International Journal of Applied Smart Interdisciplinary Technologies (IJASIT)

Home Page: https://ijasit.org **ISSN: 3139-759X**

https://doi.org/10.68104/ijasit.v1.i3.29

Free Space Optics: Present Applications and Emerging Future Challenges

Pankaj Kumar[1], Alisha[2]

[1] Department of Physics, Akal University, Raman Road, Talwandi Sabo, Bathinda (Punjab), INDIA-151302. *pankajkullu2241@gmail.com*

[2] Department of Physical and Mathematical Science, Baba Farid College of Engineering and Technology, Bathinda, Punjab, 151002, India. *alishanarula56@gmail.com*

*** Corresponding author.**
E-mail: *pankajkullu2241@gmail.com*

Article History:
Received Date: 07 August 2026
Revised Date: 22 August 2026
Accepted Date: 28 August 2026
Published Date: 13 September 2026

Keywords:

Free Space Optics; Optical wireless communication; Line of sight; Atmospheric turbulence; Weather effects.

ABSTRACT

Free Space Optics (FSO) is a communication method that uses open space as the medium between transceivers, which must be in line of sight (LOS) for successful optical signal transmission. The medium can be air, outer space, or a vacuum. This system is suitable for communication in various environments and offers advantages like high bandwidth and no need for spectrum licensing. However, FSO performance depends on atmospheric conditions, as factors such as rain, fog, haze, physical obstructions, scattering, and turbulence can affect transmission. This paper discusses different weather conditions and methods to mitigate their impact. The review is further extended to examine the impact of haze and rain on the propagation of FSO signals. The scalability of an FSO network through the use of hybrid multi-beam FSO systems with wavelength division multiplexing (WDM) technology is the last goal we discuss.

1. Introduction

Free space optics (FSO), is an optical communication system that uses light propagation in free space to convey data and provide optical connectivity. The sole distinction between FSO and OFC (optical fibre cable) networks is that optical beams are transmitted through free air rather than OFC cores, which are made of glass fibre [1]. An optical transceiver at each end of the FSO system allows for full duplex (bidirectional) functionality. The technology of FSO communication is not new. Although it dates back to the eighth century, it has since evolved. FSO is a LOS (line of sight) technology that uses full duplex (bidirectional) connectivity to enable data, phone, and video transmission at a maximum data rate of 10 Gbps [2]. The following qualities should be present in an efficient FSO system:

a. FSO systems ought to be able to run for longer distances at higher power levels.
b. High-speed modulations are crucial for high-speed FSO systems.
c. Due to maintenance requirements, a system's overall design should have a small footprint and low power consumption.
d. FSO systems should be able to function in a wide temperature range, and outdoor systems would have less performance deterioration.
e. The system mean time between failures (MTBF) ought to exceed ten years.

2. Space-Based Applications of Free Space Optical Links

Telecom networks are struggling to provide ultra-high-speed, secure, and low-latency communication in a range of contexts, from the ground to space, due to the rapidly increasing global data needs. Free Space Optical communication fills this gap by transmitting data via light beams rather than conventional radio frequencies. The "Application of FSO Communication Links" diagram we posted illustrates how FSO technology connects terrestrial networks, satellites, UAVs, and ground stations to form a unified optical communication system, as shown in Figure 1 [3]. The main applications, deployment structures, and operating principles of FSO systems in modern communication networks will all be covered in this article.

Fig. 1. Overview of Various Applications of Free Space Optical Communication Links

By substituting laser-based connections for conventional radio frequency (RF) linkages, FSO communication is quickly revolutionizing both terrestrial and space communication systems. These optical links, which provide low latency, large capacity, and secure worldwide data transfer, are currently being used for satellite-to-satellite, satellite-to-ground, and satellite-to-aerial communications [4]. For applications including broadband internet, Earth observation, and worldwide communication, FSO systems are essential to Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellite constellations. While LEO satellites function at altitudes between 500 and 2,000 km, GEO satellites in space communication orbit roughly 35,786 km above the Earth. Inter-Orbital Links (IOL) and Inter-Satellite Links (ISL) between these satellites are made possible by FSO, enabling smooth communication across various orbits [5]. Smooth worldwide coverage and effective bandwidth utilization are ensured by GEO satellites' ability to communicate with LEO satellites as well as with one another as Figure 2. These linkages are perfect for broadband networks and Earth observation because they reduce latency and signal delay. Laser-based ISLs are used by well-known constellations like Starlink, OneWeb, and Telesat to transmit massive amounts of data quickly. FSO communication is revolutionizing mobile satellite communication for airborne and maritime platforms in addition to satellite constellations. Even when in motion or in isolated locations, ships and aircraft with FSO terminals can sustain dependable, fast internet connectivity [6]. This feature facilitates marine communication for ships and cruise ships, in-flight broadband services, and aerial relay-based disaster relief activities. Uninterrupted worldwide coverage is ensured by the system's resistance to ground-based interference, especially over remote areas and oceans. FSO is also used by unmanned aerial vehicles (UAVs) to transmit data quickly and securely. High-altitude platform stations (HAPS) that expand 5G connection, remote sensing, and military surveillance are all supported by these optical links [7]. Lightweight optical terminals, improved jamming resistance, and real-time high-definition video transmission all essential for tactical and research missions are provided by FSO-based UAV communication. FSO ground stations serve as the foundation of Earth-side communication networks. They send commands, telemetry, and data to satellites via laser beams. While requiring smaller antennas and simpler connection with current fibre networks, ground-based FSO systems offer incredibly high data throughput with lower latency than RF systems. Hybrid optical-RF systems are also used by many contemporary ground stations to provide dependability in inclement weather [8]. FSO has equally interesting terrestrial uses. To improve communication networks, FSO lines are being installed in Point-to-Point, Ring, and Mesh topologies on Earth. Point-to-Point communications provide fiber-like speeds (up to 10 Gbps) between two fixed locations, like corporate buildings or data centres, without requiring physical cables. Ring topology, which is perfect for 5G small cell systems and metropolitan area networks, uses several FSO nodes to construct a circular network in which each node connects to its two neighbours [9]. This ensures ongoing operation even if one connection breaks. By linking several nodes in a self-healing network that automatically reroutes data in the event of a breakdown, mesh topologies go beyond reliability and are appropriate for military operations, disaster relief, and smart city communication.

The technical advantages of FSO communication systems make them unique. Because laser beams are highly directed and challenging to intercept, they offer great security, multi-gigabit bandwidth similar to optical fibre, and no need for spectrum licensing or trenching for implementation [10]. Additionally, they are resistant to electromagnetic interference and RF congestion, guaranteeing steady performance in loud settings. FSO systems are easily scalable and interoperable with current infrastructure, while significantly lowering capital and operating expenses. All things considered, FSO is transforming both terrestrial and space-based communication by providing a quick, safe, and affordable substitute for conventional radio technology [11].

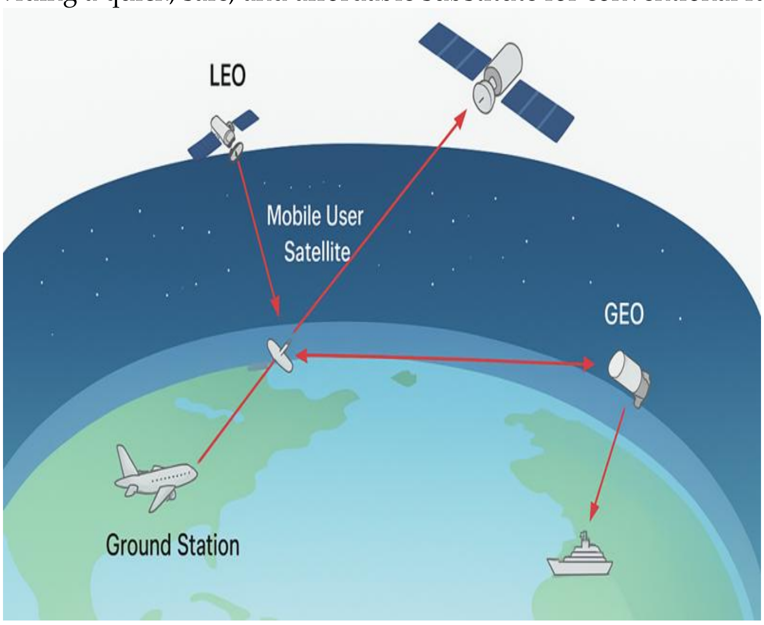

Fig. 2. Space-based applications of Free Space Optical links for satellite communication, inter-satellite data transfer, and deep-space networks

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

a. Outdoor wireless access: wireless service providers can use it for communication, and unlike microwave bands, it doesn't require a licence to utilize the FSO.
b. Storage Area Network (SAN): A SAN can be created using FSO cables. Consolidated, block-level data storage is known to be accessible via this network.
c. Last-mile access: Because it would make sense to build as much fibre as possible, it is very expensive for service providers to install user cables in the last mile due to the high cost of digging. By integrating FSO with other networks in the final mile, this issue can be resolved. Bypassing local-loop systems in other types of networks is another use for it [12].

d. Enterprise connectivity: Installing FSO systems is simple. Because of this functionality, it can be used to connect two buildings or other properties by connecting LAN segments.
e. Fibre backup: If transmission via a fibre link fails, FSO may also be used to provide a backup link.
f. Bridging WAN Access: FSO is useful in WAN because it serves as a backbone for high-speed trucking networks and supports high-speed data services for mobile users and small satellite terminals [13].
g. It can be used for both short- and long-range communication between point-to-point links, such as two buildings or two ships, and point-to-multipoint links, such as from an aeroplane to the ground or a satellite to the earth.
h. Military access: It is appropriate for military applications since it is a safe, undetectable technology that can connect vast areas with little preparation and deployment time.

