**OPTICAL FREE SPACE COMMUNICATION**

**SILAS ISUWA**

**(st/cs/nd/21/097)**

**A SEMINAR PRESENTED TO THE DEPARTMENT OF COMPUTER SCIENCE, SCHOOL OF SCIENCE AND TECHNOLOGY, FEDERAL POLYTECHNIC MUBI, ADAMAWA STATE, NIGERIA**

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**Abstract**

*This paper presents a comprehensive survey on various challenges faced by Optical Free Space communication system for both terrestrial and space links. In recent years, free space optical (FSO) communication has gained significant importance owing to its unique features: large bandwidth, license free spectrum, high data rate, easy and quick deployability, less power and low mass requirement. It will provide details of various performance mitigation techniques in order to have high link availability and reliability of FSO system. The first part of the paper focus on various types of impairments that poses a serious challenge to the performance of FSO system for both terrestrial and space links. It also presents a recently developed technique in FSO system using orbital angular momentum to combat the effect of atmospheric turbulence.*

# **INTRODUCTION**

In the recent few years, tremendous growth and advancement has been observed in information and communication technologies. With the increase in usage of high-speed internet, video-conferencing, live streaming etc., the bandwidth and capacity requirements are increasing drastically. This ever-growing demand of increase in data and multimedia services has led to congestion in conventionally used radio frequency (RF) spectrum and arises a need to shift from RF carrier to optical carrier. Unlike RF carrier where spectrum usage is restricted, optical carrier does not require any spectrum licensing and therefore, is an attractive prospect for high bandwidth and capacity applications. “Wireless optical communication” (WOC) is the technology that uses optical carrier to transfer information from one point to another through an unguided channel which may be an atmosphere or free space. WOC is considered as a next frontier for high speed broadband connection as it offers extremely high bandwidth, ease of deployment, unlicensed spectrum allocation, reduced power consumption, reduced size (improved channel security (Chan, 2006).

## **Free Space Optics**

Free Optical Space Communication, also known as Free-Space Optical Communication (FSO), is a cutting-edge technology that utilizes light beams to transmit data through open space without the need for physical media or cables. FSO is not new. It was developed more than three decades ago. Then, it was used by the military and space aviation pioneers to provide secure and rapidly deployable communications links. For example, it is being used to carry data within digital computing systems (Gourlay, 2018), in cross-bar switching (Rajkumar, 2016), optical interconnections (Jahns, 2014), and optoelectronic sampling (Wu & Zhang, 2017). Recent developments in optical technology have advanced FSO to mainstream communications applications and make it an alternative to RF wireless.

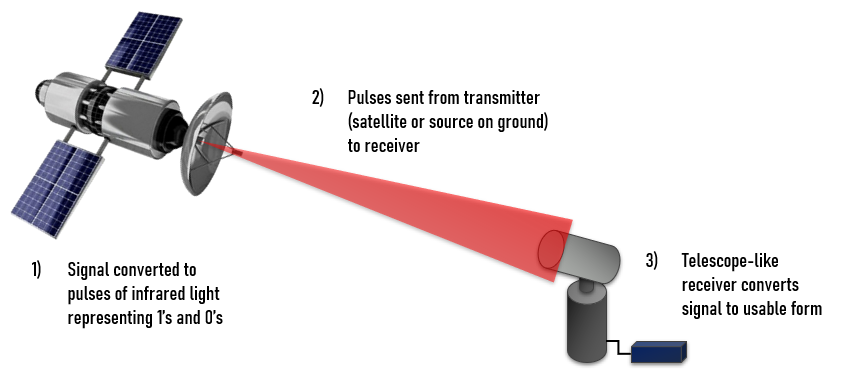


Figure 1: Free Optical Space Communication

**Literature Review**

Optical fiber transmission has been the dominant technology for the past decade for data communications over long and medium distances (see Fig. 1). However, for short distances, optical communications has some technological disadvantages. As a result of this, optical communications have not been able to penetrate into areas such as chip-to-chip and board-to-board communication (Jahns, 2014).

Fiber-optic cable and FSO share some similarities. The theory of FSO is essentially the same as that for fiber optic transmission. The use of lasers is a simple concept similar to optical transmissions using fiber-optic cables. The only difference is the medium; the signal is sent through air or free space from the source to the destination, rather than guided through an optical fiber. Light travels through air faster than it does through glass. So, one may regard FSO as optical communications at the speed of light (Jahns, 2014).

