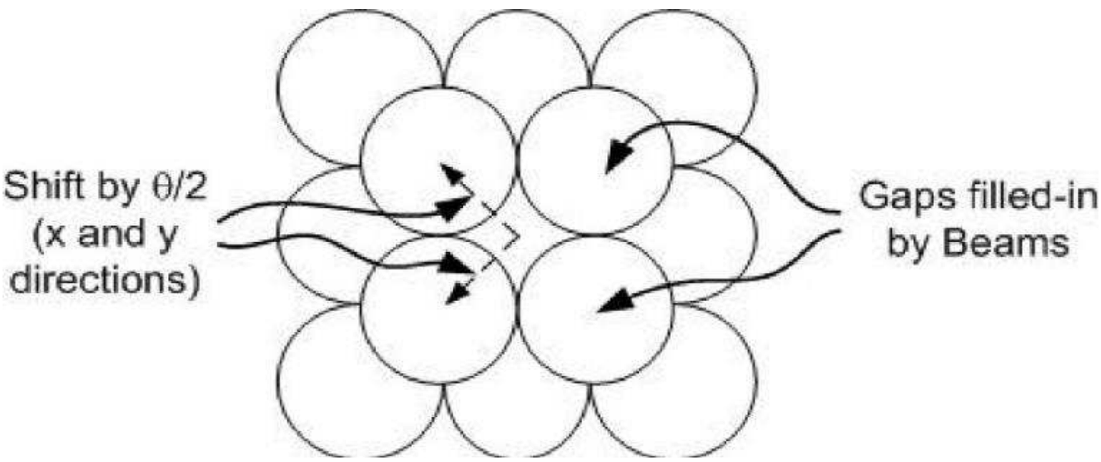

Figure 1.9 Gaps filled by pointing Resolution θ/2 [11]

There are no gaps when the pointing resolution of the laser beam is equal to half of the beam divergence. This is seen in Figure 1.9 below. As a result, a laser beam should be linked with a system that allows it to focus on the receiver while also providing high security and efficient energy reception. If security and received energy are not a major issue in FSO, however, a greater beam divergence can be employed, requiring less accurate aiming precision.

