A Precise Review on Different Aspects of Free Space Optical Communication (FSOC) Systems

Simran Bagga[1] · Charu Madhu[1] · Sharmelee Thangjam[1]

Abstract

Radio frequency (RF) is perceived as one of the most popular wireless transmission candidate in the last decade however due to ever-increasing current generation bandwidth demands; it becomes incompetent to fulfil the requirements. A futuristic and high speed data transmission technique is replacing RF nowadays i.e. Free space optical communication (FSOC) because of its great potentials. Future generation communication systems require competent FSOC technology to sustain wireless traffic in 5G and 6G services. Because the features of FSOC and RF are complimentary, combining the two technologies is seen as a potential way to enable future communication systems. Hybrid RF/FSOC is a good way to overcome the limits of separate systems while still taking use of the beneficial aspects of each technology. Wireless systems use e.g. in hybrid RF/FSOC can increase individual network performance in terms of performance, dependability, and economical operations. In this work, a detailed review on FSOC systems is presented by doing the extensive literature review of reported research. Review covered key ideas consisting all sorts of FSOC systems, FSOC design with multiple and single beams, as part of the evaluation. The examination of rainfall and hazy effects on FSO signal transmission is also included in the review. The key benefits, future potential, and obstacles that must be addressed in order to successfully implement FSOC for 5G paradigms are presented.

1 Introduction

The FSOC system is among the most well-known wireless technologies, with a huge increase in attention and advancement over the previous decade [1]. Optical wireless communication (OWC) [2], without fiber communication [3], and Laser Communication (Lasercom) [2] are several additional terms for FSOC. FSO is recognized as a potential option to make avail-

---

✉ Charu Madhu
    charu_uiet@pu.ac.in

1   University Institute of Engineering and Technology, Panjab University, Chandigarh 160025, India

able broadband communication services to last part customers who have a special desire for point-to-point connections in clean air condition among transmission and reception. FSOCs are fundamentally the identical as fiber optic communication technologies. The distinction is that the output of an FSO is collimated and communicated via the atmosphere, whereas the optical signal is sent via an optical fiber [4]. In comparison to current technologies, FSO presents a complete solution that can handle the rapidly expanding need for bandwidth. Most crucially, FSO systems can substitute optical fiber cable in situations where lines cannot be deployed or when large capital expenditure (CAPEX) is required [5–6]. Channel capacity, immunity to electromagnetic interference, no spectrum registration, and greater data speed are only a few of the benefits of FSOC. An FSOC, on the other hand, is vulnerable to non-ideal circumstances caused by inclement weather. To put it another way, a sole beam FSOC is vulnerable to meteorological circumstances like weather instability, dust, drizzle, fog, and smog [7], which cause light source attenuation. As a result, the weather conditions for the FSO system should be fully evaluated to guarantee the sufficient power reception. Alternate approach to accomplish longer FSOC reaches, multiple and single beam system with multiple channels is demonstrated in to suppress the effects of weather instabilities [7]. Different studies are reported in literature to quell the effects of atmospheric turbulences but results are not up to the desired level [8–9]. As per our best knowledge, certain researchers have looked at FSO transmission circumstances in their studies. As a result, this paper will go through the features of FSOC link performances in tropical circumstances.

In addition, choosing the right wavelength for an FSO is a crucial decision. The safety issue of the FSO beam's impact on human vision and skin needs to be taken into account. The most widely utilised wavelength range for optical communication is 0.85–1.55 μm. FSO installers use a lot of 780 nm, 850 nm and more recently 1550 nm beams. 1550 nm wavelength is more eye-safe and delivers more power than 780 nm and 850 nm wavelengths. Light can focus on the cornea and lens at wavelengths shorter than 1400 nm, potentially endangering human vision. In contrast, the lens and cornea absorb wavelengths longer than 1400 nm. Thus, the eye is better safeguarded. Furthermore fog, smog, and haze can all be penetrated by a higher wavelength laser. Compared to 850 nm and 780 nm, the laser light with a wavelength of 1550 nm experiences less air attenuation [10].

One of the most significant environmental and developmental threats to natural ecosystems and socioeconomic systems is climate change. Consequently, natural ecosystems and human cultures are already being impacted by climate change, according to the Intergovernmental Panel on Climate Change (IPCC 2014). A system's vulnerability is a theoretical concept since it is an unobservable and unmeasurable state (Hinkel 2011). It shows that a natural environment or a socioeconomic system is more likely to suffer negative consequences [11].

Meteorological risks can result in fatalities as well as harm to buildings, infrastructure, and crops. Examples of these risks include strong winds, heavy rains, and hail. There are different types of indicators to reduce the impact of vulnerabilities. The selection of indicators depend on different hazardous weather like hail storm, heavy rainfall and windstorms. Indicators like roof slope, roof material, window glazing, presence and type of shutters, number of floors etc. [12].

Homeowners are able to evaluate the building's risk and make appropriate adjustments. When making decisions, local authorities can utilise a comprehensive understanding of the physical vulnerability and how it varies geographically within a community. The informa-

tion produced can be used by emergency services, engineers, scientists, and insurance firms to optimise building design, determine premiums, and look into the relationship between structures and natural processes. However, indicator-based vulnerability analysis is still in its infancy for buildings susceptible to meteorological warnings [12].

The following sections constitute: introduction about FSOC given in Sect. 1, general working of FSOC is elaborated in Sect. 2, detailed description of FSOC components is discussed in Sect. 3, hybrid FSOC systems are listed in Sect. 4 followed by Sect. 5 which includes conclusion and future scope.

2 Detailed Discussion of FSOC Systems

A modulated narrow optical laser beam transports the digital data from the transmitter to the receiver via the free space environment before being processed at the receiving station [13]. The ability of the transmitter and receiver at both networking locations to see each other is referred to as "line of sight." Unlike microwave systems, which require additional route clearance to allow for the development of Fresnel zones [14], IR beams have a less strict line of sight requirement since they propagate and extend in a linear manner.

The Fresnel zone is taken into account while modeling any free space channel [15]. Figure 1 depicts several instances of proper and inappropriate wireless antenna placement on towers in the Fresnel zone. Radio waves spread outward from the antenna into the Fresnel Zone, which is the area around the visible line of sight. Fresnel Zones are circular cross sections between two wireless devices that must be clear of any obstacles or impediments to prevent signal loss [16]. Because the Fresnel Zone's size is proportional to the signal's wavelength, it's been observed that the longer the wavelength, the larger the Fresnel Zone (the area that must be clear). The 5 GHz Fresnel Zone is estimated to be around half the size of the 2.4 GHz Fresnel Zone, requiring less free space between the two locations [17] to avoid difficult calculations.
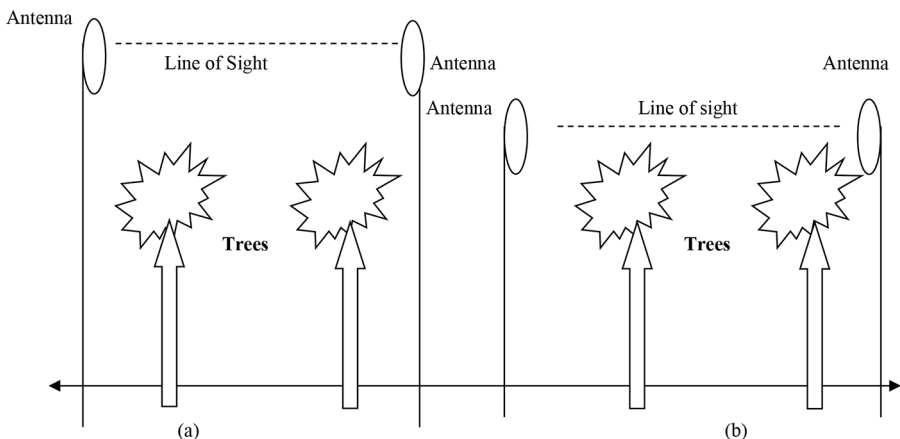