Like other networks, FSO networks can assume different configurations depending on the end user's needs and the desired application. As shown in Fig. 4, there are four common topologies are point-to-point, point-to-multipoint, a mesh, and a ring. In a point-to-point arrangement, FSO can support speeds between 155 Mbps to 10 Gbps at a distance of 2 to 4km. A point-to-multipoint or star configuration involves multiple links originating from a single node and it can support the same speeds at a distance of 1 to 2km. A mesh topology can support 622 Mbps at a distance of 200m to 450m. It is possible to combine these topologies. Generally, point-to-point link provides a dedicated connection with higher bandwidth, but does not scale cost-effectively. Point-to-multipoint is cheaper but offers less bandwidth. Point-to-multipoint systems suffer not only from the single point-of-failure problem but also from costs related to hub development, lower reliability (because of longer distances), and issues with hub location, which is critical for maximizing the number of buildings within LOS. Mesh architectures are most useful, because they can transmit data to a node from several directions, avoiding an obstructed path if necessary. Their chief benefit is service restoration (redundancy) via multiple network nodes. The tradeoff is that the distance covered declines. Because of the need for scalability, most analysts would prefer a mesh topology, which allows carriers to add nodes to the network more easily. The mesh also allows for alternate routing, while other topologies suffer from a single point of failure. The ring is the common topology used by the metropolitan service providers. The backbone is represented by high-speed rings, which are fiber or FSO based. A typical application of point-to-point link connecting two fast Ethernet-based networks is shown in Fig. 5. A typical installation is on 4.1 km path which is essentially horizontal and lies 50m above the street level with the wavelength of the carrier λ = 830 nm (Jahns, 2014).

Without a doubt, optical fiber is the most reliable means of providing optical communications. However, the digging, delays and associated costs to lay fiber often make it very expensive. Moreover, once fiber is deployed, it becomes a "sunk" cost and cannot be re-deployed if a customer needs to relocate or switch to another service provider, making it extremely difficult to recover the investment in a reasonable timeframe. Furthermore, most of the recent trenching to lay fiber has been to improve the metro core (backbone), while the metro access and edge have completely been ignored. Free space optical technologies offer an effective and economical way to address the "last mile" bottleneck by connecting to fiber backbone infrastructure directly to customer premises. FSO network is designed with short optical links (typically range from 200 to 2000 m), whereas fiber optic cable can be used for long-haul (up to 200 km without repeaters). It provides levels of bandwidth comparable to fiber optic cable. It promises high connectivity and dispersion-free dynamic optical paths – a feature that is lacking in fiber optic communication networks. FSO is compared with other access technologies in Table 1.

Table 1: Comparison of FSO with other access technologies (Buckley, 2001).

|  |  |  |  |
| --- | --- | --- | --- |
| **Features** | **FSO** | **Fiber** | **DSL** |
| Deployment time | Days to weeks | 4-12 months | 6-12 months |
| Provisioning time | Immediate | Complex | Complex |
| Initial investment for few subscribers | Low | High | High |
| Reliability | Medium | High | High |
| Topology/flexibility | PP, PM, Mesh | PP, PM, Mesh | PP |
| Distance Limitation | 200 – 2000 m | 200 km | 5.5 km |
| Bandwidth/speed | 1.25 Gbps | 10 Gbps | 2 Mbps |

## **Free Space Optical Communication Technology**

Transmission using FSO technology is relatively simple. It involves two systems each comprising of an optical transceiver which consists of a laser transmitter and a receiver to provide full duplex (bi-directional) capability. FSO uses low-power lasers and a telescope to transmit single or multiple wavelengths through the air to a receiver. Each FSO system uses a high-power optical source such as laser or LED and a telescope that transmits light through the atmosphere to another telescope that receives the information. At that point, the receiving telescope connects to a high-sensitivity receiver through an optical fiber. At the source, the visible or IR energy is modulated with the data to be transmitted. At the destination, the beam is intercepted by a photodetector, the data is extracted from the visible or IR beam (demodulated), and the resulting signal is amplified and sent to the hardware. If the energy source does not produce a sufficiently parallel beam to travel the required distance, collimation can be done with lenses (Wisely, 2008).