These merits indicate the significance of the FSO system over different communication systems. Comparison of different systems based on various parameters is mentioned in Table 1 [14].

Table 1
Comparison of Free Space Optics with other communication systems based on key performance parameters.

Parameter	Free Space Optics (FSO)	Optical Fiber Communication	Radio Frequency (RF)	Microwave Communication	Satellite Communication
Bandwidth	Very high (in THz range)	High (GHz range)	Limited (MHz–GHz)	Moderate (GHz range)	Limited (MHz–GHz)
Data Rate	Up to several Gbps or more	Up to several Tbps	Mbps–Gbps	Mbps–Gbps	Mbps
License Requirement	Unlicensed	Licensed (depends on region)	Licensed	Licensed	Licensed
Installation Cost	Low (no trenching or cables)	High (fiber deployment required)	Moderate	Moderate	Very High
Maintenance	Low	High	Moderate	Moderate	High
Signal Interference	Immune to EMI/RFI	Immune	Prone to interference	Moderate	Prone to space interference
Security	High (narrow beam, hard to intercept)	High	Low–Moderate	Moderate	Low
Environmental Effects	Affected by fog, rain, turbulence	Minimal	Affected by weather to some extent	Moderate	Weather and atmospheric delays
Mobility	Limited (requires line of sight)	Fixed	High	High	Very High
Range	Up to a few kilometers (LOS)	Long (hundreds of km with repeaters)	Medium	Long	Very Long (global)
Deployment Time	Fast	Slow	Moderate	Moderate	Slow

3. Limitations of FSO

The benefits of free space optics are readily apparent. However, some environmental issues are inevitable because FSO uses air as its transmission medium and light travels through it. The majority of atmospheric phenomena took place in the troposphere [14]. Figure 3 illustrates how these restrictions affect the atmosphere.

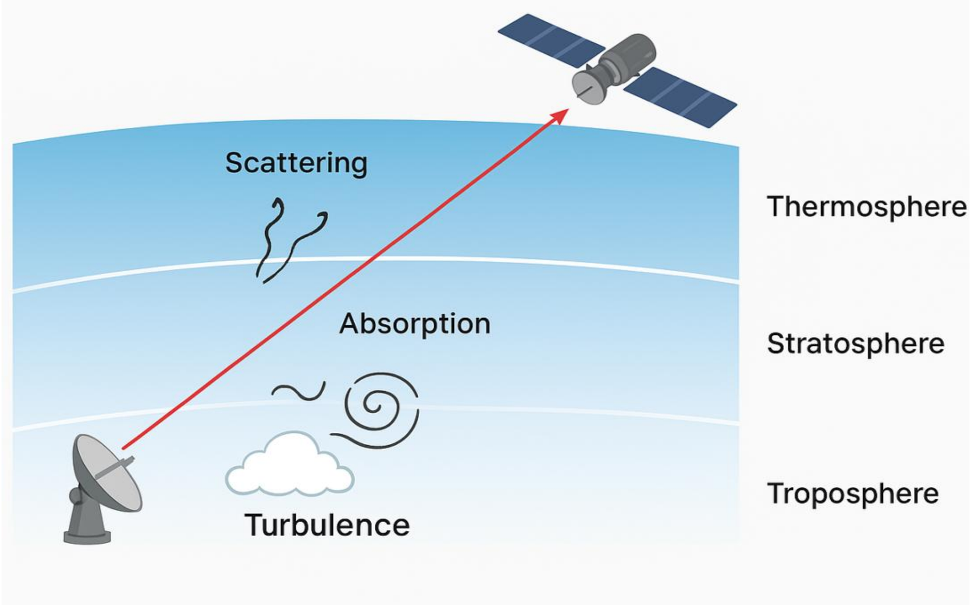

Fig. 3. Atmospheric effects influencing Free Space Optical communication links

Below is a brief description of a few of these restrictions:

a. Physical barriers: When a single beam emerges in the line of sight (LOS) of the FSO system's transmission, it can be momentarily blocked by flying birds, trees, and towering buildings.

b. Scintillation: Because of the heat emanating from the earth and artificial drivers like heating ducts, there would be temperature differences between various air packets. The signal's amplitude may fluctuate as a result of these temperature changes, leading to "image dancing" at the FSO receiving end. Light Pointe's special multibeam system addresses the effect of scintillation [15].

c. Geometric losses: Also known as optical beam attenuation, geometric losses are caused by beam spreading, which lowers the signal's power level as it moves from the sent end to the receiving end.

d. Absorption: The water molecules floating in the terrestrial atmosphere are responsible for absorption. These particles would absorb the power of the photons. Absorption immediately affects the availability of transmissions in an FSO system and reduces the power density of the optical beam. Signal absorption can also be caused by carbon dioxide [16].

e. Atmospheric turbulence: weather and environmental structure cause atmospheric disturbance. It is brought on by convection and wind, which combine air parcels with varying temperatures. This results in variations in air density, which in turn affects the air refractive index [18]. The turbulence cell's scale size can have a variety of effects, the most prevalent of which are listed below:

   i. Beam wander would be the main effect if the turbulence cell's width were greater than that of the optical beam. The fast shifting of the optical beam point is known as beam wander.

   ii. The optical beam's intensity fluctuation or scintillation predominates if the turbulence cell's diameter is lower than the optical beam. The optical beam of transmission may deteriorate as a result of turbulence. A shift in the refractive index results in beam refraction at various angles and optical beam spreading.

f. Atmospheric attenuation: Fog and haze typically cause atmospheric attenuation. Rain and dust are also factors. Contrary to popular belief, air attenuation is not wavelength-dependent. Wavelength affects haze. In hazy weather conditions, attenuation at 1550 nm is lower than at other wavelengths [19]. In foggy conditions, attenuation is independent of wavelength.

g. Scattering: When the optical beam and scatterer clash, scattering processes take place. It is a wavelength-dependent phenomenon in which the optical beam's energy remains constant. However, only directional redistributions of optical energy occur, which causes the beam's intensity to decrease over longer distances. There are three categories of atmospheric attenuation [20]:

   i. Molecule scattering is another name for Rayleigh scattering.
   ii. Aerosol scattering is another name for Mie scattering.
   iii. Geometric scattering is a type of nonselective scattering. The scatterer's physical size determines the type of dispersion.
   iv. Rayleigh scattering occurs when it is smaller than the wavelength.
   v. Mie scattering occurs when the scatterer's size and wavelength are similar.
   vi. Nonselective scattering occurs when it is significantly larger than the wavelength.

4. Atmospheric Weather Conditions

An FSO link uses the atmosphere as its transmission medium. Its attenuation is dependent on a number of factors. The primary cause of attenuation is the weather. To have prior knowledge of attenuation, the area where a link is being constructed must have certain weather conditions. For instance, the two main weather conditions in temperate climates are fog and heavy snow. The availability of FSO links in tropical regions is significantly impacted by two primary weather conditions: heavy rain and haze [20]. Below is a description of some of the weather conditions.

a) Fog.

Visible radiation is significantly attenuated by fog. The obstruction generated by fog absorbs, scatters, and reflects an optical beam of light. Increasing the transmitted power is a major factor in fog-induced scattering, sometimes referred to as Mie scattering [21].

(b) Rain.

Rainfall causes rain attenuation, which is a nonselective scattering. Wavelength has no bearing on this kind of attenuation. Rain might cause fluctuations in laser delivery. The amount of rain determines how visible the FSO system is. When there is a lot of rain, the solid composition of the water droplets can either change the characteristics of the optical beam or limit its passage as it is absorbed, dispersed, and reflected [22].

(c) Haze

Haze particles can cause atmospheric attenuation by remaining in the air for extended periods of time. Therefore, the visibility level at that moment determines the attenuation values. There are two methods to collect data on attenuation in order to assess the FSO system's performance: first, the system can be temporarily installed at the site and its performance evaluated; second, the Kim and Kruse model can be used [23].

(d) Smoke

It is produced when various materials, including carbon, glycerol, and home emissions, are burned. It impacts the gearbox medium's visibility [24].

(e) Sandstorms

The most well-known issue with outdoor link transmission is sandstorms. The size of the wind particles, which is determined by the texture of the soil, and the wind speed required to blow the particles up in the shortest amount of time, are two approaches to characterize these [25].

(f) Clouds

The earth's atmosphere is primarily composed of cloud layers. Water condenses or deposits above the surface of the earth to create clouds. The portions of optical beams that are transmitted from Earth to space can be totally blocked by it. Because cloud particles are diverse and non-uniform, it is challenging to compute the attenuation caused by clouds [26].

(g) Snow

The geometric scattering is caused by the bigger particles seen in snow. The impact of the snow particles is comparable to Rayleigh scattering [27].