Fig. 1 Fresnel zone installation of RF systems (**a**) Correct (**b**) Incorrect [13]

2.1 FSO Transmitter and Receiver Modules

In a static configuration, the FSOC consists of three basic components: transmitter, space medium, and recipient, which are further subdivided into several components [18], as shown in Fig. 2. At the transmitter, a modulated laser beam converts an electrical signal to an optical signal. The transmitter is made up of four primary components, as indicated in Fig. 2: a laser modulator, a pulse generator, a cw laser source, and a transmission antenna [98].

Binary data stream is passed to electrical pulse linecoder and through intensity modulator and cw laser, signal is converted into optical signal. There are utmost important two types of intensity modulation that are incorporating only laser without intensity modulator and with the intensity modulator [19]. Performance of output pulse shape after external modulation is better than direct modulation because of higher efficiency of intensity modulator. For light pulse stream train, two sources can be incorporated in the system such as Laser and Light emitting diode (LED). Former one has directionality, coherence, narrow beam size and later one has broad spectrum, non-coherence, non-directionality. In order to support higher speed, high capacity and better performance, laser should be used in the system. Diverse models of lasers are available in the market such as Vertical Cavity Surface Emitting Laser (VCSEL), Distributed-Feedback Laser (DF), and Fabry-Perot (FP) [20].

The telescopic lens collects LD's photon stream and transmits binary data into the wireless medium channel. After transmitter, the channel is next component, with the open air environment serving as the propagation medium for the FSO system. This medium has been shown to have a number of concentric gas layers all across the cosmos. The troposphere, stratosphere, and mesosphere are the three basic layers that make up the hemisphere. These strata can be differentiated by their temperature gradients in relation to their elevations.
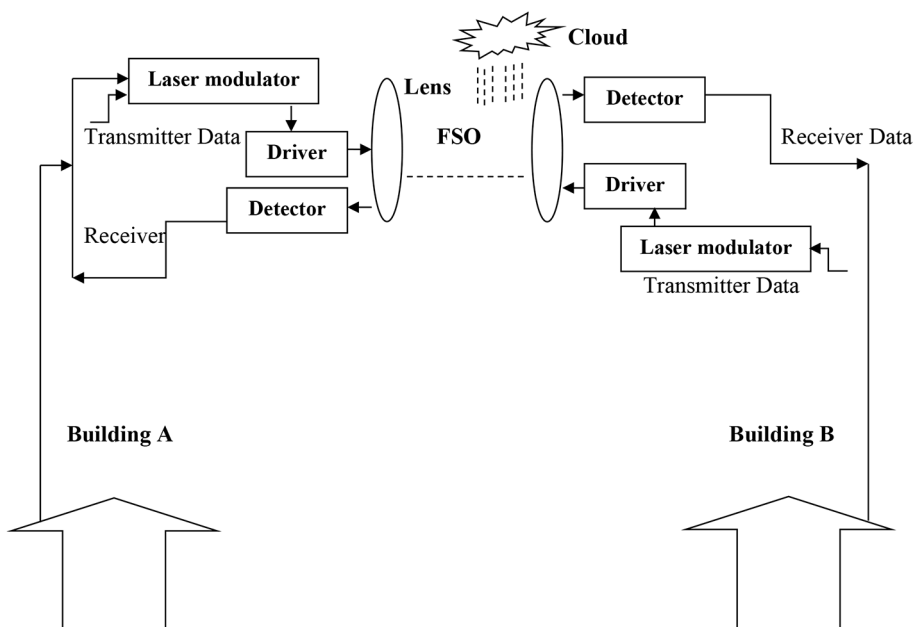

Fig. 2 FSOC transmitter and receiver (Transceiver) between two buildings [18]

FSOC communicates inside troposphere, and following operation performed like scintillation, geometrical losses, physical abstractions, absorption, and weather instability, take place in the troposphere. After signal transmission across the FSO channel, the signal is received and processed using an optical receiver as shown in Fig. 2 [21].

A telescope collects and focuses the incoming optical light from the channel, which is then directed towards the photo detector (PD). Receiving multiple uncorrelated radiations, averaging, and concentrating the radiation onto the PD all need a wide detector telescope's aperture. The averaged signal is then linked to optical filters, which filter out unwanted wavelength components and minimise solar irradiation significantly. The photodetector's detecting component is a photo diode, which is a semiconductor device that converts the photon energy of light into an electrical signal by releasing and accelerating current conducting carriers inside semiconductors. The two most often used photodiodes are the pin photodiode (PIN) and the avalanche photodiode (AVL) (APD). The possibilities are limited to only two kinds commercial-off-the-shelf (COTS) [21–22] due to their high quantum efficiency, semiconductor design, and widespread availability from commercial-off-the-shelf sources.

FSOC have amplifiers for a variety of reasons, including the following:

- The optical preamplifier can be used to enhance the intensity of optical signals that have been weakened by a range of weather instabilities.
- To obtain better eye opening.
- To effectively improve receiver sensitivity by suppressing the limiting impact of the electrical amplifier and thermal noise.

The demodulator's design is determined by the modulator's symbol set [23]. Its goal is to identify the phase of a received signal and map it back to the symbol it represents, allowing for the recovery of original data. On the other hand, the receiver must be able to match the received signal's phase to that of a reference signal [24]. Lastly, the received pulse is integrated over a one-bit period, sampled, and especially in comparison to a threshold value to decide if a 'one' or 'zero' bit is present on the demodulator side. The bit error rate (BER) is reduced to the absolute minimum using the maximum likelihood detector [25].

2.2 FSOC Classes

Single beam FSOC and multiple beam FSOC are two types of the prominently used types. Positive and negative characteristics can be found in the system categories. Figure 3 depicts a FSOC system with multiple beams with purpose of transmitting data using just one beam. The major disadvantage of a FSOC system with single beam is dispersing of light in outer space owing to weather instability caused by haze and rain. As a result, under these scenarios, the likelihood of a low power beam at receiver occurs. Therefore, employment of multiple beam is preferred to single beams FSOC system [7].