## **Key Strengths and Weaknesses**

FSO has many benefits besides its massive bandwidth. These include the following:

1. It operates in a completely unregulated frequency spectrum (range of THz). Because there is little or no traffic currently in this range, the FCC has not required licenses above 600 GHz. This means FSO is not likely to interfere with other transmissions.
2. Cost is a major advantage. Significantly lower cost on average than the construction of a new fiber optical solution, or leased lines. With FSO, there is also no capital overhang.
3. It can be deployed in days to weeks versus months to years (no excavation of sidewalks, building permits, etc.)
4. Bandwidth can easily be scaled with virtually unlimited headroom (10 Mbps to 1.25 Gbps) per link.
5. An FSO network architecture need not be changed when other nodes (buildings) are added; customer capacity can be easily increased by changing the node numbers and configurations.
6. The technology is easily upgradeable, and its open interfaces support equipment from a variety of vendors, which helps carriers protect the investment in their embedded infrastructures.

One would think that security is problematic with wireless, but FSO is fairly difficult to intercept. Because its beams are invisible, narrow, and very directional (aimed at a particular antenna), it is hard to find a particular traffic link in the air, let alone crack the code. In addition, links from customer to hub are typically encrypted (Fernandes, 2014).

Like any new technology, FSO does have its potential drawbacks, which will be discussed later. In spite of these drawbacks, however, FSO is poised to become a major player in the local broadband access market, particularly among small and medium-size businesses, which typically lack fiber connections.

## **Free-Space Optical Networks**

Free space optical networking technologies provide an effective and economically compelling solution to the "last mile" problem of connecting to fiber infrastructure in metropolitan areas. Free-space optical networking technology enables businesses to transmit and receive data transmission among buildings up to 2.5 miles apart at speeds much faster than a typical high-speed/leased line (Ghassemlooy, 2010).

## **Major Market Drivers**

The market forces behind FSO networks include (Willebrand & Ghuman, 2012):

1. Increasing demand for bandwidth: Demand for bandwidth has been increasing exponentially for the past few years. Service providers have been struggling to keep up with such high demand, with DWDM being used to meet that need.
2. Increasing Internet traffic: The Internet is generating a great need for high bandwidth at the edge of the network. The number of Internet users is increasing daily and is expected to grow to about 796 millions by 2005.
3. Increasing e-commerce: With the growing number of businesses involved in e-commerce activities, e-commerce is fast becoming a user of high bandwidth.
4. High capacity desktops: With multimedia and an exponential increase in processor speeds, the desktop computer is now an enabler of high bandwidth applications.
5. Upgrading of MAN: Deploying DWDM-based optical metropolitan area networks (MANs) and upgrading them is a direct result of the increase in bandwidth usage at the edge.
6. Advances in optics: New developments in fiber optical devices are making broadband free-space optical transmission an appealing alternative to RF wireless, and a flexible cost-effective adjunct to optical fiber as well. Due to these recent advances, fiber optic technologies have made the transition from use in expensive long-haul communication medium to low cost medium between computing systems and peripherals, local area networks (LANs), and other computers.

Free-space optics offers a cost-effective, quick and available infrastructure that is not only easily deployed (within days), redeployed, and easy to manage, but can also offer a multitude of options—distance, speed, topology and installations.

## **Advantages Free Space Optical Communication (FSO)**

Free Space Optical Communicationsystem offers several advantages over RF system. The major difference between FSO and RF communication arises from the large difference in the wavelength. For FSO system, under clear weather conditions (visibility > 10 miles), the atmospheric transmission window lies in the near infrared wavelength range between 700 nm to 1600 nm. The transmission window for RF system lies between 30 mm to 3 m. Therefore, RF wavelength is thousands of times larger than optical wavelength. This high ratio of wavelength leads to some interesting differences between the two systems as given below:

1. **Huge modulation bandwidth**: It is a well known fact that increase in carrier frequency increases the information carrying capacity of a communication system. In RF and microwave communication systems, the allowable bandwidth can be up to 20% of the carrier frequency. In optical communication, even if the bandwidth is taken to be 1% of carrier frequency (≈1016 Hz), the allowable bandwidth will be 100 THz. This makes the usable bandwidth at an optical frequency in the order of THz which is almost 105 times that of a typical RF carrier (Franz, 2020).
2. **Narrow beam divergence:** The beam divergence isproportional to *λ/DR*, where *λ* is the carrier wavelength and *DR* the aperture diameter. Thus, the beam spread offered by the optical carrier is narrower than that of RF carrier. This leads to increase in the intensity of signal at the receiver for a given transmitted power. Fig. 2 shows the comparison of beam divergence for optical and RF signals when sent back from Mars towards Earth (Franz, 2020).
3. **Less power and mass requirement**: For a given transmitter power level, the optical intensity is more at the receiver due to its narrow beam divergence. Thus, a smaller wavelength of optical carrier permits the FSO designer to come up with a system that has smaller antenna than RF system to achieve the same gain (as antenna gain scales inversely proportional to the square of operating wavelength). The typical size for the optical system is 0.3 m vs 1.5 m for the spacecraft antenna (Henniger, 2010).
4. **High directivity**: Since the optical wavelength is very small, a very high directivity is obtained with small sized antenna. The directivity of antenna is closely related to its gain.
5. Unlicensed spectrum: In RF system, interference from adjacent carrier is the major problem due to spectrum congestion. This requires the need of spectrum licensing by regulatory authorities. But on the other hand, optical system is free from spectrum licensing till now. This reduces the initial set up cost and development time (Franz, 2020).
6. High Security: FSO communication cannot be detected by spectrum analyzers or RF meters as FSO laser beam is highly directional with very narrow beam divergence. Any kind of interception is therefore very difficult. Unlike RF signal, FSO signal cannot penetrate walls which can therefore prevent eavesdropping (Franz, 2020).

In addition to the above advantages, FSO communication offers secondary benefits as: (i) easily expandable and reduces the size of network segments, (ii) light weight and compact, (iii) easy and quick deployability, and (iv) can be used where fiber optic cables cannot be used. However, despite of many advantages, FSO communication system has its own drawbacks over RF system. The main disadvantage is the requirement of tight acquisition, tracking and pointing (ATP) system due to narrow beam divergence.

**Disadvantages of Free Space Optical Communication**

Free Space Optical Communication (FSO) offers several advantages, such as high data transfer rates, immunity to radio frequency interference, and quick deployment. However, like any technology, FSO also has its share of disadvantages. Here are some of the main disadvantages of Free Space Optical Communication:

**Weather Dependency:** FSO communication heavily relies on the transmission of light signals through the atmosphere. Adverse weather conditions, such as heavy rain, fog, snow, or dust storms, can significantly attenuate or scatter the optical signals, leading to reduced signal quality and potential link interruptions. This weather dependency can make FSO less reliable in certain climates or geographic locations.

**Limited Range:** FSO systems are typically designed for relatively short-range communications, typically within a few kilometers. The performance of the link degrades with increasing distance due to factors like atmospheric absorption and beam spreading. As a result, FSO may not be suitable for long-distance communication, making it less versatile for some applications.

**Line-of-Sight Requirement:** For FSO to function effectively, there must be an unobstructed line of sight between the transmitter and the receiver. Any physical obstacle, such as buildings, trees, or terrain, can block the light signal and disrupt communication. This limitation can be challenging in urban environments with tall structures and irregular terrain.

**Security Concerns:** While FSO offers inherent security advantages, such as the difficulty of intercepting light signals in free space, it also presents certain vulnerabilities. Since FSO relies on a clear line of sight, it is susceptible to deliberate physical obstruction or intentional disruption using lasers or other light sources.

**Scalability:** Expanding or scaling an FSO network can be more challenging than traditional wired or wireless networks. Adding new links or extending the range requires precise alignment and coordination, making the process time-consuming and costly.

**Regulatory Challenges:** FSO technology operates in the optical spectrum, which is regulated by government authorities. Licensing and regulatory compliance can be complex, especially when deploying FSO in international or cross-border applications.

**Installation and Maintenance Costs:** While FSO does not require physical cabling, its installation can still be costly, particularly when considering the need for high-quality optics, precise alignment, and redundant systems for reliability. Maintenance costs can also be significant, requiring skilled personnel and regular inspections.

**Energy Consumption:** FSO systems require power to operate the equipment, including lasers, detectors, and other components. Although the power requirements are relatively modest compared to some wireless technologies, it still adds to the overall energy consumption.

**Interference from Other Light Sources:** FSO systems are susceptible to interference from other light sources, including artificial lighting and sunlight. Bright light sources in the vicinity of the FSO link can disrupt communication and degrade signal quality.