1.10.2. Line of Sight Obstruction

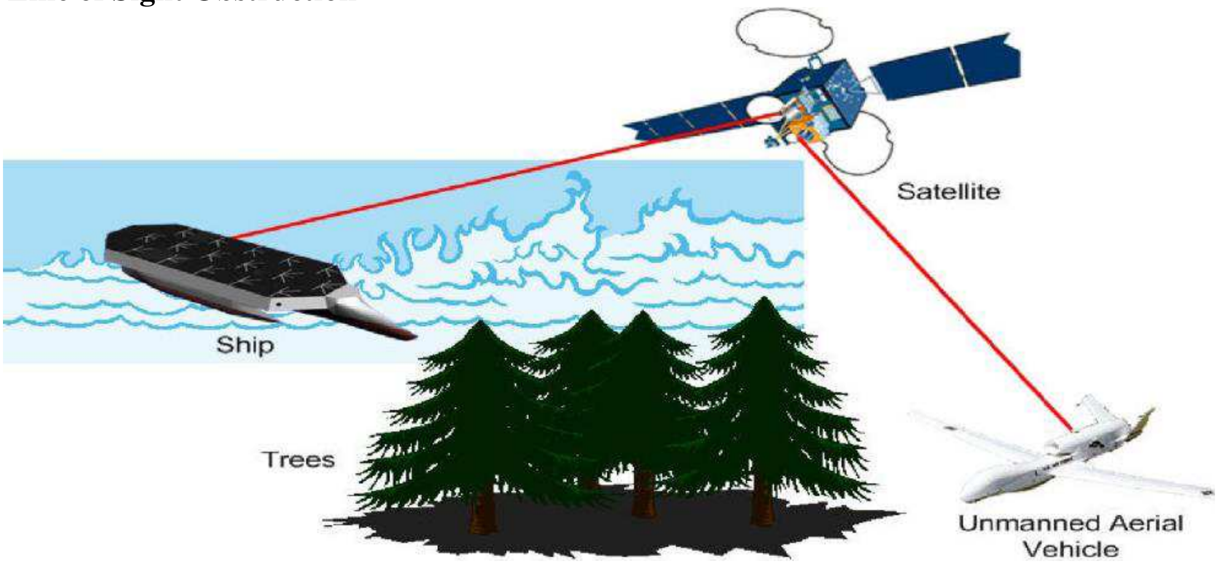

Figure 1.10 Spatial Diversity to overcome Line of Sight [16]

Because FSO lines are line-of-sight, they can be harmed by things like buildings, trees, and planes. Because the FSO system has a tiny beam and fast data rates, it can be harmed by small objects such as birds. The error correction approach can repair mistakes produced by transient barriers such as flying objects. When blockages are large or persist for an extended period of time, spatially varied linkages can deliver superior outcomes [54].

The spatial variety depicted in Fig. 1.10 aids in overcoming line-of-sight limitations. Due to some trees, the Unmanned Aerial Vehicle (UAV) in Figure 1.10 has lost its direct link to its mother ship. However, the satellite allows it to connect with its mother ship.

1.11. Q factor BER calculation in optical communication systems

The signal-to-noise ratio (SNR) at the receiver's decision circuit is defined as Q for a digital transmission signal and is expressed as:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (2)$$

Rather than linear numbers, the Q-factor can be expressed in decibels:

Q (decibels) = $20 \times \log_{10}$ Q (linear) (3)

where μ_1 and μ_0 is the mean voltage level of the 1 and 0 levels. σ_1 and σ_0 are the standard deviations of the noise distribution on the 1 and 0 levels.

There is a one-to-one correspondence between the Q value and the BER. The Q value can be used to indicate the system tolerance in decibels, much as dBm can be used to express optical power instead of mW. A lower pre-FEC BER denotes a higher Q value and improved network performance. The bit error rate (BER) is the gold standard for determining transmission quality.

The waveforms of optical signals coupled into fibers will be distorted when they reach at the end of fiber connections due to variables such as noise, non-linear effects, and dispersion (PMD/CD). When the receiver translates the optical impulses into electrical signals, bit errors occur [55].

1.12. Comparison of Different Reported Studies

In the literature, extensive work has been reported in the context of FSO communication on performance improvement, capacity enhancements, and reach extension. Modulations, amplifiers, multiple receivers, mode division multiplexing (MDM), polarization division, and spectrum slicing and relay communication are some of the widely used techniques. In Table 1.3, comparisons of different studies are shown in terms of data rate, capacity, channels, modulation, and limitations etc. It is noteworthy that polarization division multiplexed (PDM) multilevel modulations such as OFDM, QPSK, QAM and MDM can provide better performance in FSO under the effects of atmospheric turbulence.