Despite its shortcomings, the economical nature of single beam FSOC is used for low cost operations and short reach systems [26]. The use of a multiple lasers approach in a multibeam FSOC decreases the deterioration of power reduction caused by atmospheric turbulence [27]. Also, notably in FSOC, the special effects of weather instabilities are reduced using this technique. One of the best examples is that it may be used to resolve detector
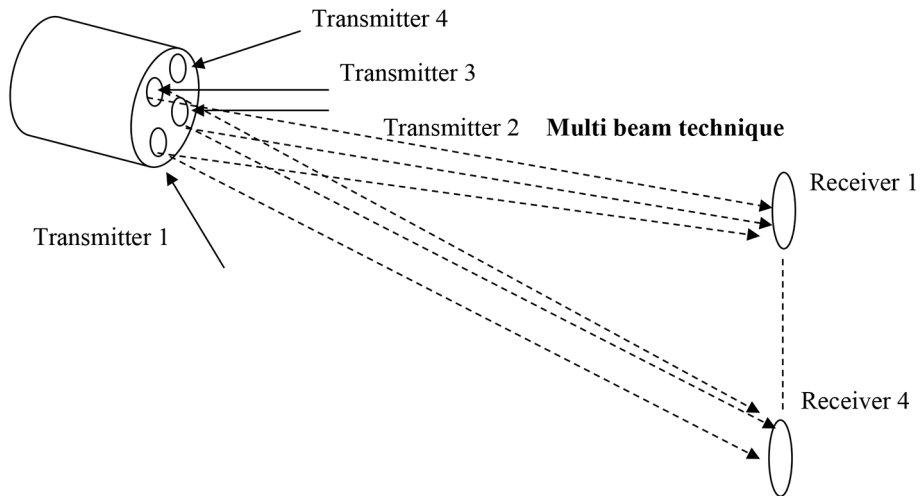
Fig. 3 Multibeam technique

beam spreading and power loss [28]. The functioning of a FSOC beams of multiple transmitter was assessed in terms of loss of transmitter and receivers, connection boundary, and power of receiver [29], regardless of atmospheric losses [30]. This technique created a "fail-safe" condition and also reduced the effects of intermittent physical impediments such as scintillation, snow, rain, insects, and birds [7]. In coastal places where reduced visibility owing to fog is regarded a limited phenomena, system with multi-beams, in meticulous, is proven to provide greater connection ease of use.

Article [7] computed the geometrical losses for a beam of single transmitter, two transmitters, three transmitters, and four transmitters and power received were 21.93 dB, 23.20 dB, 24.92 dB, and 27.959 dB, respectively. It is perceived that multiple beams increase system performance. FSOC system with multiple beams was reported at 1 Gbps and covered 1200 m. BER of $10-9$ was obtained for 1140 m link distance. Distance of 833 m covered with one transmitter, 991 m for two and 1075 m for three transmitter beams.

2.3 Modulations in FSOC Systems

A literature review looks into hybrid modulation techniques (Table 1), a novel modulation method employed in FSO communion systems. According to [31], modulation differential phase shift keying and its incorporation with multi pulse position modulation and polarization division multiplexed was performed to enhance the performance of system. Due to hybridization of the modulations, bandwidth efficiency of M-ary pulse position modulation MPPM becomes more than binary phase shift keying. The hybrid arrangement complication is decreased at the disbursement of bit error rate performance when compared to coherent demodulation of PDM-QPSK-MPPM.

This strategy involves installing a series of relay nodes between the sender and receiver [31]. The signal is received and relay node accept it and sent to the next node, and so on until bits reach at end destination. The goal of deploying a large no. of units of relays was to

Table 1 Literature of different modulations in FSOC systems

S. no.	Reference and modulations used	Conclusion
1	On Off Keying [32, 33]	Highly sensitive, moderate SNR, low cost, ease in implementation
2	OFDM [34]	Long reach, low inter symbol interference
3	QAM [35]	High spectral efficiency, more power
4	QPSK [32]	High capacity, improved spectral efficient
5	CAP [36]	less costly, implementation easy

Fig. 4 Conceptual diagram of OWC

Basestation ----- Space optical link ——— Wired backbone
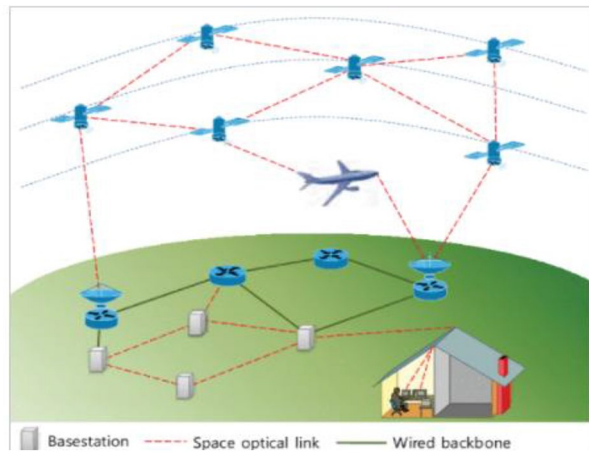
reduce turbulence and increase the FSO link's dependability. The joint modules of multiple dimensions have modulated the laser signals in various ways, improving the FSO system's bandwidth usage efficiency and BER performance.

Because the FSO system is widely employed in today's communication systems, FSO networks have become a hot issue for development for networks with link lengths ranging from a meters to kilometers [37–40]. In wireless communication technology, free space signal transmission is categorized in three different flavours such as (a) laser satellite networks (LSN) (b) Laser terrestrial wireless networks (LTWN) and Laser wireless indoor networks (LWIN) [41]. Figure 4 [42] represents aforementioned categories in single place having LSN, LTWN and LWIN [43–46].

LSN The LSNs are constructed in such a manner that they give end-users with high speed wireless optical access by utilizing satellites in outer space that cover up significant regions of globe [, 40–49]. As given in Fig. 4, line of sight is essential requirement for satellites to establish link between them and can cover earth geographical areas using constellations. Deployment of lasers in space for satellite communication has replaced RF communication due to many advantages such as security, speed, capacity and absence of electromagnetic induction (EMI). LSNs are extensively deployed in the different earth orbits such as Lower earth orbits (LEO) ranges from 160 km to 1,000 km, Medium earth orbit (MEO) extends from 10,000 to 20,000 km from earth, and Geosynchronous earth orbit (GEO) cover distance greater than 35,786 km [50].

LTWN LTWN is replacing the RF communication because of its premier advantages and nowadays, it also acting as backup of optical fiber communication due its potential to provide fiber like data rates. Optical fiber is tedious to deploy in the area like hills, intar-universities, military stations etc. The expansion in the transfer speed and limit necessities prompts a shift from RF to optical correspondence. The benefits like high velocity of requests Gbps, enormous data transfer capacity, unlicensed range, and high security expands its use in huge applications. Regardless of the various benefits, FSO has some major issues, for example, climatic condition has extraordinary deteriorative impact its exhibition [11, 51–53]. Irrespective of the advantages of FSO, it is encountered by some serious issues such as weather turbulences like rain, dust, fog, snow which limits the data rates, distance reach, and performance etc. It is also evident that even if atmosphere is clear, even though non-homogeneity arises due to temporal and spatial effects and introduces fluctuations in the refractive index which puts different effects in different wavelengths. This non-homogeneity is termed as the scintillation and it is experienced by signal at receiver due to weather through which it travelled.

LWIN Indoor communication is inevitable part of current generation and wireless fidelity is widely used which is based on RF technology [54] Optical indoor communication is an ultimate solution to RF communication due to immunity to electromagnetic interferences, high security, potential to cater high data rates, wide bandwidth and particularly a great last-mile solution [55]. Developments in optical communication is accelerating day by day and light emitting diodes are being used instead of traditional incandescent bulbs as well as fluorescent lights. LEDs has numerous advantages like ubiquitous data transmission way out, extended lifetime, economical, high switching, and power efficiency which makes it optimal for optical indoor communication typically VLC [56]. Transmission of information in VLC takes place through modulating the illumination intensity of light emitting diode more rapidly as compared to the response time of eye of human which provide high speed transmission and also at the same time solve illumination purposes. Visible light spectrum does not need regulation, no harmful to human and open up a new window for broad bandwidth services.