5. Different Studies Based on Attenuation Effect

To create new models based on the system's effectiveness, several researches are conducted under various weather conditions. These studies are mostly concerned with weather conditions such as fog, haze, rain, and snow. The findings of this research can be used to inform real system decisions. The authors of a study used both theoretical and experimental research to examine the impact of smoke and fog. The laboratory-based empirical hypothesis suggesting the most lasting wavelength windows are 830, 940, and 1550 nm was confirmed by experimental results. The results indicate that the disambiguation is decreasing linearly when the experimental results for the continuous attenuation spectrum of fog and smoke conditions are compared using an empirical model [28]. The author investigates whether or not fog depends on wavelength in another investigation. In an experimentation chamber, a fog-like atmosphere is created. It has been confirmed that fog-induced attenuation is a wavelength-dependent characteristic. Power is measured at the receiving end in both fog-filled and fog-free scenarios using an FSO link with parallel wavelengths of 830 nm and 1550 nm in the same chamber. Mie theory can be used to quantify the scattering caused by fog particles. The attenuation caused by fog can be calculated using one of the three well-known models empirical, Kim, and Ferdinandov [29]. Rain-based research examines the relationship between precipitation rates and rain attenuation at a short wavelength (785 nm). The turbulence model is determined by comparing measured data with estimated results using the four-existing-model rain attenuation [30]. Another study focusses on how variations in rain intensity affect the forecast of its attenuation. To investigate the relationship between FSO and fluctuations in rain intensity, seven reduction format models are analyzed. One model has a reduction factor value of 0.7, whereas six models have a value of unity. It shortens the FSO link's effective path length. When the rain rate is low, the distribution of rainfall along a longer path appears to be more dispersed; when the rain rate is high, it appears to be more concentrated [31]. The impact of tropical Malaysian weather on FSO links is examined in a study using the single and multiple transceiver concept based on the received power and link distance values. It is determined that, depending on the signal-to-noise ratio (SNR), geometrical and atmospheric losses, and bit error rate (BER), a four-beam FSO system can function effectively during heavy rain for a greater distance [32].

6. Various Techniques to Enhance System Performance

Numerous methods are being introduced to improve system performance. A detailed discussion of some of these methods is provided below, and the section that follows compares them.

6.1 Performance of SAC OCDMA-Based FSO System

The researchers employ the Spectral Amplitude Coding Optical Code Division Multiple Access technology in the FSO system as Figure 4. The flexibility of channel allocation, the ability to operate asynchronously, the improvement of privacy, and the expansion of network capacity are only a few benefits of this multiplexing method [33]. SDD (spectral direct decoding) is used in conjunction with KS (Khazani-Syed) codes. The code sequence is modulated with data using an optical external modulator (OEM). The information is a separate, unipolar digital signal [34]. A combination of modulated code sequences is sent across the FSO link using a Mach-Zehnder modulator (MZM), and an optical splitter at the receiving end separates these sequences. To prevent interference at the receiver end, the overlapping chips are deleted, and the decoder only filters the nonoverlapping chips [35]. Optical band pass filters are used as decoders and encoders. The original data is recovered using a low-pass filter (LPF). This system's performance utilizing the SDD technique is compared to that of the FSO system using the intensity modulation with direct detection (IM/DD) technique. The link distance is increased by 22.7% and the SDD approach works better [36].

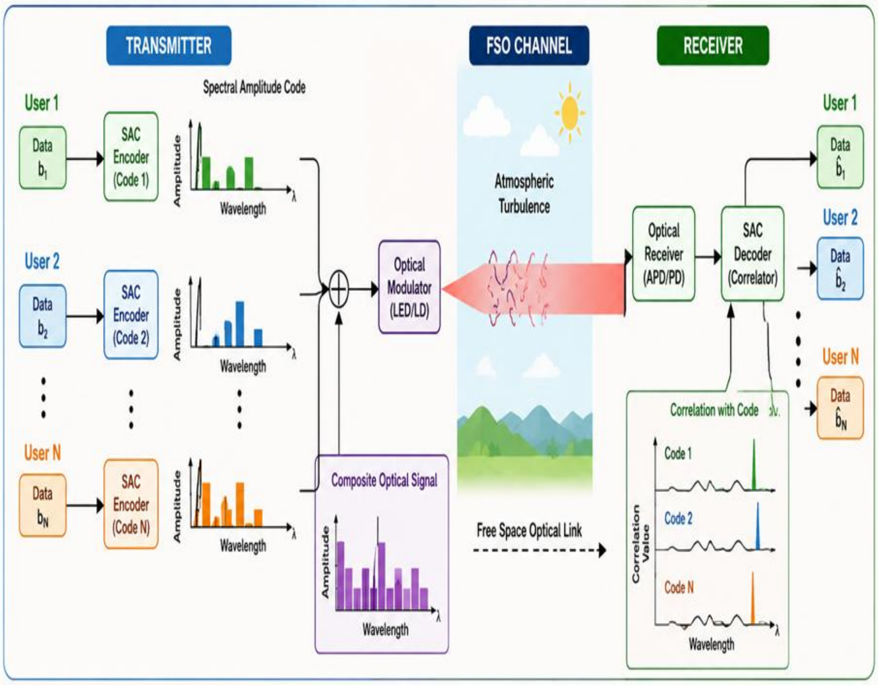

Fig. 4. Schematic illustration of Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) technology in a Free Space Optical communication system

6.2 High Speed, Long Reach OFDM-FSO Transmission Link Incorporating OSSB and OTSB Schemes

An attempt has been made to investigate the effects of environmental variables and to develop a high-speed, long-range FSO system immune from multipath fading by incorporating the OFDM scheme. Various weather conditions, such as clear, foggy, and hazy channels, are employed to simulate various system circumstances [37]. CW laser diodes are employed with a wavelength of 1550 nm and a line-width of 10 MHz. The optimal antenna aperture is 15 cm, and the hybrid system must consume 0 dBm of power. A 4-QAM sequence generator produces the data at a rate of 5 Gbps, and an OFDM modulator with 512 subcarriers is employed [38]. Instead of employing the ODSB scheme, which is prone to fading issues, OTSB/OSSB techniques are used to send the data via the FSO link. A phase shifter and a Dual Electrode Mach-Zehnder Modulator (DEMZM) are used to accomplish this modulation. The hybrid OFDM-FSO system is found to perform better in a variety of channel situations. When OSSB and OTSB schemes are compared, OSSB outperforms OTSB at high data rates because it is more resistant to fading caused by weather [39].

6.3 Optimization of Free Space Optics Parameters Using WDM System

The researchers designed a unidirectional WDM system as mentioned Figure 5. The number of users, data throughput, power, link range, and channel spacing are all optimized based on the weather. For light, medium, and severe rain, the attenuation is 6.27, 9.64, and 19.28 dB/km, respectively [40]. Because there is less attenuation than at any other wavelength, 1550 nm is the ideal wavelength for both rain and haze. Prioritizing parameter optimization is necessary to improve system performance. In this work, geometric losses are not considered. The top priority is optical amplifier gain, followed by laser power, data rate, aperture size, and link length. The data throughput for a 150-kilometer journey might approach 2.5 Gbps in clear conditions [41]. The FSO system can be optimized for successful transmission in severe weather circumstances by using a short link distance and a reduced data rate [42]. These investigations are compared according to various factors such as wavelength, power level, data rate, and link distance. Table 2 summarizes all parameters using various methods, indicating that the link distance decreases with increasing attenuation [43].

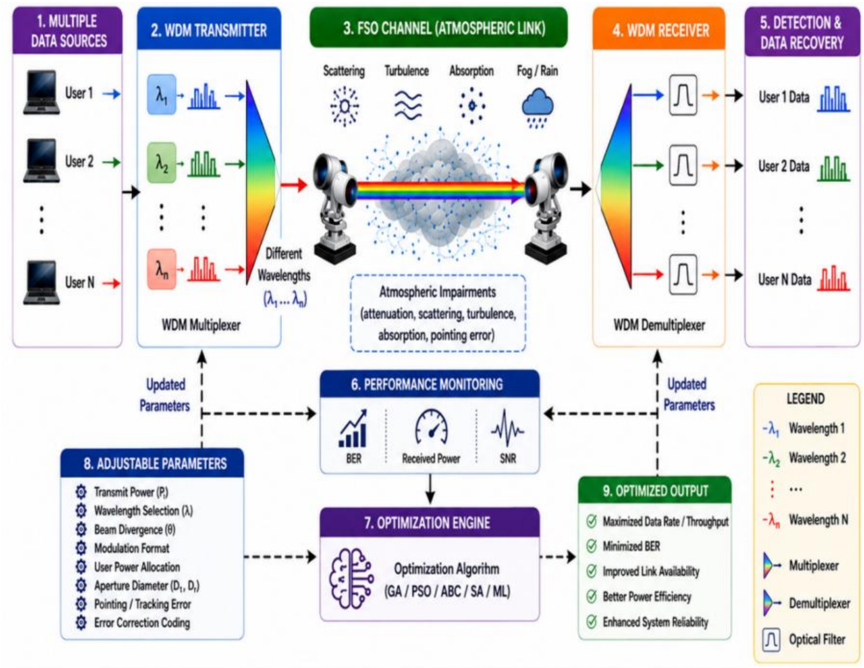

Fig. 5. Schematic representation of optimization of Free Space Optical communication parameters using a Wavelength Division Multiplexing (WDM) system

Table 2 Summarization of various Free Space Optics techniques demonstrating the performance and adaptability of different configurations under varying operational conditions.