S. No	Author, Publisher and Year [reference]	WDM Channels Distance and data rate	Modulation and technique	Results	Limitations
1	K. Murugan et al., Springer and 2020 [56]	4 channels Ro-FSO, 15 km and 20 Gbps/channel	4-QAM-OFDM and MDM-WDM	80 Gbps MDM-WDM system covered 15 km over FSO at SNR 20 dB	Two consecutive LG modes were used which increased mode coupling and deteriorate system performance
2	M. Singh et al., Springer and 2020 [57]	2 × 40 Gbps–40 GHz, Ro-FSO system, 40 km and 40 Gbps/channel	RZ-DPSK, AMI, and NRZ-DPSK, Hermite Gaussian (HG) modes (HG00 and HG01)	Demonstrated system covered 40 km over FSO and NRZ-DPSK found best and offered Q=11.38	Capacity was low as only 2 channels were used
3	S. Chaudhary et al., Taylor and Francis and 2019 [58]	2 channel Ro-FSO, 14 km and 2.5 Gbps	MDM-AMI and MDM-NRZ	Achieved 14 km over FSO at SNR 16.42 For AMI and 10.5 for NRZ	Very low data rate
4	A. Thakur et al., Springer and 2018 [59]	4 channel spectrum slicing FSO using highly nonlinear fiber, 5 km and 2.5 Gbps and EDFA, RFA, SOA performance investigation	NRZ, RZ, CSRZ	Investigated system can covered 5 km using CSRZ EDFA and found best with Q factor 9.57	Data rate and distance covered are less
5	A. Thakur et al., Springer and 2018 [60]	4 channel spectrum slicing FSO using highly nonlinear fiber, 5 km and 2.5 Gbps	NRZ and Spectrum sliced FSO system four wavelengths were generated from single laser source using HNLF	Maximum link range is observed in case of clear weather (>8Km) and the system works for 1.5 Km in case of Fog at BER 10^{-9}.	Capacity was less
6	M. Kaur et al., IJCRT and 2017 [61]	4 channels, FSO with spectrum slicing using HNLF, at 2.5 Gbps	NRZ, RZ, CSRZ, MDRZ	Covered 5 km at BER 10^{-9} using MDRZ.	Data rate was less
7	Shaina et al., Elsevier and 2016 [62]	Single channel FSO under 3 wavelength windows, 500 m and 2.5 Gbps	NRZ considered	System obtained 500 m distance over FSO under worst weather 70 dB/km at BER 10^{-5} for 850 nm, 10^{-4} for 1310 nm, 10^{-3} for 1550 nm	Distance was very low
8	H. Zhou et al., Elsevier and 2015 [63]	8 WDM channels Radio over-FSO, 1 km and 10 Gbps	NRZ	Got distance of 1 km at BER 10^{-9}	Distance was very short

9	A. Malik et al., Springer and 2014 [64]	32 WDM channels, 47 km and 2.5 Gbps	NRZ, two system investigated i.e WDM-FSO, Multiple Tx/Rx FSO	Investigated system achieved distance 47 km at BER 10^{-10} in Tx/Rx FSO system and 31.7 km in WDM FSO	Data rate per channel was less
10	F. Hossain et al., IEEE and 2013 [65]	Multiple Tx/Rx FSO using SOA, 1 km and 10 Gbps	NRZ, 1 Tx/Rx to 8 Tx/Rx	Obtained distance of 1 km at BER 10^{-9} and with the increase in Tx/Rx, result improved	Distance was very short

1.13. Conclusion

A prominent issue encountered by researchers and developers of optical fiber transmission is high cost of trenching and cost. Basically the cost of installation of fiber optic is very high which is due to labor and machines. Solution for the cost saving and elimination of trenching, a radio frequency was assumed to be a solution. However, RF occupies the large part of the spectrum and also security of these systems is less. In passive optical networks, optical fiber based users exist but due to different geographical areas such as hilly areas, deployment of optical fiber becomes tedious. In order to give them wireless access, FSO is an ultimate solution. Major requirement of the FSO communication is LoS link amid receiver and transmitter. Requirements of compact antenna size, short wavelength makes it better over RoF. FSO provides license free communication and provides high data rates in the range of 5 Gbps to 40 Gbps. Major Benefits of FSOC are industry, health care, security, disaster recovery, education, voice and data etc. Despite the many benefits over RF communication, the researchers are trying to increase the link length reach and bit rate supportability. In the literature, extensive work has been reported in the context of FSO communication on performance improvement, capacity enhancements, and reach extension. Modulations, amplifiers, multiple receivers, MDM, polarization division, spectrum slicing and relay communication are some of the widely used techniques. It is noteworthy that polarization division multiplexed (PDM) multilevel modulations such as OFDM, QPSK, QAM and MDM can provide better performance in FSO under the effects of atmospheric turbulence. In the near future, ultra high capacity and long reach FSO systems are required even under the worst weather conditions.