3 FSOC Parameters

Internal and external parameters are the two types of system parameters used by FSO.

3.1 Internal Parameters

3.1.1 Link Margin

One of the most critical aspects of system design is generating an exact link budget, which determines how well an FSO connection will function under given weather conditions [57]. A link budget, to put it another way, is a tool for estimating the margin or additional power in a connection under specific operating conditions. The projected available power based on free space losses is then calculated using this increased available power and a static model

of air attenuation. It is required to construct a link budget equation before appropriately setting an FSO system.

where $P_e(i)$ and $S_r(j)$ denote the ith transmitter power and the jth receiver sensitivity, respectively, and $\alpha_{tgoe}(i, j)$, $\alpha_{atmo}(i, j)$, and $\alpha_{sys}(i, j)$ denote geometrical, atmospheric, and system losses, respectively, between link I j). The expressions for the parameters $\alpha_{tgoe}(i, j)$, $\alpha_{atmo}(i, j)$, and $\alpha_{sys}(i, j)$ are as follows:

$$LM(i,j) = P_e(i) + |S_r(j)| - [10log_{10}\propto_{tgoe}(i,j) - [\propto_{rain}(i,j) \times d(i,j)] - \propto_{sys}(i,j) \quad (1)$$

3.1.2 Launched Power and Sensitivity of Receiver

The amount of transmitted power is the amount of optical energy launched by the FSO system. On the other hand, detector sensitivity is defined as the smallest optical input magnitude that yields a given output energy with a certain BER at the FSO system receiver. The measurement point might be at the transmitter (laser source) or detector (FSO receiver) apertures, and peak or average power is used to evaluate these two features. When recording a measurement from a laser or receiver spot, any additional losses suffered by the optical power that propagates over the entire system must be taken into account [58–59].

3.1.3 Bandwidth

This study presents new findings from research in the field of Free Space Optics (FSO) for the certification of various wavelengths for future communication (including space) [60]. Its purpose is to connect well-established technologies such as Wavelengths of 850 nm and 1064 nm, as well as 1550 nm, are now being developed, with future technologies such as 10 m wavelengths in the works.

3.1.4 BER in FSOC

The FSO system's performance may be evaluated in a variety of ways, including by looking at the BER and Q-factor. The bit error rate is defined as the number of bit mistakes detected in the receiver divided by the number of bits delivered by the transmitter (BER). When a digital transmission contains noise (unwanted signals), the receiver makes erroneous judgements, resulting in a high BER rating. For assessing optical performance and measuring the BER, Q is often one of the most essential quality variables [61]. The bit error rate (BER) and signal to noise ratio (SNR) are two metrics used to evaluate the quality of optical communication networks. Using the approach suggested by, the SNR with turbulence is stated in terms of the mean signal and noise intensity I0 and in [62].

$$SNR(dB) = 10log\left[\frac{1}{0.31C_n^2(\frac{2\pi}{\lambda})^{\frac{7}{6}}L^{\frac{11}{6}}}\right] \quad (2)$$

where λ is the wave length, L is the transceiver link distance, and C_n^2 is the index of refraction structural parameter For light to high turbulence, C_n^2 is considered to be constant, with average values of 10^{-16} to 10^{-13}.

3.1.5 Power Loss

The geometrical loss of any FSO connection is totally determined by the optical transmitters' beam width, transmitter route length, and detector aperture area.

$$P_r = 4A_r P_t / \pi (l\theta)^2 \tag{3}$$

The power of transmitter P_t which is transmitted over a total area of $\pi(l\theta)^2/4$.

The beam often extends to a radius bigger than the receiving aperture, causing the excess energy to dissipate. The multi-beam FSO system, wide detector apertures, or modest transmission divergence are employed to minimize geometrical losses. In general, under a uniform transmitted power distribution, for a single and multi-beam FSO system [63–64].

3.1.6 Misalignment Losses

Because the FSO system uses a narrow-beam (Gaussian distribution) emitter and operates in a wireless medium, alignment loss from the transmitter to the receiver is quite common. The requirement of alignment in an FSO system may be well-achieved when the Gaussian power distribution centre is positioned at the detectors' centre. This is due to the detector's inability to accurately gather light at the beam's margins, where the intensity is low. This is due to the detector's inability to accurately gather light at the beam's margins, where the intensity is low. The principal cause of misalignment in a The base motion (building sway) of buildings is a viable FSO system, especially for FSO systems installed on skyscrapers, which are prone to sway. It's possible to add an automatic pointing and tracking system with an FSO system to reduce misalignment loss, with the tracking system adjusting the FSO system for optimal alignment on a regular basis [65–68].

3.2 External Parameters

3.2.1 Rain

On FSO modulated light travelling through free space, atmospheric properties such as absorption, scattering, and non-selective scattering have a significant impact [14]. The wavelength characteristic of absorption-based attenuation is largely dependent on wavelength, with UV wavelengths experiencing the most severe absorption (below 200 nm). Aside from that, wavelength has a considerable impact on light scattering, with rain adding non-selective scattering due to large rain particles [69–70]. Fog and heavy snow are common in the European region, which has a direct influence on an FSO link [7]. The Rainfall Type Stratiform is This sort of rainfall is caused by frontal weather systems. This type of rain forms in low-pressure zones where warm air collides with chilly air. Convective clouds produce convective rainfall. These clouds form when a wet atmosphere becomes overheated in compared to the ambient temperature. The rain cell is an area of space made up of con-

nected locations when the rainfall rate exceeds a certain threshold [71–78]. A variety of studies have employed radar to assess the size and shape of rain cells [79–86]. Signal attenuation in FSO communication can also be caused by rain. The radius of the raindrops is larger than the wavelength of the FSO source. The connection may be disrupted if it rains heavily. Rain attenuation, on the other hand, has a minor effect when compared to fog. At frequencies less than 10 GHz, rain causes less specific attenuation. Rain is the primary attenuation factor for RF communications when the frequency exceeds 10 GHz. For frequencies greater than 40 GHz, the attenuations for RF connections are greater.

3.2.2 Haze

Particulate matter, often known as haze, is created when dust, smoke, and other particles are spread in the atmosphere. Mie Scattering is the name given to the phenomena because the size of the haze particles is roughly equal to the wavelength of the transmitted signal.

3.2.3 Fog

Because fog causes both dispersion and absorption, it is the most problematic communication barrier for FSOs. The density of the fog varies according to the particle size. Fog can be classified as thin fog, light fog, moderate fog, or dense fog. The fog density varies with altitude, making modelling challenging. The link is switched to RF due to the difficulty of sustaining the communication link in extreme fog. Increase the transmission power under mild fog conditions to improve the system's performance. The power budget of the system can be increased when the visible range is limited by using a multi-hop link [87].