Study / Technique	Wavelength (nm)	Transmitted Power (mW or dBm)	Data Rate (Gbps)	Link Distance (km)	Key Features / Remarks
Direct Line-of-Sight FSO	850	20 mW	1	1.5	Simple setup; moderate performance under clear weather
WDM-Based FSO Link	1550	10 dBm	10	2	High data rate using multiple wavelength channels
MIMO-FSO System	1550	15 dBm	5	3	Improved reliability under atmospheric turbulence
Hybrid RF/FSO Communication	1550/2.4 GHz	12 dBm	2	4	Provides link redundancy during fog or rain conditions
Adaptive Optics-Assisted FSO	1550	8 dBm	10	5	Compensates for atmospheric distortions; enhanced range
Modulation-Diversity FSO (OOK, PPM)	850-1550	10 dBm	1–2.5	2	Trade-off between power efficiency and bandwidth
Machine Learning-Based FSO Optimization	1550	Variable	Up to 20	10	Intelligent control for turbulence mitigation and power optimization

Link distance decreases as data rate increases. Depending on the power level, link distance improves as the power level rises. If the power level is high, the effect of attenuation is reduced, but the power level cannot be raised over the value specified by different organizations that establish the laser safety concept. A human eye, for example, can be impacted by a laser when it comes into direct contact with it at a specific wavelength and power, such as 10 mW power for a Class 1 M laser at a wavelength of 1550 nm that is allowed by IEC (International Electrotechnical Commission) standards [44].

7. Present Applications of Free Space Optics

7.1 Atmospheric Effects on Communication Links

The atmospheric conditions impact the communication processes between ground stations and satellites, as well as satellite-to-ground interactions as Figure 6. FSO technology leverages environmental opportunities that possess characteristics similar to both time and space variables. In terms of inter-satellite FSO connections, several limiting factors come into play, including link availability, background noise levels, and precise pointing requirements [45]. This paper addresses various challenges faced by data engineers concerning laser uplink/downlink operations alongside inter-satellite FSO links. Notably, these links are insulated from atmospheric variations or disturbances caused by cloud cover due to the fact that satellites operate at altitudes above the atmosphere's influence. A practical test was conducted involving two satellites moving at significant relative speeds to evaluate their acquisition and tracking capabilities [46]. Given the extensive distances involved in inter-satellite communications, it is crucial for transmission methods to exhibit high power efficiency while maintaining good sensitivity on the receiving end. Therefore, coherent phase techniques such as homodyne or heterodyne detection are preferred over direct detection approaches for inter-satellite FSO links because they offer enhanced sensitivity at high-capacity channels. Currently, one of the highest transmission rates recorded between Low Earth Orbit (LEO) satellites stands at 5.6 Gbps using homodyne Binary Phase Shift Keying (BPSK) [47]. The European Data Relay Satellite System (EDRS), developed by a prominent European space agency in 2014, successfully demonstrated a connection between Alphasat in Geostationary Orbit (GEO) and Sentinel-1 in LEO with a data rate of 1.8 Gbps. A thorough analysis was necessary regarding elements influencing intersatellite FSO links across a distance of 1000 km operating at speeds up to 2.5 Gbps; this examination took into account that these FSO connections remain unaffected by climatic conditions or airspace limitations. Nevertheless, difficulties stemming from Doppler shifts, background radiation interference during acquisitions along with point-ahead angles must be addressed alongside ensuring stable satellite platform performance these issues represent critical constraints affecting all cases related to FSO technology.

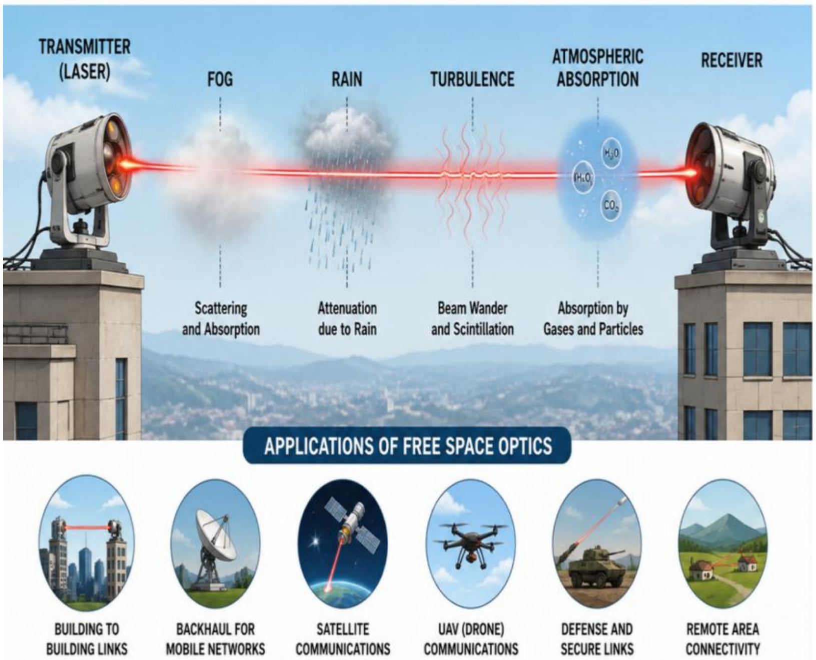

Fig. 6. Schematic illustration of Free Space Optics communication links and the influence of atmospheric effects on signal transmission.

7.2 5G and Beyond Networks

As floating base stations (BSs) are set to play a crucial role in data transmission within 5G free space optical (FSO) networks, an atmospheric turbulence suppression algorithm has been developed as Figure 7. This algorithm employs avalanche photodiode adaptive gain control (APDAGC), which enhances the performance of laser beam transmission by addressing atmospheric disturbances that directly impact FSO link efficiency [48]. The results demonstrate exceptional performance from APDAGC regarding bit error rate (BER) and intensity fluctuations. Additionally, this technology can be utilized on airship platforms for 5G FSO data transfer.

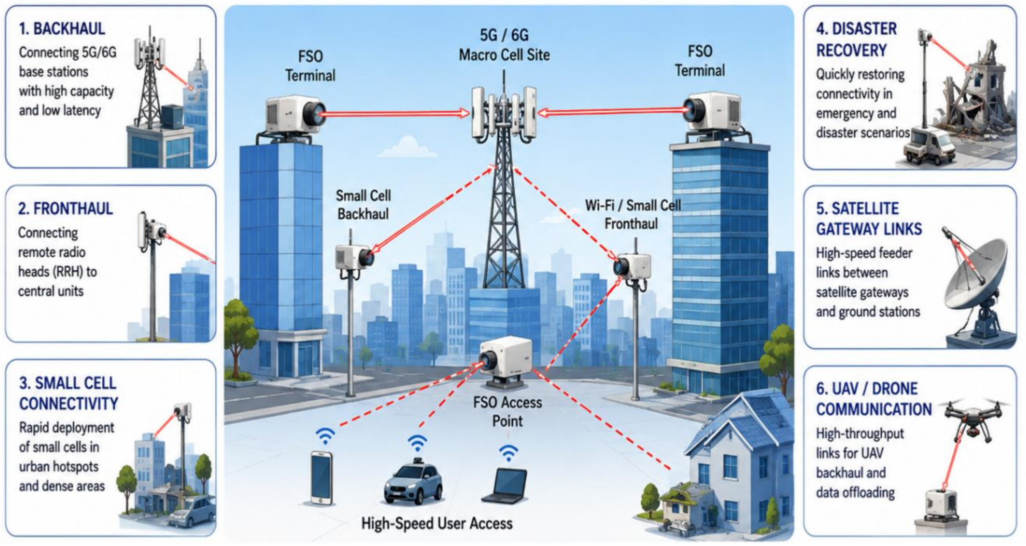

Fig. 7. Illustration of the applications of Free Space Optics technology in 5G and beyond wireless communication networks.

The analysis indicates that adaptive gain control surpasses fixed gain methods; indeed, actual BER measurements exceed theoretical calculations. Specifically, the established two-way 5G FSO link facilitates a feasible connection allowing an air platform BS to transmit a laser signal at speeds of 2.5 Gbps from airships to ground stations with downlink and uplink rates of 854 Mbps and 149 Mbps respectively. Moreover, there is an investigation into the efficacy of a WDM FSO system operating at 16×10 Gbps across various regions in India specifically hilly, plain, coastal, and desert areas for implementing effective communication under the umbrella of 5G technologies [49]. This proposed project integrates digital signal processing along with orthogonal frequency-division multiplexing (OFDM) techniques to mitigate channel-induced limitations while also incorporating erbium-doped fiber amplifiers (EDFA) characterized by optimized gains.

Results indicate that in coastal locations where weather disturbances are minimal the achievable link distance reaches up to 10.75 km with a BER rating of 10-9. Conversely, links situated within plains and deserts attain distances measuring 6.53 km and 7.85 km, respectively with both maintaining identical BER levels at 10-9 as well; however, these figures drop significantly in mountainous terrain where only a reach of about 5.3 km is possible [50]. This system's operational characteristics suggest it would be highly beneficial for use within mobile networks supporting IoT technologies due to its capacity for high-speed connectivity reaching up to 160 Gbps. Notably though some challenges persist such as installing optical fiber networks over rugged terrains like mountains a problem potentially alleviated through hybrid RF/FSO systems designed as backup options utilizing free-space optics connections instead. Additionally, presented is experimental work demonstrating a 200 Gbps multi-wavelength WDM-based FSO communication framework leveraging directly modulated TOSA technology capable of transmitting eight distinct laser beams across wavelengths ranging between 1545-1557 nm [51]. The findings affirm that employing four-level pulse amplitude modulation (4-PAM) boosts overall system capacity effectively achieving outdoor test conditions yielding throughput rates around 25 Gbps using this modulation technique alone. As a continuation, both one-hop and forwarding systems were evaluated based on eye diagrams and Bit Error Rate (BER), utilizing 8×25 Gbps for a 50-meter outdoor link between two buildings [52]. The findings indicate distinct eye diagrams along with consistent BER performance across all wavelengths in the one-hop system. Conversely, the BER for the forwarding system fluctuates between 1E-2 to 1E-3 over duration of 30 minutes [53]. Overall, the performance of this system is appropriate for FSO fronthaul/backhaul communication in fifth-generation wireless cellular networks as well as extending optical access networks since it achieves low power consumption alongside high link reliability through an effective channelization scheme.