References

[1] H. Henniger and O. Wilfert, ‘‘An introduction to free-space optical communications,’’ Radio engineering, vol. 19, no. 2, pp. 203–212, 2010.

[2] H. E. Nistazakis, T. A. Tsiftsis, and G. S. Tombras, ‘‘Performance analysis of free-space optical communication systems over atmospheric turbulence channels,’’ IET Commun., vol. 3, no. 8, pp. 1402–1409, 2009.

[3] L. Dordova and O. Wilfert, ‘‘Optimal laser diode operating mode with unstable operating temperature in turbulent atmosphere,’’ Semiconductor Lasers and Laser Dynamics III, vol. 6997, no. 69971G, pp. 1-11, 2008.

[4] S. S. Murhty, ‘‘Laser beam propagation in atmospheric turbulence”, Prec. Indian Acad. Sci., vol. C 2, no. 2, pp. 179-195, 1979.

[5] L. S. A. and Jabeena, T. Jayabarathi, and R. Aggarwal, ‘‘Review on optimization of wireless optical communication system,’’ Trends OptoElectro Opt. Commun., vol. 4, pp. 9–19, 2019.

[6] R. K. J. A. Gupta, P. Anand, R. Khajuria, and S. Bhagat, ‘‘A survey of free space optical communication networks,’’ Digital Communications and Networks, vol. 3, no. 2, pp. 67-77, 2017.

[7] 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.

[8] S. A. Al-Gailani, A. B. Mohammad, R. Q. Shaddad, U. U. Sheikh, and M. A. Elmagzoub, ‘‘Hybrid WDM/multibeam free-space optics for multigigabit access network,’’ Photonic Netw. Commun., vol. 29, no. 2, pp. 138–145, 2015.

[9] J. A. R. P. de Carvalho, H. Veiga, P. A. J. Gomes, C. F. F. P. R. Pacheco, and A. D. Reis, ‘‘Experimental performance study of a very high speed free space optics link at the university of beira interior campus: A case study,’’ in Proc. IEEE Int. Symp. Signal

Process. Inf. Technol., IEEE, Sarajevo, Bosnia and Herzegovina, 2008.

[10] O. Bouchet and P.-N. Favennec, Wireless Optical Communication Title. Hoboken, NJ, USA: Wiley, 2012.

[11] A. S. Hamza, J. S. Deogun, and D. R. Alexander, ''Classification framework for free space optical communication links and systems,'' IEEE Commun. Surveys Tuts., vol. 21, no. 2, pp. 1346–1382, 2019.

[12] N. Badar and R. K. Jha, ''Performance comparison of various modulation schemes over free space optical (FSO) link employing Gamma–Gamma fading model,'' Opt. Quantum Electron., vol. 49, no. 5, pp. 1-10, 2017.

[13] J. Pourahmadazar, S. Sahebghalam, S. Abazari Aghdam, and M. Nouri, ''A millimeter-wave fresnel zone plate lens design using perforated 3D printing material,'' in IEEE MTT-S Int. Microw. Symp. Dig., IEEE, Ann Arbor, MI, USA, 2018.

[14] D. C. Calvo, A. L. Thangawng, M. Nicholas, and C. N. Layman, ''Thin fresnel zone plate lenses for focusing underwater sound,'' Appl. Phys. Lett., vol. 107, no. 1, pp. 1-4, 2015.

[15] H. A. Willebrand, B. S. Ghuman, "Fiber optic Without Fiber", Spectrum, IEEE, vol. 38, no. 8, pp. 40–45, 2001.

[16] J. Mikoáajczyk, Z. Bielecki, M. Bugajski, J. Piotrowski, J. Wojtas, W. Gawron, D. Szabra, and A. Prokopiuk, ''Analysis of free-space optics development,'' Metrol. Meas. Syst., vol. 24, no. 4, pp. 653–674, 2017.