3.2.4 Atmospheric Turbulence

Atmospheric turbulence is a random phenomena caused by changes in air temperature and pressure. The atmosphere behaves like various cells called eddies due to variations in the refractive index. The light transmission route is deflected by these eddies. The refractive index structure coefficient is used to measure turbulence. The value depending on the time of day, it changes. Another significant component reduces the optical signal along the FSO channel. Atmospheric turbulence is this factor. Atmospheric turbulence is caused by differences in refractive index along the FSO route. The FSO receiver then experiences optical scintillation. Various statistical models have been developed through time to represent atmospheric turbulence channels of varying intensities. The K distribution was chosen as a useful model for severe turbulence channels because it provides high agreement between theoretical and experimental evidence. Three forms of air turbulence are used to test the laser beam. The three are scintillation, beam wandering, and beam spreading. Random fluctuation develops in the beam when the size of the cells refractive indices exceeds the beam size, creating deflection in the beam's propagation direction. Beam wandering has an impact on signal quality. Beam spreading is the spread of a propagating optical beam in the atmosphere. To prevent beam dispersion, the average aperture radius is raised.

4 Market Growth of FSOC

Fiber optics is a fantastic solution for high data transmission, low piece errors, and serving as the backbone for web structures. The metro area has been developed to a large extent as a result of the ongoing burrowing to lay fibre. They have given deeply of their frameworks, but less liberally at the framework boundaries. In the last mile bottleneck, this lopsidedness has happened. When capital uses are required, service providers are challenged with the necessity to deliver assistance immediately and at a reasonable cost. There are a few options for addressing this last-mile network bottleneck from a development standpoint, but most aren't viable.

Fibre Optic Cable: Optical communications are fully dependent on optical mediums, and optical fibre is a capable and promising medium that is frequently used due to its numerous advantages. Despite the numerous benefits of optical fibres, there are also drawbacks, such as time spent excavating and trenching, rights of way, and licence requirements. Optical fibre cannot be relocated once installed, and joining fibres in MAN networks can cost as much as $100 000-$200 000 per kilometre, with trenching and drilling accounting for 85% of the total cost. RF communication: RF communication is used in a variety of geographical areas and is a mature technology that requires a significant investment. Although RF may reach greater distances than FSO, the capacity constraint in RF is a primary reason why FSO is preferred. RF systems can handle 622 Mbps, whereas FSO can handle several gigabits per second. FSO makes financial sense for telecom firms when it comes to extending optical communication systems.

Copper cables are practical and available in almost every place for digital subscriber loop connectivity. Even though optical fibre is much thinner than copper cable lines, hybrid systems that combine optical fibre and copper wire are not the best choice. The largest issue is bandwidth scalability, and copper wires can give a temporary answer by providing 2–3 Mbps per user.

Several factors have accelerated the need for FSO. To begin with, the end client is requiring more transmission capacity, which means that more information must be provided. In reality, by the end of 2005, the number of web users will have risen to around 796 million. It has been proved that using FSOs is not only less expensive than using fibre optics, but also less expensive than using other common improvements like DSL or link modem services. It's difficult and expensive to provide last-mile availability. In metropolitan areas, 95% of structures are planned to be within 1.5 km of fiber-optic infrastructure. In any case, they are currently unable to access it. Burrowing and digging roads are expensive and generate traffic congestion. Trees are dislodged as a result of the weather conditions. FSO supports 100 Mbps and can cater to LOS receivers. This office is a node on a metropolitan-territory ring that is linked to a territorial ring using standard fiber-optics components.

5 Advantages

Optical communication in free space provides a number of benefits over radio frequency communication. The wavelength of an RF signal is longer than that of an optical signal. The fact that FSO is more favourable than RF is demonstrated by the wavelength difference.

License Free Operations The fundamental distinction between RF and FSO is spectrum licencing. FSO does not require spectrum licence, resulting in a simple and cost-effective implementation. To avoid interference, Spectrum licencing is required for RF. The visible and infrared light spectrums can both transfer data. However, because the infrared zone does not require a licence, it is simple and inexpensive. The radiation level has been set by the International Electrotechnical Commission (Standard IEC60825-1) and must not be exceeded. The unlicensed operation is primarily due to a lack of line of sight.

Bi-Directional Communication FSO systems have the ability to communicate in both directions as well as in a single direction. They're utilised in LANs and Mans to give high capacity and data speeds through bi-directional communication.

Large Bandwidth As the carrier frequency grows, so does the data rate of transmission. The optical carrier frequency in optical communication is higher than in RF transmission. Because of the tiny beam divergence, the optical intensity of the transmitted beam power is greater at the receiver than at the RF, requiring less power. The lesser wavelength of the FSO results in a smaller antenna when compared to the RF.

High Security Because the optical beam cannot pass through walls, data communication is safe. Unlike RF, FSO beams cannot be identified using a spectrum analyzer. Without trenching and at a low cost: The procedure of laying optical fibres in the earth is known as trenching, and it is a costly operation. These free-space frameworks cost around a quarter as much as comparable ground-based fiber-optic advancements. In this way, FSO operates at a low cost.

Rapid Deployment Free-space optics enables designs to quickly set up broadband access. If the FSO can be installed below windows rather than on housetops, introducing an FSO framework should be remarkably fast, if not much faster. To communicate in free space, sender and receiver need maintain a clear vision.

6 Limitations

In Free Space Optical Communication, the optical wave propagates over free space, which is susceptible to numerous disturbances. Disturbances such as absorption, scattering, and turbulence cause the wave to be attenuated. The electromagnetic characteristics, shape, and direction of the beam are all affected by these interruptions, lowering the overall performance of the optical connection. Weather circumstances such as fog, rain, and haze affect the FSO connection distance [88]. Some of the challenges include the following:

a) **Physical obstructions**: when flying birds, trees, or towering structures occur in the line of sight (LOS) of the FSO system's transmission, they can momentarily block a single beam.

b) **Scintillation**: Due to the heat emanating from the ground and man-made drives such as heating ducts, temperature fluctuations between distinct air packets would occur.

Temperature differences can induce signal amplitude changes, resulting in "image dancing" at the FSO receiving end. The scintillation effect is handled by Light Pointe's multibeam technology.

c) **Geometric losses**: The spreading of the beam, which diminishes the signal's power level as it travels from the transmitter to the receiver, causes geometric losses, also known as optical beam attenuation.

d) **Absorption**: Water molecules floating in the terrestrial atmosphere are responsible for absorption.

e) **Air turbulence**: weather and environmental structure cause atmospheric disturbance.

f) **Atmospheric attenuation**: In most cases, fog and haze cause atmospheric attenuation.

g) **Scattering**: When an optical beam and a scatterer clash, scattering occurs. It's a wavelength-dependent phenomena in which the energy of an optical beam remains constant. However, only directional redistribution of optical energy occurs, resulting in a decline in beam intensity over longer distances.

7 Applications

The FSO communication connection is now in use for a variety of services in a variety of locations. These are detailed descriptions below:

- High security military communication systems.
- "Last-Mile" solution.
- Re-establish connectivity when fiber fails.
- Satellite communication.
- Indoor communication.
- Accelerate speed.
- Application in CCTV systems.
- In universities, science parks, industries.