7.3 Post-Flood Based UAV Communication

FSO presents a compelling option during flood events when traditional base stations across multiple cities are compromised, as it facilitates connectivity to affected regions while minimizing disruption in nearby unaffected areas. FSO technology offers high data bandwidth and enables quick deployment without the need for spectrum licensing fees. Additionally, light signals can easily penetrate through water droplets [54]. While satellites and High-Altitude Platforms (HAPs) may cover broader geographical zones, they require longer timescales for deployment. Given the swift setup capabilities of Unmanned Aerial Vehicles (UAVs), an UAV-based FSO system is proposed to serve as a wireless access solution aimed at enhancing recovery communications amidst flooding situations as Figure 8.

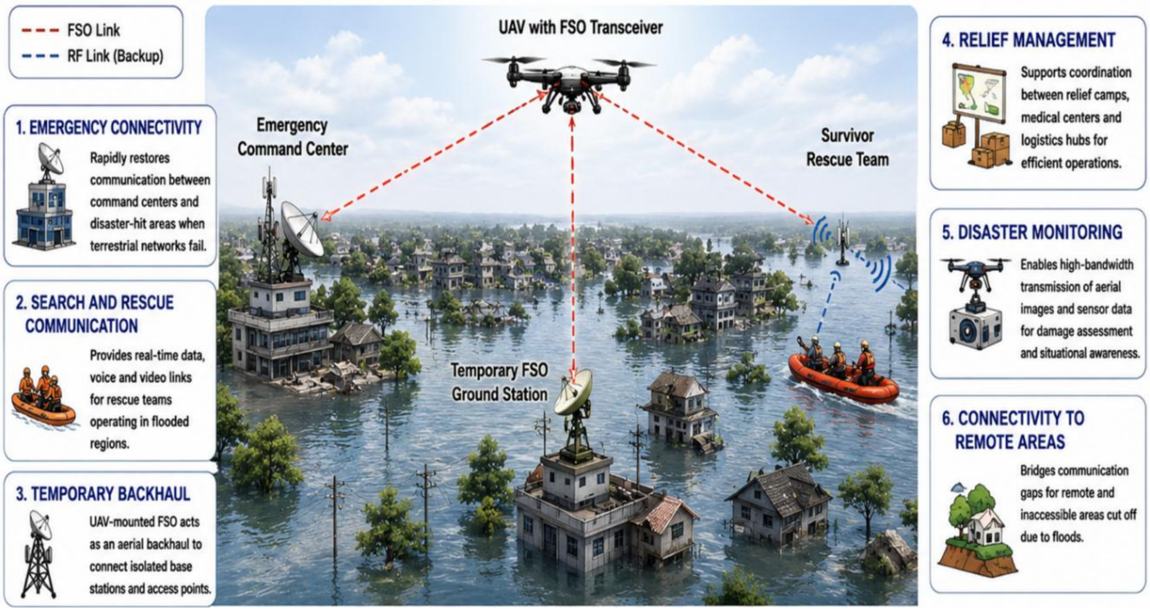

Fig. 8. Proposed UAV-based Free Space Optics communication system for post-flood disaster recovery and emergency wireless access.

Prior work has established various UAV-based FSO methodologies focused on facilitating recovery communications between base stations, addressing aspects such as downlink scheduling, positioning of FSO transceivers, divergence angles, or integrating hybrid radio frequency (RF)/FSO connections [55]. A significant challenge facing UAV-centric FSO systems involves preserving a high Signal-to-Noise Ratio (SNR) between the base station and relay units; this proves difficult due to rapid movements from both the UAV's propellers and its body which cause quick variations in beam alignment coupled with scattering effects from floodwaters. This situation often results in frequent interruptions of communication links. To mitigate these challenges, implementing spatial mode diversity is suggested to enhance system resilience against disturbances caused by UAV motion.

The use of spatial modes as separate information carriers through space division multiplexing (SDM) techniques has recently attracted attention amid concerns over potential data capacity shortages. Spatial modes introduce an additional dimension into wireless communication systems: within SDM frameworks, distinct beams carrying independent data are arranged along different spatial paths that can be multiplexed at the transmitter's aperture for simultaneous transmission and subsequently demultiplexed at the receiver's aperture with minimal interference [56]. To bolster an FSO network's robustness further, various forms of multiplexing encompassing amplitude, frequency, polarization, and time-domain strategies have been utilized. Recently explored avenues include leveraging new degrees of freedom based on spatial modes; this approach allows concurrent transmission across several spatial configurations without requiring separation among apertures thereby reducing equipment size requirements. Each individual spatial mode experiences unique refractive index fluctuations resulting from atmospheric turbulence even though all travel along identical pathways [57]. By utilizing these spatial modes for transmitting independent streams of data effectively enhances link reliability while helping avert potential disruptions within networks.

Several methods for achieving spatial mode diversity in FSO systems have been explored. One study utilized spatial mode diversity alongside multiple pairs of transmitter-receiver apertures to enhance the reliability of FSO links amid atmospheric turbulence. In this instance, three aperture pairs were employed, with each pair using a Gaussian beam and an Orbital Angular Momentum (OAM) beam simultaneously in both uplink and downlink directions to transmit the same data stream. Another research designed a three-mode photonic lantern coupling FSO receiver combined with digital maximal ratio combining techniques, resulting in an improvement of over 10 dB in the worst signal-to-noise ratio (SNR) while also reducing interruption probability due to atmospheric disturbances.

Additionally, there was a demonstration involving three-mode reception via free-space optical links connecting low-Earth orbit satellites to ground terminals through mode coupling into few-mode fibers aimed at tracking power variations across different elevation angles. To minimize outage probabilities, one approach implemented aperture diversity by utilizing several transmitting apertures that sent identical data streams on fundamental Gaussian beams; concurrently, mode diversity was achieved through multiple receiving apertures that decomposed incoming beams into various OAM modes paired with digital signal processing. Moreover, OAM modes contributed to spatial mode diversity within a 2 km FSO link intended for enhancing system capacity and link resilience. The overall channel capacity saw maximization by carefully selecting optimal OAM modal numbers corresponding to specific SNR values and turbulence conditions. Spatial mode diversity applications also extended into photonic crystal fibers as demonstrated in prior studies. An additional strategy showcased involved employing Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) modes of equivalent dimensions which improved bit error rates by up to 54% without necessitating any increase in total transmitted power or receive aperture radius. Furthermore, strategies leveraging unmanned aerial vehicles (UAVs)-based FSO technology have been investigated aiming at extending coverage between base stations during emergency communications amidst natural disasters focusing particularly on aspects such as downlink scheduling along with the positioning of FSO transceivers alongside hybrid RF/FSO connections.

7.4 Military and Defense

In Free Space Optical Communication (FSOC), light is directed through a free-space medium to transmit information for remote communication across various domains, including space, land, air, sea, military operations, and civilian uses as Figure 9. This technology facilitates connections between different source points such as receivers (Rx), transmitters (Tx), handsets, machines, and networks that require Line of Sight (LOS) [60]. FSOC offers several advantages: it has lower costs and shorter setup times compared to Radio Frequency (RF) networks; it provides immunity from Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC); and its equipment is generally simpler than RF systems.

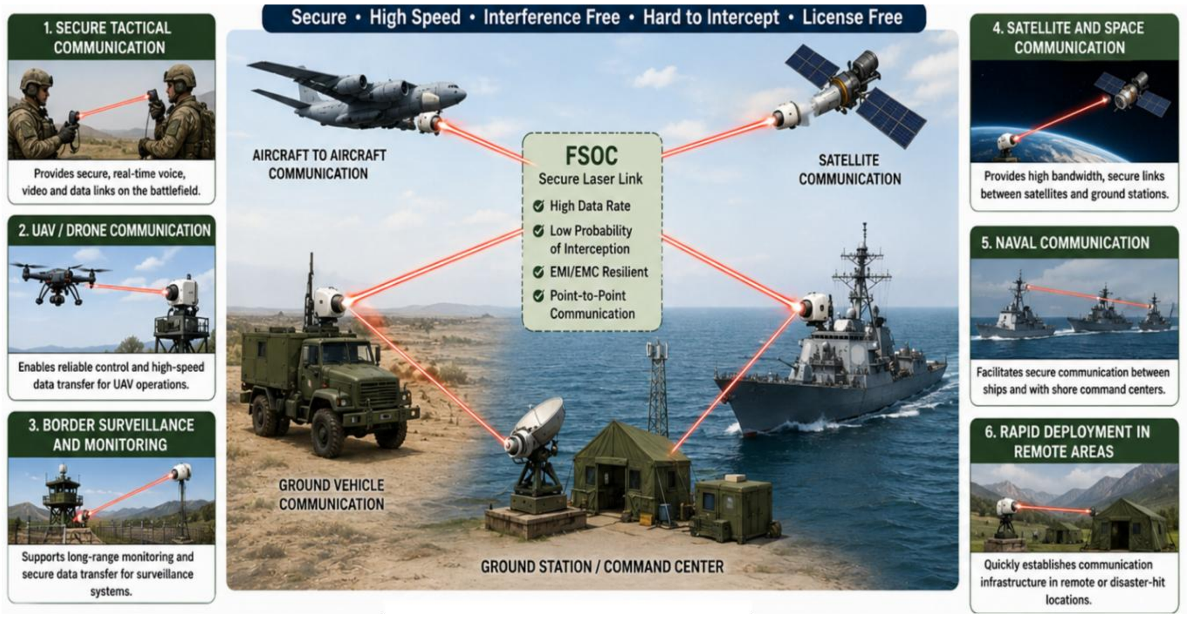

Fig. 9. Illustration of military and defense applications of Free Space Optical Communication systems for secure and high-speed wireless communication**.**