[17] 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.

[18] F. A. Wahab, T. K. Leong, H. Zulkifli, M. I. Ibrahim, M. A. B. Talib, N. A. Zamri, and O. K. Ibrahim, ''Multiple transmitters & receivers for free space optical communication link performance analysis", J. Telecommun. Electron. Comput. Eng., vol. 8, no. 5, pp. 29–32, 2016.

[19] M. C. Teich and B. Saleh, Fundamentals of Photonics, vol. 3. Hoboken, NJ, USA: Wiley, 1991.

[20] A. Malik and P. Singh, ''Free space optics: Current applications and future challenges,'' Int. J. Opt., vol. 2015, no. 945483, pp. 1–7, 2015.

[21] S. Saurabh, ''To study the effect of fog, snow and rain attenuation on FSO link,'' CT Int. J. Inf. Commun. Technol., vol. 2, no. 1, pp. 16–22, 2014.

[22] S. R. Forrest, ''Optical detectors: Three contenders: Depending on the application, the photoeonductor, p-i-n diode, or avalanche photodiode may prove the best choice,'' IEEE Spectrum., vol. 23, no. 5, pp. 76–84, 1986.

[23] J. C. Juarez, A. Dwivedi, A. R. Hammons, S. D. Jones, V. Weerackody, and R. A. Nichols, ''Free-space optical communications for next generation military networks,'' IEEE Commun. Mag., vol. 44, no. 11, pp. 46–51, 2006.

[24] S. Trisno, ''Design and analysis of advanced free space optical communication systems", Ph.D. dissertation, Univ. Maryland, College Park, MD, USA, 2006.

[25] 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 Proc. IEEE Bus. Eng. Ind. Appl. Colloq. (BEIAC), IEEE, Langkawi, Malaysia, 2013.

[26] I. I. Kim, M. Mitchell, and E. J. Korevaar, ''Measurement of scintillation for free-space laser communication at 785 nm and 1550 nm,'' Proc. SPIE Opt. Wireless Commun., SPIE, Boston, MA, United States, 1999.

[27] F. D. Kashani, M. Reza Hedayati rad, M. Reza Mahzoun, and B. Ghafary, ''Beam propagation analysis of a multi beam FSO system with partially flat-topped laser beams in turbulent atmosphere,'' Optik, vol. 123, no. 10, pp. 879–886, 2012.

[28] N. H. Md Noor, W. Al-Khateeb, and A. W. Naji, ''Experimental evaluation of multiple transmitters/receivers on free space optics link,'' Proc. IEEE Student Conf. Res. Dev., IEEE, vol. 2, pp. 128–133, 2011.

[29] N. H. Md Noor, A. W. Naji, and W. Al-Khateeb, ''Performance analysis of a free space optics link with multiple transmitters/receivers,'' IIUM Eng. J., vol. 13, no. 1, pp. 49–58, 2012.

[30] A. Vats, H. Kaushal, "Analysis of free space optical link in turbulent atmosphere", Optik, vol. 125, no. 12pp. 2776-2779, 2014.

[31] S. Kaur, M. Kumar, A. Verma, "An Integrated High-Speed Full Duplex Coherent OFDM-PON and Visible-Light Communication System", Journal of Optical Communications, Published Ahead of Print, De Gruyter, 10.1515/joc-2018-0236, 2019.

[32] L. Gao, C. Gao, T. Zhu, Y. Li, Y. Long Cao, and G. Yin, ''Incoherent optical modulation of graphene based on inline fiber Mach-Zehnder interferometer,'' Opt. InfoBase Conf. Pap., vol. 122, pp. 5–6, 2017.