8 Comparison of Different Reported Studies

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 [88]	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

S. No	Author, Publisher and Year [reference]	WDM Channels Distance and data rate	Modulation and technique	Results	Limitations
2	M. Singh et al., Springer and 2020 [89]	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 [90]	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 [91]	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 [92]	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 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 [93]	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 [94]	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 [95]	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 [96]	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 im WDM FSO	Data rate per channel was less
10	F. Hossain et al., IEEE and 2013 [97]	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 BER10^{-9} and with the increase in Tx/Rx, result improved	Distance was very short

9 Conclusion

FSO is a wireless communication technology that uses light to transport data in free space. FSO has two advantages: unlicensed spectrum and greater bandwidth. The benefits and drawbacks of the FSO system, as well as the issues that FSO and other channel types face, are discussed. The main challenges in FSO are turbulence, absorption, and scattering. To increase the quality of FSO communication, a variety of mitigation strategies are employed. It is necessary to choose and model channel distributions based on turbulence conditions in order to deploy mitigation techniques. Air turbulence mitigation, cost reduction, and improved performance are the most pressing challenges in the near future. To solve these issues, polarisation multiplexing, the best spectrum slicing approach, optical code division, multilayer modulations, the best amplifier and channel model, and other techniques can be utilised. The next-generation FSO network must be built for great scalability, with the capacity to scale up to 64 or 128 channels, providing connection to multiple end users.

Author contribution Study Conception and Design: Simran Bagga, Dr Charu Madhu and Sharmelee Thangjam. Material preparation, data collection and analysis: Simran Bagga and Dr Charu Madhu. First draft of manuscript: Simran Bagga. Approval to final manuscript: Simran Bagga, Dr Charu Madhu, Sharmelee Thangjam.

Declarations

Compliance with Ethical Standards This article does not contain any study involving animals and human participants performed by any of the authors.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article. The authors have no financial interest in any material discussed in this manuscript.

Research Data Policy and Data Availability Statements The authors confirm that the data used to support the findings of this study are available with in the manuscript and the Raw data that support the findings of this study are available from the corresponding author upon request.

Conflict of interest The authors have no financial or non-financial interest in the subject matter or materials discussed in this manuscript. This manuscript is a part of research work performed. The authors declare that they have no conflicts of interest.

References

1. Henniger, H., & Wilfert, O. (2010). An introduction to free-space optical communications, *Radioengineering*, *19*(2), pp. 203–212.
2. Nistazakis, H. E., Tsiftsis, T. A., & Tombras, G. S. (2009). Performance analysis of free-space optical communication systems over atmospheric turbulence channels. *IET Commun*, *3*(8), 1402–1409.
3. Dordova, L., & Wilfert, O. (2008). Optimal laser diode operating mode with unstable operating temperature in turbulent atmosphere, *Semiconductor Lasers and Laser Dynamics III*, *6997*(69971G), 1–11.
4. Murhty, S. S. (1979). Laser beam propagation in atmospheric turbulence, Prec. *Indian Acad Sci, C 2*(2), 179–195.
5. Jabeena, T., Jayabarathi, & Aggarwal, R. (2019). Review on optimization of wireless optical communication system'. *Trends OptoElectro Opt Commun*, *4*, 9–19.
6. Gupta, R. K. J. A., Anand, P., Khajuria, R., & Bhagat, S. (2017). A survey of free space optical communication networks, *Digital Communications and Networks*, *3*(2), pp. 67–77.
7. Al-Gailani, S. A., Mohammad, A. B., & Shaddad, R. Q. (2013). Enhancement of free space optical link in heavy rain attenuation using multiple beam concept, *Optik*, *124*, 21, pp. 4798–4801.

8. Al-Gailani, S. A., Mohammad, A. B., Shaddad, R. Q., Sheikh, U. U., & Elmagzoub, M. A. (2015). Hybrid WDM/multibeam free-space optics for multigigabit access network. *Photonic Netw Commun*, *29*(2), 138–145.

9. de Carvalho, J. A. R. P., Veiga, H., Gomes, P. A. J., Pacheco, C. F. F. P. R., & Reis, A. D. (2008). 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.

10. Naimullah, B. S., Othman, M., & Rahman, A. K., S.I.Sulaiman, S.Ishak, S.Hitam and S.A. Aljunid (2008). Comparison of Wavelength Propagation for Free Space Optical Communications, *2008 International Conference on Electronic Design*.

11. Jagmohan Sharma, Indu, K., Murthy, T., Esteves, P., Negi, Sushma, S., Shyamasree Dasgupta, A., Barua, G. B., & Ravindranath, N. H. Climate Vulnerability and Risk Assessment: Framework, Methods and Guidelines, *Indian Himalayas climate adaptation programme*.

12. Papathoma-Köhle, M., Ghazanfari, A., Mariacher, R., Huber, W., Lücksmann, T., & Fuchs, S. (2023). Vulnerability of buildings to Meteorological hazards: A web-based application using an Indicator-Based Approach. *Appl Sci*, *13*(10), 6253. https://doi.org/10.3390/app13106253.

13. Bouchet, O., & Favennec, P. N. (2012). *Wireless Optical Communication*. Wiley.

14. Hamza, A. S., Deogun, J. S., & Alexander, D. R. (2019). Classification framework for free space optical communication links and systems. *IEEE Commun Surveys Tuts*, *21*(2), 1346–1382.

15. Badar, N., & Jha, R. K. (2017). Performance comparison of various modulation schemes over free space optical (FSO) link employing Gamma–Gamma fading model, opt. *Quantum Electronics*, *49*(5), 1–10.

16. Pourahmadazar, J., Sahebghalam, S., Abazari Aghdam, S., & Nouri, M. (2018). 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.

17. Calvo, D. C., Thangawng, A. L., Nicholas, M., & Layman, C. N. (2015). Thin fresnel zone plate lenses for focusing underwater sound. *Applied Physics Letters*, *107*(1), 1–4.

18. Willebrand, H. A., & Ghuman, B. S. (2001). Fiber optic without Fiber. *Spectrum IEEE*, *38*(8), 40–45.

19. Singh, J., & Kumar, N. (2013). Performance analysis of different modulation format on free space optical communication system, *Optik*, *124*(20), pp. 4651–4654.

20. Teich, M. C., & Saleh, B. (1991). *Fundamentals of Photonics*, *3*. Wiley.

21. Malik, A., & Singh, P. (2015). Free space optics: Current applications and future challenges, *Int. J. Opt*, *2015*(945483), pp. 1–7.

22. Saurabh, S. (2014). To study the effect of fog, snow and rain attenuation on FSO link, CT int. *J Inf Commun Technol*, *2*(1), 16–22.

23. Forrest, S. R. (1986). Optical detectors: Three contenders: Depending on the application, the photoconductor, p-i-n diode or avalanche photodiode may prove the best choice. *IEEE Spectrum*, *23*(5), 76–84.

24. Juarez, J. C., Dwivedi, A., Hammons, A. R., Jones, S. D., Weerackody, V., & Nichols, R. A. (2006). Free-space optical communications for next generation military networks. *IEEE Communications Magazine*, *44*(11), 46–51.

25. Trisno, S. (2006). *Design and analysis of advanced free space optical communication systems*, Ph.D. dissertation, Univ. Maryland, College Park, MD, USA.

26. Al-Gailani, S. A., Mohammad, A. B., Shaddad, R. Q., & Jamaludin, M. Y. (2013). 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.

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

28. Kashani, F. D., Reza Hedayati rad, M., Mahzoun, M. R., & Ghafary, B. (2012). Beam propagation analysis of a multi beam FSO system with partially flat-topped laser beams in turbulent atmosphere, *Optik*, *123*(10), 879–886.

29. Md Noor, N. H., Naji, A. W., & Al-Khateeb, W. (2012). Performance analysis of a free space optics link with multiple transmitters/receivers. *IIUM Eng J*, *13*(1), 49–58.