FSOC presents multiple benefits related to features such as increased Bandwidth (BW), improved Bit Error Rates (BER), and elevated data rates. These strengths have been systematically documented in this text to serve as a foundational reference for future research within the FSOC field. Nonetheless, transmissions via FSOC can be adversely affected by environmental conditions and atmospheric turbulence factors like rain, mist fog heatwaves physical obstructions scattering phenomena among others [61]. To address these challenges numerous techniques are under exploration globally including coding strategies modulation approaches channel modeling along with RF/Hybrid FSOC solutions. A summary of both limitations faced by FSOC technologies alongside emerging mitigation methods has been compiled from diverse sources providing researchers an accessible point of reference [62]. Information regarding military applications specific to FSOC tends not to be readily available due their customized sensitive or classified nature. Efforts have been made here to collect relevant details offering clear practical guidance for future advancements in this area. The integration of mitigation strategies combined with insights on evolving trends pertaining specifically towards military use represents a unique contribution seldom seen collectively which motivated the present discussion. Additionally, modulated collimated infrared lasers function within the framework of FSOC enabling secure data transmission between Tx & Rx nodes while delivering critical advantageous traits characterized by significantly lowered Probability of Detection (LPD)/Probability of Intercept (LPI). Such properties ensure minimal interference unlike traditional RF methods without stringent regulatory constraints [63]. As connectivity bottlenecks continue presenting challenges FSC technology emerges prominently positioned supplementary support alongside existing radio frequency links.

Optical Wireless Communication (OWC) plays a crucial role in alleviating the substantial data traffic encountered within microwave and RF networks. Consequently, integrating Radio over Free Space Optics (RoFSO) with Free Space Optics/Radio Frequency (FSO/RF) systems presents an effective approach to support 5G technologies and their associated advancements. This paper highlights several significant technologies and applications of RoFSO, emphasizing its advantages. FSOC) is under thorough investigation due to its potential to enhance reach and last-mile connectivity for optical fiber communication networks. It offers rapid redeployability along with increased operational flexibility essential for disaster recovery efforts as well as military initiatives. Currently, OWC has successfully demonstrated data rates of up to 100 Gb/s for both indoor and outdoor scenarios across distances reaching up to 10,000 km.

Recent studies conducted by researchers globally focus on various aspects of OWC technology including optical cameras, visible light communication systems, FSOC implementations, lasers, and light detection ranging methods [64]. The latest trends in FSOC encompass subcarrier multiplexing (SCM), wavelength division multiplexing (WDM) specific to OWC applications; visible light communications (VLC); worldwide interoperability for microwave access (WiMAX); vehicular visible light communications (VVLC); next-generation FSO wireless terrestrial/global network frameworks; as well as deep space optical communication setups. Researchers are encountering challenges while developing FSOC applications pertinent to 5G environments alongside the Internet of Everything/Things (IoE/IoT), mobile phone networking solutions, underwater optical technologies, and quantum communication approaches [65]. The evolution trajectory of OWC technologies stretches back from ancient innovations leading up through contemporary FSOC developments today. This review article is structured into multiple sections.

8. Future of FSO Communication

FSO systems have the potential to completely transform global connection in a number of industries because to ongoing developments in optical components, AI-driven beam tracking, and quantum communication. These developments will increase the resilience, autonomy, and scalability of FSO networks, which will be crucial in closing the digital divide. The creation of quantum FSO networks for extremely secure data transmission, AI-based optimization methods for accurate and flexible beam alignment, and hybrid optical-RF systems that improve network dependability in a variety of environmental circumstances are some of the emerging trends in this sector [66]. Furthermore, high-speed interplanetary communication is being made possible via deep-space optical networks, opening the door for the next wave of data interchange and space exploration. FSO ability to transform communication systems in space and on Earth is what will determine its destiny. By offering ultra-high-speed, secure, and interference-free lines, FSO provides an efficient option as data needs continue to rise. The precision, dependability, and scalability of the system will be greatly improved by the integration of adaptive optics, quantum communication, and artificial intelligence. In the upcoming years, AI-driven beam alignment will optimize network performance in real time, and hybrid FSO-RF designs will guarantee smooth data transmission even in inclement weather [67]. Ultra-secure information transit for deep-space missions, finance, and defense will be made possible by quantum-based FSO devices. Additionally, FSO will enhance global broadband connection and interplanetary communication by enabling high-capacity communication between Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary (GEO) satellites through the development of inter-satellite optical networks. In general, FSO technology's outlook for the future indicates a robust, intelligent, and globally integrated communication infrastructure that can meet the constantly rising demands for sustainability, speed, and security.

9. Conclusion

FSO offers several advantages over traditional communication methods like optical, radio, or microwave systems, including lower setup costs and quicker deployment. While it is increasingly popular due to its benefits and various applications, FSO is affected by medium attenuation, which can lead to power loss and impact performance. Research on this attenuation can help identify factors to consider prior to installation. Numerous studies are focusing on enhancing system performance in Wavelength Division Multiplexing (WDM)-based Free Space Optics (FSO) systems to mitigate attenuation effects. Performance evaluations are conducted through various models prior to system installation, potentially leading to improvements. Innovative approaches, such as Orthogonal Frequency Division Multiplexing (OFDM)-FSO and WDM-FSO systems, can boost performance over longer distances and higher speeds. By merging and refining these techniques, system design can be optimized, addressing limitations in existing FSO systems. FSO communication lines play a vital role in various environments, such as space, aerial, and terrestrial, providing fiber-like speeds with the flexibility of wireless communication. They are essential for connecting satellites, offering in-flight internet, and enabling urban 5G backhaul, becoming increasingly important as telecom networks progress toward 6G and beyond, contributing to a globally connected and fast communication network.

References

1. Saiyyed, Riyaz, Manoj Sindhwani, Bhavna Ambudkar, Shippu Sachdeva, Abhishek Kumar, and Manoj Kumar Shukla. 2025. "Free Space Optical Communication System: A Review of Practical Constraints,

Applications, and Challenges." *Journal of Optical Communications* 46 (2): 357–363. https://doi.org/10.1515/joc-2024-0011.
2. Alhosani, A., F. Alshehhi, A. Almenhali, and H. Abu Hilal. 2025. "Optical Communication Advancements in Free Space and Applications of Free Space Orbital Technology." *Journal of The Institution of Engineers (India): Series B* 106 (2): 805–814. https://doi.org/10.1007/s40031-024-01137-5.
3. Bibi, S., M. I. Baig, F. Qamar, and R. Shahzadi. 2024. "A Comprehensive Survey of Free-Space Optical Communication—Modulation Schemes, Advantages, Challenges and Mitigations." *Journal of Optical Communications* 45 (s1): s2373–s2385. https://doi.org/10.1515/joc-2023-0265.
4. Guiomar, Filipe P., Miguel A. Fernandes, João L. Nascimento, Vítor Rodrigues, and Paulo P. Monteiro. 2022. "Coherent Free-Space Optical Communications: Opportunities and Challenges." *Journal of Lightwave Technology* 40 (10): 3173–3186. https://doi.org/10.1109/JLT.2022.3164736.
5. Farajzadeh, Amin, Animesh Yadav, and Halim Yanikomeroglu. 2025. "Federated Learning in NTN: Design, Architecture, and Challenges." *IEEE Communications Magazine* 63 (6): 26–33. https://doi.org/10.1109/MCOM.001.2400484
6. Al-Allaq, Zaid Jabbar, Wafaa M. R. Shakir, and Jinan Charafeddine. 2025. "A Comprehensive Review of Cutting-Edge Disaster Response: UAVs Equipped with FSO-Based Communications." *Wireless Personal Communications* 141: 329–394. https://doi.org/10.1007/s11277-025-11782-8
7. Erotokritou, Chrystel, Sofia Stellatou, Isadora Formenton Vargas, and Edison Pignaton de Freitas. 2025. "Regulatory and Operational Integration of High Altitude Platform Stations (HAPS) Considering the Brazilian and the European Perspectives." In *2025 International Conference on Unmanned Aircraft Systems (ICUAS)*, 944–951. IEEE. https://doi.org/10.1109/ICUAS65942.2025.11007823
8. Ullah, R., S. Ullah, J. Ren, H. S. Alwageed, Y. Mao, Z. Qi, F. Wang, S. A. Khan, and U. Farooq. 2025. "Beyond Fiber: Toward Terahertz Bandwidth in Free-Space Optical Communication." *Sensors* 25 (7): 2109. https://doi.org/10.3390/s25072109
9. Ullah, R., S. Ullah, J. Ren, H. S. Alwageed, Y. Mao, Z. Qi, F. Wang, S. A. Khan, and U. Farooq. 2025. "Beyond Fiber: Toward Terahertz Bandwidth in Free-Space Optical Communication." *Sensors* 25 (7): 2109. https://doi.org/10.3390/s25072109.
10. Wang, Zihan, Jiarong Li, Hongfa Zhao, Jian Song, Zhong Lin Wang, and Wenbo Ding. 2025. "Self-Powered Optical Communication: Opportunities, Challenges and Future Prospects." *Advanced Energy Materials* 15 (42): e02803. https://doi.org/10.1002/aenm.202502803
11. Li, Z., W. Li, K. Sun, D. Fan, and W. Cui. 2025. "Recent Progress on Underwater Wireless Communication Methods and Applications." *Journal of Marine Science and Engineering* 13 (8): 1505. https://doi.org/10.3390/jmse13081505.
12. Dhruv and Hemani Kaushal. 2025. "A Review of Pointing Modules and Gimbal Systems for Free-Space Optical Communication in Non-Terrestrial Platforms." *Photonics* 12 (10): 1001. https://doi.org/10.3390/photonics12101001.
13. Sharma, D., A. Tripathi, and M. Kumari. 2024. "FSO Systems for Next Generation Networks: A Review, Techniques and Challenges." *Journal of Optical Communications* 45 (s1): s1005–s1019. https://doi.org/10.1515/joc-2022-0288.
14. Phuchortham, S., and H. Sabit. 2025. "A Survey on Free-Space Optical Communication with RF Backup: Models, Simulations, Experience, Machine Learning, Challenges and Future Directions." *Sensors* 25 (11): 3310. https://doi.org/10.3390/s25113310.
15. Abdulwahid, M. M., S. Kurnaz, A. K. Türken, M. R. Hayal, E. E. Elsayed, and D. A. Juraev. 2025. "Performance Analysis of Input Power Variations in High Data Rate DWDM-FSO Systems under Various Rain Conditions." *Journal of Optics*. https://doi.org/10.1007/s12596-025-02544-7.
16. Khalid, H., S. M. Sajid, H. E. Nistazakis, and M. Ijaz. 2024. "Survey on Limitations, Applications and Challenges for Machine Learning Aided Hybrid FSO/RF Systems under Fog and Smog Influence." *Journal of Modern Optics* 71 (4–6): 101–125. https://doi.org/10.1080/09500340.2024.2402428.
17. Gupta, A., D. Dhawan, and N. Gupta. 2024. "Review on UAV-Based FSO Links: Recent Advances, Challenges, and Performance Metrics." *Optical Engineering* 63 (4): 041204. https://doi.org/10.1117/1.OE.63.4.041204.