[33] H. Sarangal, A. Singh, J. Malhotra, and S. Chaudhary, "A cost effective 100 GBPS hybrid MDM–OCDMA–FSO transmission system under atmospheric turbulences,'' Opt. Quantum Electron., vol. 49, no. 5, pp. 1–10, 2017.

[34] K. Kiasaleh, ''Performance of APD-based, PPM free-space optical communication systems in atmospheric turbulence,'' IEEE Trans. Commun., vol. 53, no. 9, pp. 1455–1461, 2005.

[35] H. Liu, R. Liao, Z. Wei, Z. Hou, and Y. Qiao, ''BER analysis of a hybrid modulation scheme based on PPM and MSK subcarrier intensity modulation,'' IEEE Photon. J., vol. 7, no. 4, pp. 1–10, 2015.

[36] Z. Wang, W.-X. Shi, and P.-X. Wu, ''PDM-DPSK-MPPM hybrid modulation for multi-hop free-space optical communication,'' Optoelectronics Lett., vol. 12, no. 6, pp. 450–454, 2016.

[37] G. Kaur, H. Singh, and A. Singh Sappal, ''Free space optical using different modulation techniques – a review,'' Int. J. Eng. Trends Technol., vol. 43, no. 2, pp. 109–115, 2017.

[38] G. Z. Popoola, Optical Wireless Communications: System and Channel Modelling With MATLAB. New York, NY, USA, CRC Press, 2013.

[39] J. Lesh, ''Capacity limit of the noiseless, energy-efficient optical PPM channel,'' IEEE Trans. Commun., vol. 31, no. 4, pp. 546–548, 1983.

[40] S. Kaur, Dr. M. Kumar, A. verma, "A Novel Hybrid Passive Optical Network, Free Space Optical and Visible Light Communication System", JETIR, vol.6, no. 4, pp. 258-261, 2019.

[41] Y. Fan and G. Rj, ''Comparison of pulse position modulation and pulse width modulation for application in optical communications,'' Opt. Eng., vol. 46, no. 6, pp. 65–72, 2007.

[42] Z. Ghassemlooy, A. R. Hayes, N. L. Seed, and E. D. Kaluarachchi, ''Digital pulse interval modulation for optical communications,'' IEEE Commun. Mag., vol. 36, no. 12, pp. 95–99, 1998.

[43] M. A. A. Ali, ''Performance analysis of terrestrial WDM-FSO link under different weather channel,'' World Sci. News, vol. 56, pp. 33–44, Oct. 2016.

[44] S. Kaur, G. Kaur, G. Singh, A. Verma, N. Julka, "Polarization Crosstalk Suppression in Wavelength Division Multiplexed Free Space Optical System Incorporating Polarization Diversity", IJCRT, vol. 5, no. 3, pp. 384-390, 2017 .

[45] S. Hranilovic, Wireless Optical Communication Systems. New York, NY, USA: Springer-Verlag, 2005.

[46] T. YoussefElganimi, ''Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical study,'' Int. J. Comput. Appl., vol. 79, no. 11, pp. 22–27, 2013.

[47] Z. Wang, W. D. Zhong, S. Fu, and C. Lin, ''Performance comparison of different modulation formats over free-space optical (FSO) turbulence links with space diversity reception technique,'' IEEE Photonic J., vol. 1, no. 6, pp. 32–40, 2009.

[48] B. Salah, L. KASSA-BAGHDOUCHE, A. Verma, "SAC-OCDMA System with EDW codes over FSO under different conditions of Weather", IJRAR, vol. 6, no. 2, pp. 749-755, 2019.

[49] D. Hossen and G. S. Alim, ''Performane evaluation of the free space optical (FSO) communication with the effects of the atmospheric turbulances,'' BRAC Univ., Dhaka, Bangladesh, Tech. Rep., 2008.

[50] J. M. Hamamreh, H. M. Furqan, and H. Arslan, ''Classifications and applications of physical layer security techniques for confidentiality: A comprehensive survey,'' IEEE Commun. Surveys Tuts., vol. 21, no. 2, pp. 1773–1828, 2nd Quart., 2019.