**Application of Free-space optical communication**

Free-space optical communication (FSO) is a technology that enables high-speed data transmission through the air using light as the medium. It operates by sending modulated light signals through free space, typically in the form of lasers or infrared beams. FSO has several applications across various industries due to its unique advantages and capabilities. Here are some key applications of free-space optical communication:

**High-Speed Internet Connectivity:** FSO can be used to provide high-speed internet access in areas where traditional wired infrastructure is challenging or costly to deploy. It is particularly beneficial in remote regions, rural areas, and disaster-stricken zones where restoring communication networks quickly is crucial.

**Wireless Backhaul:** In telecommunications, FSO serves as a viable alternative to traditional microwave and fiber optic links for wireless backhaul. It enables the seamless and rapid transmission of data between cellular base stations, supporting the expansion of cellular networks and enhancing network performance.

**Data Center Interconnectivity:** Within metropolitan areas, FSO can establish high-capacity, low-latency connections between data centers. This helps in load balancing, data redundancy, and disaster recovery, ensuring reliable and efficient data exchange between data centers.

Satellite Communications: FSO can enhance satellite communication systems by providing high-speed links between satellites in orbit and ground stations. This enables faster data transmission and reduces the risk of data congestion, which is especially beneficial for Earth observation, remote sensing, and space exploration missions.

**Military and Defense Applications:** The military employs FSO for secure and reliable communication in situations where traditional communication channels might be compromised or unavailable. FSO allows rapid deployment and reconfiguration of communication links on the battlefield.

**Aerospace and Aviation:** Free-space optical communication has the potential to revolutionize communication within and between aircraft, enabling faster and more efficient data exchange for flight control, in-flight entertainment, and passenger communication.

**Broadcasting and Live Events:** FSO can be used for temporary high-bandwidth connections during live events, sports broadcasts, or news coverage, where traditional wired solutions might be impractical.

**Inter-Satellite Links (ISL):** For satellite constellations, FSO can be employed to establish inter-satellite links, facilitating seamless communication and data exchange between satellites in orbit.

**Environmental Monitoring:** FSO can aid in environmental monitoring, such as monitoring pollution levels, greenhouse gases, and other critical environmental factors. Its ability to quickly transmit data allows for real-time analysis and response to environmental changes.

**Security and Surveillance:** FSO can be used for high-bandwidth communication in security and surveillance systems. It enables the rapid and reliable transmission of data from cameras and sensors to central monitoring stations, enhancing overall security measures.

While FSO offers numerous advantages, it also has some limitations, such as susceptibility to atmospheric conditions like fog, rain, and snow, as well as limitations on the maximum distance of transmission. Despite these challenges, ongoing research and technological advancements continue to improve the reliability and efficiency of free-space optical communication, making it a promising solution for various communication needs in the future.

## **Conclusion**

Free Optical Space Communication has witnessed significant advancements in recent years, enabling high-speed data transmission, secure quantum-based communication, and space-based applications. Ongoing research efforts are addressing the challenges associated with atmospheric effects and weather resilience. With continuous innovation and collaboration, FSO holds immense potential to revolutionize the way we communicate over long distances in the future. The growth of communications networks has accelerated last-mile access needs for high speed links. Free Space Optics is now a viable choice for connecting the LAN, WAN, and MAN; and carrying voice, video and data at the speed of light. However, FSO links in the mid-infrared spectrum seemed to be more favorable as lower atmospheric transmission losses increase the reliability of the system, particularly under bad weather conditions with low visibility. While fiber-optic communication has gained acceptance in the telecommunications industry, FSO communication is still a relatively new entrant. Its apprehension has not been universal; its development activity has been concentrated in the US. Its primary advantages are high throughput, solid security, and low cost. With current availability of up to 1.25 Gbps, throughputs of hundreds of Gbps are possible in the future. Free space optics is a technology that is poised for exponential growth in the coming years.

# **Recommendations**

FSO communication seems to have promising future as it provides a cost-effective connectivity alternative for several applications like: last mile access, cell cite back haul for mobile networks, fiber backup and much more.

The following recommendations are made in this paper:

1. The FSO communication has experienced a rapid growth in the last few years despite of various crisis in the global market and therefore should be studies and implemented.
2. This technology has demonstrated less capital expenditure with huge returns in very little time due to (i) easy availability of components, (ii) quick deployment (as it does not seek permission from municipal corporation for digging up of street), and (iii) no licensing fee required, it is therefore recommended for use by telecommunication network providers.

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