18. Mesri, L., and A. Djebbari. 2022. "Performance Limits of FSO Based SAC-OCDMA System under Weather Conditions." *Journal of Optical Communications* 43 (2): 265–272. https://doi.org/10.1515/joc-2018-0204.
19. Chen, Shun-Ping. 2022. "Investigations of Free Space and Deep Space Optical Communication Scenarios." *CEAS Space Journal* 14: 357–364. https://doi.org/10.1007/s12567-021-00388-y
20. Guiomar, F. P., M. A. Fernandes, J. L. Nascimento, V. Rodrigues, and P. P. Monteiro. 2022. "Coherent Free-Space Optical Communications: Opportunities and Challenges." *Journal of Lightwave Technology* 40 (10): 3173–3186. https://doi.org/10.1109/JLT.2022.3164736.
21. Bekkali, A., H. Fujita, and M. Hattori. 2022. "New Generation Free-Space Optical Communication Systems with Advanced Optical Beam Stabilizer." *Journal of Lightwave Technology* 40 (5): 1509–1518. https://doi.org/10.1109/JLT.2022.3146252.
22. Dhasarathan, Vigneswaran, Mehtab Singh, and Jyoteesh Malhotra. 2020. "Development of High-Speed FSO Transmission Link for the Implementation of 5G and Internet of Things." *Wireless Networks* 26 (4): 2403–2412. https://doi.org/10.1007/s11276-019-02166-5.
23. Guo, L., X. Guo, T. Luan, S. Zhu, and K. Lyu. 2021. "Radiative Effects of Clouds and Fog on Long-Lasting Heavy Fog Events in Northern China." *Atmospheric Research* 252: 105444. https://doi.org/10.1016/j.atmosres.2020.105444.
24. Nia, S. E., and A. Shokri. 2025. "Exploring the Impact of Rainfall Intensity on the Attenuation-Rainfall Relationship." *Journal of Quantitative Spectroscopy and Radiative Transfer* 334: 109364. https://doi.org/10.1016/j.jqsrt.2025.109364.
25. Alozie, E., A. Abdulkarim, I. Abdullahi, A. D. Usman, N. Faruk, I. F. Y. Olayinka, K. S. Adewole, A. A. Oloyede, H. Chiroma, O. A. Sowande, and L. A. Olawoyin. 2022. "A Review on Rain Signal Attenuation Modeling, Analysis and Validation Techniques: Advances, Challenges and Future Direction." *Sustainability* 14 (18): 11744. https://doi.org/10.3390/su141811744.
26. Matus, V., V. Guerra, S. Zvanovec, J. Rabadan, and R. Perez-Jimenez. 2021. "Sandstorm Effect on Experimental Optical Camera Communication." *Applied Optics* 60 (1): 75–82. https://doi.org/10.1364/AO.405952.
27. Ivanov, H., P. Pezzei, and E. Leitgeb. 2021. "Estimation of Cloud-Induced Optical Attenuation over Near-Earth and Deep-Space FSO Communication Systems." In *2021 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, 1–5. IEEE. https://doi.org/10.23919/SoftCOM52868.2021.9559077.
28. Kumar, S., and P. Sharma. 2023. "Study of Nonlinearities in FSO Communication System: A Detailed Review." *Journal of Physics: Conference Series* 2571 (1): 012036. https://doi.org/10.1088/1742-6596/2571/1/012036.
29. Qu, Tongzhang. 2022. *Microstrain Mechanical Testing of Ultramafic Materials: The Onset of Anelastic Relaxation, Its Grainsize Sensitivity, and the Role of Orthopyroxene*. PhD diss., The Australian National University. https://doi.org/10.25911/0378-PQ49
30. Zhang, H., W. Nie, Y. Liang, J. Chen, and H. Peng. 2021. "Development and Performance Detection of Higher Precision Optical Sensor for Coal Dust Concentration Measurement Based on Mie Scattering Theory." *Optics and Lasers in Engineering* 144: 106642. https://doi.org/10.1016/j.optlaseng.2021.106642.
31. Wani, M. Y., H. Pathak, K. Kaur, and A. Kumar. 2019. "Free Space Optical Communication System under Different Weather Conditions." *Journal of Optical Communications* 44 (1): 103–110. https://doi.org/10.1515/joc-2019-0064.
32. Yan, P., J. Mensah, A. Adesina, E. Kennedy, and M. Stockenhuber. 2020. "Highly-Dispersed Ni on BEA Catalyst Prepared by Ion-Exchange-Deposition-Precipitation for Improved Hydrodeoxygenation Activity." *Applied Catalysis B: Environmental* 267: 118690. https://doi.org/10.1016/j.apcatb.2020.118690.
33. Abd El-Mottaleb, S. A., A. G. Mohamed, H. Y. Ahmed, and M. Zeghid. 2024. "Performance Enhancement of FSO Communication System under Rainy Weather Environment Using a Novel Encryption Technique." *IEEE Access* 12: 13729–13746. https://doi.org/10.1109/ACCESS.2024.3357396.
34. Kumar, N., and V. Khandelwal. 2023. "Performance Limits of SAC-OCDMA-Based FSO System over Gamma–Gamma Fading Using DDDW Code." *Journal of Optics* 52 (4): 2176–2187. https://doi.org/10.1007/s12596-022-01075-9.