30. Md Noor, N. H., Al-Khateeb, W., & Naji, A. W. (2011). Experimental evaluation of multiple transmitters/receivers on free space optics link, *Proc. IEEE Student Conf. Res. Dev., IEEE*, *2*, 128–133.

31. Wang, Z., Shi, W. X., & Wu, P. X. (2016). PDM-DPSK-MPPM hybrid modulation for multi-hop free-space optical communication. *Optoelectronics Lett*, *12*(6), 450–454.

32. Kaur, G., Singh, H., & Singh Sappal, A. (2017). Free space optical using different modulation techniques – a review. *Int J Eng Trends Technol*, *43*(2), 109–115.

33. Popoola, G. Z. (2013). *Optical Wireless communications: System and Channel Modelling with MATLAB*. CRC.

34. Ali, M. A. A. (2016). Performance analysis of terrestrial WDM-FSO link under different weather channel, *World Sci. News*, *56*, 33–44.

35. Ghassemlooy, Z., Hayes, A. R., Seed, N. L., & Kaluarachchi, E. D. (1998). Digital pulse interval modulation for optical communications. *IEEE Communications Magazine*, *36*(12), 95–99.

36. Salah, B., Kassa-Baghdouche, L., & Verma, A. (2019). SAC-OCDMA System with EDW codes over FSO under different conditions of Weather, *IJRAR*, *6*(2), 749–755.

37. Lesh, J. (1983). Capacity limit of the noiseless, energy-efficient optical PPM channel. *IEEE Transactions on Communications*, *31*(4), 546–548.

38. Kaur, S., M. Kumar, D., & verma, A. (2019). A Novel Hybrid Passive Optical Network, Free Space Optical and visible light communication system. *JETIR*, *6*(4), 258–261.

39. Fan, Y., & Rj, G. (2007). Comparison of pulse position modulation and pulse width modulation for application in optical communications. *Opt Eng*, *46*(6), 65–72.

40. Singh, M., Malhotra, J., ManiRajan, M. S., Dhasarathan, V., & Aly, M. H. (2021). A long-haul 100 gbps hybrid PDM/CO-OFDM FSO transmission system: Impact of climate conditions and atmospheric turbulence. *Alex Eng J*, *60*(1), 785–794.

41. Son, I. K., & Mao, S. (2017). A survey of free space optical networks, digit. *Commun Netw*, *3*(2), 67–77.

42. Son, K., & Mao, S. (Eds.). A Survey of Free Space Optical Networks, *Digital Communications and Networks*, https://doi.org/10.1016/j.dcan.2016.11.002.

43. Kaur, S., Kaur, G., Singh, G., Verma, A., & Julka, N. (2017). Polarization crosstalk suppression in Wavelength Division Multiplexed Free Space Optical System incorporating polarization diversity, *IJCRT*, *5*(3), 384–390.

44. Hranilovic, S. (2005). *Wireless Optical Communication systems*. Springer.

45. YoussefElganimi, T. (2013). Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical study, *Int. J Comput Appl*, *79*(11), 22–27.

46. Wang, Z., Zhong, W. D., Fu, S., & Lin, C. (2009). Performance comparison of different modulation formats over free-space optical (FSO) turbulence links with space diversity reception technique. *IEEE Photonic J*, *1*(6), 32–40.

47. Hossen, D., & Alim, G. S. (2008). *Performane evaluation of the free space optical (FSO) communication with the effects of the atmospheric turbulances*. BRAC Univ., Dhaka, Bangladesh, Tech. Rep.

48. Hamamreh, J. M., Furqan, H. M., & Arslan, H. (2019). Classifications and applications of physical layer security techniques for confidentiality: A comprehensive survey, *IEEE Commun. Surveys Tuts.*, *21*(2), 1773–1828, 2nd Quart.

49. Poonam, L. (2015). Performance Analysis of IsOWC System Using Advanced Modulation Formats and Schemes over Wavelength Spectrum, *IJEDR*, *3*(3), 1–4.

50. Singh, M., & Malhotra, J. (2020). 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*, *111*, 495–511.

51. Davis, C. C., Smolyaninov, I. I., & Milner, S. D. (2003). Flexible optical wireless links and networks. *IEEE Communications Magazine*, *41*(3), 51–57.

52. I. Agarwal, (2013) Performance Evaluation of Intersatellite Free Space Optical Communication System with Varied Parameters and Transceiver Diversity. *Advance in Electronic and Electric Engineering*, *3*(7), 847–852.

53. Giggenbach, D., Horwath, J., & Epple, B. (2007). Optical satellite downlinks to optical ground stations and high-altitude platforms, in *Proc. 16th IST Mobile Wireless Commun*. Summit, Budapest, Hungary.

54. Al-Kinani, A., Wang, C. X., Zhou, L., & Zhang, W. (2018). Optical wireless communication channel measurements and models, *IEEE Commun. Surveys Tuts.*, *20*(3), 1939–1962, 3rd Quart.

55. Sheikh, S., Tripathi, A., & Verma, A. (2019). Performance analysis of high speed spectrum sliced FSO System. *International Journal of Research in Engineering Science and Management*, *2*(4), 381–384.

56. Kim, D. R., Yang, S. H., Kim, H. S., Son, Y. H., & Han, S. K. (2012). Outdoor visible light communication for inter- vehicle communication using controller area network, in *Proc. 4th Int. Conf. Commun. Electron. (ICCE)*, IEEE, Hue, Vietnam.

57. Bloom, S., Korevaar, E., Schuster, J., & Willebrand, H. (2003). Understanding the performance of free-space optics [invited]. *J Opt Netw*, *2*(6), 178–200.

58. Kiran, K. V., Kumar, V., Turuk, A. K., & Das, S. K. (2018). Estimation of link margin for performance analysis of FSO network. In *Commun. Comput. Inf. Sci.*. Springer.

59. Kumar, A., Tripathi, A., & Verma, A. (2019). Mode Division Multiplexing in Free Space Optical Communication. *International Journal of Research in Engineering Science and Management*, *2*(4), 520–526.

60. Uysal, M., Capsoni, C., Ghassemlooy, A. B. Z., & Udvary, E. (2016). *Optical Wireless Communications: An Emerging Technology*. Springer.