[51] I. K. Son and S. Mao, ''A survey of free space optical networks,'' Digit. Commun. Netw., vol. 3, no. 2, pp. 67–77, May 2017.

[52] M. Singh, J. Malhotra, "Modeling and Performance Analysis of 400 Gbps CO-OFDM Based Inter-satellite Optical Wireless Communication (IsOWC) System Incorporating Polarization Division Multiplexing with Enhanced Detection", Wireless Personal Communications, vol. 111, pp. 495–511, 2020.

[53] M. Singh, J. Malhotra, M. S. ManiRajan, V. Dhasarathan, M. H. Aly, "A long-haul 100 Gbps hybrid PDM/CO-OFDM FSO transmission system: Impact of climate conditions and atmospheric turbulence", Alex. Eng. J., vol. 60, no. 1, pp. 785–794, 2021.

[54] Poonam, Lovkesh, "Performance Analysis of IsOWC System Using Advanced Modulation Formats and Schemes over Wavelength Spectrum", IJEDR, vol. 3, no. 3, pp. 1-4, 2015.

[55] C. C. Davis, I. I. Smolyaninov, and S. D. Milner, ''Flexible optical wireless links and networks,'' IEEE Commun. Mag., vol. 41, no. 3, pp. 51–57, 2003.

[56] K. Murugan, A. Sharma, J. Malhota, "Performance analysis of 80 Gbps Ro-FSO system by incorporating hybrid WDM-MDM scheme" Optical and Quantum Electronics, vol. 52, no. 505, pp. 1-12, 2020.

[57] M. Singh, J. Malhotra, "Performance Comparison of Different Modulation Schemes in High-Speed MDM Based Radio Over FSO Transmission Link Under the Effect of Atmospheric Turbulence Using Aperture Averaging", Wireless Personal Communications, vol. 111, no. 4, pp. 825–842, 2020.

[58] S. Chaudhary, A. Amphawan, "High speed MDM-Ro-FSO communication system by incorporating AMI scheme", International Journal of Electronics Letters, vol. 7, no. 3, pp. 304-310, 2019.

[59] A. Thakur, S. Nagpal, A. Gupta, "A Performance Enhancement and High Speed Spectrum Sliced Free Space Optical System", Wireless Personal Communications, vol. 100, no. 4, pp. 1775–1789, 2018.

[60] A. Thakur, S. Nagpal, A. Gupta, "Kerr effect based spectrum sliced wavelength division multiplexing for free space optical communication", Optik, vol. 157, no. 11, pp. 31-37, 2018.

[61] M. Kaur, G. Singh, "Analysis of different modulation formats in spectrum slices free space optical communication system", IJCRT, vol. 5, no. 3, pp. 448-452, 2017.

[62] Shaina, A. Gupta, "Comparative Analysis of Free Space Optical Communication System for Various Optical Transmission Windows under Adverse Weather Conditions", Procedia Computer Science, vol. 89, no. 2, pp. 99-106, 2016.

[63] H. Zhoua, S. Mao, P. Agrawala, "Optical power allocation for adaptive transmissions in wavelength-division multiplexing free space optical networks", Digital Communications and Networks, vol. 1, no. 3, pp. 171-180, 2015.

[64] A. Malik, P. Singh, "Comparative Analysis of Point to Point FSO System Under Clear and Haze Weather Conditions", Wireless Pers Commun, vol. 80, vol. 7, pp. 483–492, 2014.

[65] F. Hossain, Z. Afroze, "Eliminating the Effect of Fog Attenuation on FSO Link by Multiple TX/RX System with Traveling Wave Semiconductor Optical Amplifier", Proceedings of 2013 2nd International Conference on Advances in Electrical Engineering (ICAEE 2013), IEEE, Dhaka, Bangladesh, 2013.