35. Ammar, S. M., N. Ali, M. A. Anuar, S. A. Aljunid, M. N. Saad, R. Endut, K. S. Manic, I. S. Al Naimi, and F. N. Hasoon. 2025. "Polarization Encoding and Decoding Techniques in a 10Gbps Hybrid OCDMA FDW/EDW System." *Nigerian Journal of Technological Development* 22 (3): 13–20. https://doi.org/10.63746/njtd.v22i3.2960.
36. de Sousa, F. B., F. M. de Sousa, I. R. Miranda, W. Paschoal Jr., and M. B. Costa. 2021. "Radio-over-Fiber Dual-Parallel Mach–Zehnder Modulator System for Photonic Generation of Millimeter-Wave Signals through Two Stages." *Optical and Quantum Electronics* 53 (5): 284. https://doi.org/10.1007/s11082-021-02868-1.
37. Elsayed, E. E., and B. B. Yousif. 2020. "Performance Evaluation and Enhancement of the Modified OOK Based IM/DD Techniques for Hybrid Fiber/FSO Communication over WDM-PON Systems." *Optical and Quantum Electronics* 52 (9): 385. https://doi.org/10.1007/s11082-020-02497-0.
38. Kaur, S. 2022. "Performance Analysis of DP-QPSK with CO-OFDM Using OSSB Generation." *Wireless Networks* 28 (4): 1719–1730. https://doi.org/10.1007/s11276-022-02933-x.
39. Rajput, S. J., M. B. Patel, and S. H. Patel. 2025. "Analysis of 25 Gbps 4-QAM-Modulated Coherent OFDM-FSO Link Employing LDPC Channel Coding across Diverse Atmospheric Scenarios." *Journal of Optical Communications*. https://doi.org/10.1515/joc-2025-0198.
40. Singya, P. K., P. Shaik, N. Kumar, V. Bhatia, and M. S. Alouini. 2021. "A Survey on Higher-Order QAM Constellations: Technical Challenges, Recent Advances, and Future Trends." *IEEE Open Journal of the Communications Society* 2: 617–655. https://doi.org/10.1109/OJCOMS.2021.3067384.
41. Periyasamy, Karuppasamy, Vinoth Rathinam, Karthikeyan Ganesan, Meenakumari Ramachandran, Suresh Muthusamy, Ravita Lamba, Hitesh Panchal, Maheswaran Shanmugam, Suji Prasad Sudarsanan Nair Jalajakumari, and Rajyalakshmi Kottapalli. 2023. "A Novel Method for Analyzing the Performance of Free Space Optical Communication in WDM Using EDFA." *Wireless Personal Communications* 131 (1): 679–707. https://doi.org/10.1007/s11277-023-10452-x.
42. Yaseen, M. A., A. K. Abass, and S. M. Abdulsatar. 2020. "Enhancing of Multiwavelength Free Space Optical Communication System via Optimizing the Transceiver Design Parameters." *Optical and Quantum Electronics* 52 (8): 383. https://doi.org/10.1007/s11082-020-02498-z.
43. Lema, G. G. 2023. "Free Space Optics Communication System Design Using Iterative Optimization." *Journal of Optical Communications* 44 (s1): s1205–s1216. https://doi.org/10.1515/joc-2020-0007.
44. Yaseen, M. A., A. K. Abass, and S. M. Abdulsatar. 2021. "Improving of Wavelength Division Multiplexing Based on Free Space Optical Communication via Power Comparative System." *Wireless Personal Communications* 119 (1): 381–391. https://doi.org/10.1007/s11277-021-08216-6.
45. Soltani, M. D., E. Sarbazi, N. Bamiedakis, P. de Souza, H. Kazemi, J. M. H. Elmirghani, I. H. White, R. V. Penty, H. Haas, and M. Safari. 2022. "Safety Analysis for Laser-Based Optical Wireless Communications: A Tutorial." *Proceedings of the IEEE* 110 (8): 1045–1072. https://doi.org/10.1109/JPROC.2022.3181968.
46. Jahid, A., M. H. Alsharif, and T. J. Hall. 2022. "A Contemporary Survey on Free Space Optical Communication: Potentials, Technical Challenges, Recent Advances and Research Direction." *Journal of Network and Computer Applications* 200: 103311. https://doi.org/10.1016/j.jnca.2021.103311.
47. Selim, H. A. O., R. M. Abdallah, M. H. Aly, and I. E. Shaalan. 2026. "Model-Free Adaptive Optics for Free Space Optical Communications: A Comprehensive Survey." *Journal of Optics* 55 (1): 1–35. https://doi.org/10.1007/s12596-025-03011-z.
48. Mouhammad, C., Z. Shi, and M. S. Alouini. 2026. "Review on Modulation Formats and Channel Coding in Free Space Optical Communication: Selection Criteria, Trade-Offs, and Emerging Trends." *Journal of Lightwave Technology* 44 (2): 1–33. https://doi.org/10.1109/JLT.2026.3664749.
49. Aboelala, O., I. E. Lee, and G. C. Chung. 2022. "A Survey of Hybrid Free Space Optics (FSO) Communication Networks to Achieve 5G Connectivity for Backhauling." *Entropy* 24 (11): 1573. https://doi.org/10.3390/e24111573.
50. Alimi, Isiaka A., and Paulo P. Monteiro. 2024. "Revolutionizing Free-Space Optics: A Survey of Enabling Technologies, Challenges, Trends, and Prospects of Beyond 5G Free-Space Optical Communication Systems." *Sensors* 24 (24): 8036. https://doi.org/10.3390/s24248036.

51. Wang, Jian, Jun Liu, Shuhui Li, Yifan Zhao, Jing Du, and Long Zhu. 2022. "Orbital Angular Momentum and Beyond in Free-Space Optical Communications." *Nanophotonics* 11 (4): 645–680. https://doi.org/10.1515/nanoph-2021-0527.
52. Dabiri, M. T., M. Rezaee, L. Mohammadi, F. Javaherian, V. Yazdanian, M. O. Hasna, and M. Uysal. 2022. "Modulating Retroreflector Based Free Space Optical Link for UAV-to-Ground Communications." *IEEE Transactions on Communications* 70 (9): 6012–6025. https://doi.org/10.1109/TWC.2022.3167945.
53. Kaushal, H., and G. Kaddoum. 2017. "Optical Communication in Space: Challenges and Mitigation Techniques." *IEEE Communications Surveys & Tutorials* 19 (1): 57–96. https://doi.org/10.1109/COMST.2016.2603518.
54. Yousif, Bedir B., and Ebrahim E. Elsayed. 2019. "Performance Enhancement of an Orbital-Angular-Momentum-Multiplexed Free-Space Optical Link under Atmospheric Turbulence Effects Using Spatial-Mode Multiplexing and Hybrid Diversity Based on Adaptive MIMO Equalization." *IEEE Access* 7: 84401–84412. https://doi.org/10.1109/ACCESS.2019.2924531
55. Huang, Shenjie, and Majid Safari. 2017. "Spatial-Mode Multiplexing with Zero-Forcing Beamforming in Free Space Optical Communications." In *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, 331–336. IEEE. https://doi.org/10.1109/ICCW.2017.7962679
56. Amhoud, El Mehdi, Boon S. Ooi, and Mohamed-Slim Alouini. 2020. "A Unified Statistical Model for Atmospheric Turbulence-Induced Fading in Orbital Angular Momentum Multiplexed FSO Systems." *IEEE Transactions on Wireless Communications* 19 (2): 888–900. https://doi.org/10.1109/TWC.2019.2949793
57. Kumar, Suresh, and Nishant Sharma. 2022. "Emerging Military Applications of Free Space Optical Communication Technology: A Detailed Review." *Journal of Physics: Conference Series* 2161 (1): 012011. https://doi.org/10.1088/1742-6596/2161/1/012011
58. Yousif, Bedir B., Ebrahim E. Elsayed, and Mohamed M. Alzalabani. 2019. "Atmospheric Turbulence Mitigation Using Spatial Mode Multiplexing and Modified Pulse Position Modulation in Hybrid RF/FSO Orbital-Angular-Momentum Multiplexed Based on MIMO Wireless Communications System." *Optics Communications* 436: 197–208. https://doi.org/10.1016/j.optcom.2018.12.034.
59. Amhoud, El Mehdi, A. Trichili, Boon S. Ooi, and Mohamed-Slim Alouini. 2019. "OAM Mode Selection and Space-Time Coding for Atmospheric Turbulence Mitigation in FSO Communication." *IEEE Access* 7: 88049–88057. https://doi.org/10.1109/ACCESS.2019.2925680
60. Ghassemlooy, Zabih, Wasiu Popoola, and Sujan Rajbhandari. 2019. *Optical Wireless Communications: System and Channel Modelling with MATLAB*. 2nd ed. Boca Raton, FL: CRC Press. https://doi.org/10.1201/9781315151724.
61. Alimi, Isiaka A., and Paulo P. Monteiro. 2024. "Revolutionizing Free-Space Optics: A Survey of Enabling Technologies, Challenges, Trends, and Prospects of Beyond 5G Free-Space Optical (FSO) Communication Systems." *Sensors* 24 (24): 8036. https://doi.org/10.3390/s24248036.
62. Chow, Chi-Wai. 2024. "Recent Advances and Future Perspectives in Optical Wireless Communication, Free Space Optical Communication and Sensing for 6G." *Journal of Lightwave Technology* 42 (11): 3972–3980. https://doi.org/10.1109/JLT.2024.3386630
63. Bibi, Sannia, Muhammad Iram Baig, Farhan Qamar, and Romana Shahzadi. 2024. "A Comprehensive Survey of Free-Space Optical Communication—Modulation Schemes, Advantages, Challenges and Mitigations." *Journal of Optical Communications* 45 (s1): s2373–s2385. https://doi.org/10.1515/joc-2023-0265
64. Saiyyed, Riyaz, Manoj Sindhwani, Bhavna Ambudkar, Shippu Sachdeva, Abhishek Kumar, and Manoj Kumar Shukla. 2025. "Free Space Optical Communication System: A Review of Practical Constraints, Applications, and Challenges." *Journal of Optical Communications* 46 (2): 357–363. https://doi.org/10.1515/joc-2024-0011
65. Mali, Sabita, Jayashree Ratnam, Farida A. Ali, and Pritam K. Sahoo. 2024. "A Review on Free Space Optical Communication Links: 5G Applications." *Journal of Optical Communications* 46 (4). https://doi.org/10.1515/joc-2024-0109
66. Chow, Chi-Wai. 2024. "Recent Advances and Future Perspectives in Optical Wireless Communication, Free Space Optical Communication and Sensing for 6G." *Journal of Lightwave Technology* 42 (11): 3972–3980. https://doi.org/10.1109/JLT.2024.3386630.

67. Karmous, Sarah, Nadia Adem, Mohammed Atiquzzaman, and Sumudu Samarakoon. 2025. "How Can Optical Communications Shape the Future of Deep Space Communications? A Survey." *IEEE Communications Surveys & Tutorials* 27 (1): 725–747. https://doi.org/10.1109/COMST.2024.3403873.