61. Vijay, J. (2016). Comparative analysis of free space optics and single mode fiber, int. *J Adv Eng Manag Sci*, *2*(1), 33–36.
62. Alam, M. S., Shawkat, S. A., Kitazumi, G., & Matsumoto, M. (2008). IrBurst modeling and performance evaluation for large data block exchange over high-speed IrDA links. *Ieice Transactions on Communications*, *E91-B*(1), 274–285.
63. Ray, P. S. (1972). Broadband complex refractive indices of ice and water. *Applied Optics*, *11*(8), 1836–1844.
64. Sahota, J., & Dhawan, D. (2016). Overcoming Atmospheric Turbulence Using OFDMFSO System: A Review, *Second International Conference On Innovative Trends In Electronics Engineering (ICITEE2)*, vol. 20, pp. 88–91. Vidya Publications.
65. Kaymak, Y., Rojas-Cessa, R., Feng, J., Ansari, N., Zhou, M., & Zhang, T. (2018). A survey on acquisition, tracking, and pointing mechanisms for mobile free-space optical communications, *IEEE Commun. Surveys Tuts.*, *20*(2), 1104–1123.
66. Liu, X. (2009). Free-space optics optimization models for building sway and atmospheric interference using variable wavelength. *IEEE Transactions on Communications*, *57*(2), 492–498.
67. Harris, A., Sluss, J. J., Refai, H. H., & LoPresti, P. G. (2005). Alignment and tracking of a free-space optical communications link to a UAV, *in Proc. AIAA/IEEE Digit. Avion. Syst. Conf., IEEE*, *1*, 1–9.
68. Latal, J., Vitasek, J., Hajek, L., Vanderka, A., Martinek, R., & Vasinek, V. (2019). Influence of simulated atmospheric effect combined with modulation formats on FSO systems, *opt. Switching Netw.*, *33*, 184–193.
69. Babani, S., Abdulmalik, Y., Abdul'aziz, A., Loko, A., & Gajibo, M. (Jul. 2014). Free space optical communication: The main challenges and its possible solution. *Int J Sci Eng Res*, *5*(7), 1–4.
70. Achour, M. (2002). Simulating atmospheric free-space optical propagation; Part II: Haze, fog, and low clouds attenuations, *Opt. Wireless Commun.*, *4873*, Boston, MA, United States.
71. Korai, U., Luini, L., & Nebuloni, R. (2018). Model for the prediction of rain attenuation affecting free space optical links, *Electronics*, *7*(12), 1–14.
72. Maraha, H., et al. (2020). DWDM over FSO under the effect of different atmospheric attenuations. *Indones J Electr Eng Comput Sci*, *18*(2), 1089–1095.
73. Townsend, A. J. (2011). *A study of the raindrop size distribution and its effect on microwave attenuation*, Ph.D. dissertation, Dept. Electron. Elect. Eng., Univ. Bath, Bath, U.K.
74. Houze, R. (1997). Stratiform precipitation in regions of convection, bull. *Amer Meteor Soc*, *78*, 2179–2195.
75. Crane, R. K. (1990). Space-time structure of rain rate fields. *Journal Geophysical Research*, *95*, 2011–2020.
76. Konrad, T. G. (1978). Statistical models of summer rainshowers derived from fine-scale radar observations. *Journal of Applied Meteorology*, *17*(2), 171–188.
77. Goldhirsh, J. (2000). Two-dimension visualization of rain cell structures. *Radio Sci*, *35*(3), 713–729.
78. Yau, M. K., & Rogers, R. R. (1984). An inversion problem on inferring the size distribution of precipitation areas from raingage measurements. *J Atmos Sci*, *41*(3), 439–448.
79. Feral, L., Mesnard, F., Sauvageot, H., Castanets, L., & Lemorton, J. (2000). Rain cells shape and orientation distribution in South-West of France, *Phys. Chem. Earth B, Hydrol. Ocean. Atmos.*, *25*(10–12), 1073–1078.
80. Lopez, J. A., (2018) Homologated propagation models for classical channel in FSO-QKD systems, *IEEE International Autumn Meeting on Power, Electronics and, Computing (2018). (ROPEC)*, IEEE, Ixtapa, Mexico.
81. Series, R. P. (2006). *Propagation Data and Prediction methods required for the design of Terrestrial Line-of-Sight systems, document rec* (pp. 1–47). ITU, ITU-R P.530–12.
82. Gilani, S. A., Mohammad, A. B., Sheikh, U. U., & Shaddad, R. (2014). Determination of rain attenuation parameters for free space optical link in tropical rain, *Optik*, *125*(4), 1575–1578.
83. Thurai, M., Bringi, V., Gatlin, P. N., Petersen, W. A., & Wingo, M. T. (2019). Measurements and modeling of the full rain drop size distribution, *Atmosphere*, *10*(1), 1–16.
84. Giannetti, F., Reggiannini, R., Moretti, M., Adirosi, E., Baldini, L., Facheris, L., Antonini, A., Melani, S., Bacci, G., Petrolino, A., & Vaccaro, A. (2017). Real-time rain rate evaluation via satellite downlink signal attenuation measurement, *Sensors*, *17*(8), 1864.
85. Testud, J., Oury, S., Black, R. A., Amayenc, P., & Dou, X. (2001). The concept of 'normalized distribution to describe raindrop spectra: A tool for cloud physics and cloud remote sensing. *Journal of Applied Meteorology*, *40*(6), 1118–1140.
86. Best, A. C. (1950). The size distribution of raindrops, Quart. *J Roy Meteorol Soc*, *76*(327), 16–36.
87. Ojo, J. S., Ajewole, M. O., & Sarkar, S. K. (2008). Rain rate and rain attenuation prediction for satellite communication in Ku and Ka bands over Nigeria, Prog. *Electromagn Res B*, *5*, 207–223.

88. Murugan, K., Sharma, A., & Malhota, J. (2020). Performance analysis of 80 gbps RoFSO system by incorporating hybrid WDMMDM scheme. *Optical and Quantum Electronics*, *52*(505), 1–12.

89. Singh, M., & Malhotra, J. (2020). 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*, *111*(4), 825–842.

90. Chaudhary, S., & Amphawan, A. (2019). High speed MDM-Ro-FSO communication system by incorporating AMI scheme. *International Journal of Electronics Letters*, *7*(3), 304–310.

91. Thakur, A., Nagpal, S., & Gupta, A. (2018). A performance enhancement and high speed spectrum sliced Free Space Optical System. *Wireless Personal Communications*, *100*(4), 1775–1789.

92. Thakur, A., Nagpal, S., & Gupta, A. (2018). Kerr effect based spectrum sliced wavelength division multiplexing for free space optical communication, *Optik*, *157*(11), 31–37.

93. Kaur, M., & Singh, G. (2017). Analysis of different modulation formats in spectrum slices free space optical communication system, *IJCRT*, *5*(3), 448–452.

94. Shaina, A., & Gupta (2016). Comparative analysis of Free Space Optical Communication System for various Optical Transmission Windows under adverse Weather conditions. *Procedia Computer Science*, *89*(2), 99–106.

95. Zhoua, H., Mao, S., & Agrawala, P. (2015). Optical power allocation for adaptive transmissions in wavelength-division multiplexing free space optical networks. *Digital Communications and Networks*, *1*(3), 171–180.

96. Malik, A., & Singh, P. (2014). Comparative analysis of point to point FSO System under Clear and Haze Weather conditions. *Wireless Personal Communications*, *80*, 483–492.

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

98. Mikoáajczyk, J., Bielecki, Z., Bugajski, M., Piotrowski, J., Wojtas, J., Gawron, W., Szabra, D., & Prokopiuk, A. (2017). Analysis of free-space optics development, Metrol. *Meas Syst*, *24*(4), 653–674.

Simran Bagga is currently a student of M.E (Electronics and Communication) at Panjab University, Chandigarh. Her area of interest includes wireless communication and optical communication.

Charu Madhu has done her B.E. and M.E. in the field of Electronics and Communication. She got her Ph.D. in the year 2017. Currently, she is working as Assistant Professor in Department of Electronics and Communication at UIET, Panjab University, Chandigarh, India. She has several publications in reputed Journals. Her area of research includes Photonics, Nanoelectronics and Optical Communication.

Sharmelee Thangjam has done her B.E. and M.E. in the field of Electronics and Communication in the year 2000 and 2002 respectively. Currently, she is working as Assistant Professor in Department of Electronics and Communication at UIET, Panjab University, Chandigarh, India. Her area of research includes Signal Processing and Wireless Communication.