



Studies On the Performance of a Short Haul Optical Link for Broadband Indoor and Outdoor Wireless Communication

¹Om Prakash Aditya

¹Faculty, Govt. Polytechnic, Electronics and Communication Engineering, Chapra, Bihar

¹opaditya2k7@gmail.com

<https://doi.org/10.64882/ijrt.v14.i4.2017>

ABSTRACT

The exponential growth of broadband wireless communication has created an increasing demand for communication technologies capable of supporting ultra-high data rates, enhanced reliability, and efficient spectrum utilization. Conventional Radio Frequency (RF) communication systems suffer from limited spectrum and high electromagnetic interference, and bandwidth congestion, therefore alternative wireless communication technologies need to be explored. Optical Wireless Communication (OWC) is an appealing technology as it can use the huge unlicensed optical spectrum to deliver fast, secure, and energy-efficient wireless communication. The review is focused on the performance of short-haul optical links for broadband indoor/outdoor wireless communication, especially Free Space Optical (FSO) and Visible Light Communication (VLC) technologies. Indoor and outdoor optical communication systems are covered in detail, along with their construction, performance characteristics, and applications. The effects of atmospheric attenuation, turbulence, scintillation, beam wander, and alignment problems on these systems' performance are also highlighted. Additionally, based on prior theoretical, computational, and experimental research, the many methods employed to enhance performance, including aperture averaging, receiver diversity, and wavelength optimization, are examined. The results demonstrate that compared to shorter wavelengths, longer wavelengths (1550 nm) exhibit improved Bit Error Rate (BER) performance and exhibit less scintillation effect. Furthermore, it is demonstrated that large receiver apertures and partially coherent optical beams can greatly improve the reliability of communication in turbulent atmosphere. The review shows that Optical Wireless Communication (OWC), when combined with hybrid RF-FSO architectures, Artificial Intelligence (AI), and the newly emerging 5G/6G communication networks, has substantial potential to deliver ultra-high speed, secure, and reliable wireless broadband connectivity for the future communication system.

Keywords: Optical Wireless Communication (OWC); Free Space Optics (FSO); Visible Light Communication (VLC); Li-Fi; Broadband Communication; Optical Link Performance; Atmospheric Turbulence; Indoor Wireless Networks; Bit Error Rate (BER).

1. INTRODUCTION

1.1 Evolution of Optical Wireless Communication

Optical Wireless Communication (OWC) has its origins in Alexander Graham Bell's 1880 photophone, which allowed for the transmission of speech via free space by means of

sunlight. Current optical equipment had limitations on the technology, but Bell's work laid the groundwork for optical wireless communication systems that are used today. With the advent of new technologies in signal processing, optical components, photodetectors, semiconductor lasers, and semiconductor lasers, OWC has emerged as a practical method of high-speed communication for broadband applications. [1–7].

1.2 Growth of Broadband Wireless Traffic

Greater bandwidth and data transmission capacity are becoming more and more crucial because to the exponential growth of wireless data traffic caused by the ubiquitous use of smartphones, cloud computing, multimedia streaming, and Internet-based applications. The global mobile data traffic is reported to have been growing fast, expected to be several exabytes per month, making it an urgent need to develop communication technologies that can help meet multi-gigabit and future terabit-per-second transmission rates [8–18]. This unprecedented growth is causing many conventional wireless systems to be challenged.

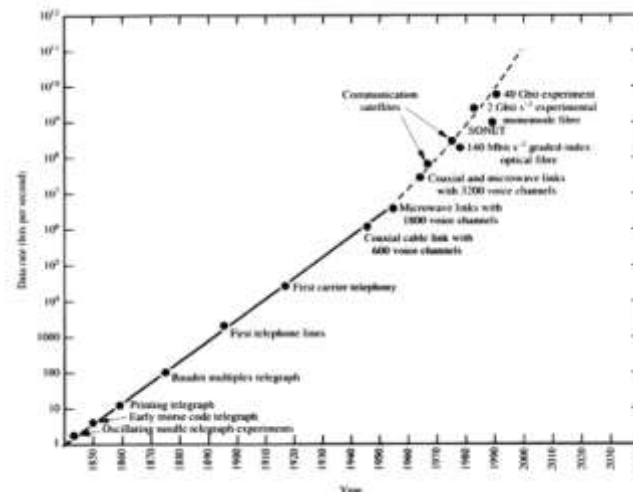


Figure 1. Roadmap of Data Rate Growth

1.3 Need for Short Haul Optical Links

Traditional radio frequency (RF) communication systems have several drawbacks such as limited availability of spectrum, limited available bandwidth, growing interference and less spectral efficiency. While advanced modulations such as OFDM and MIMO have significantly enhanced RF system performance, the available spectrum still limits the data rates that can be achieved. [19–29]. As a result, the use of optical and terahertz frequency short-haul optical links as alternatives to delivering ultra-high-speed broadband communication links over short distances has become attractive.

1.4 Indoor and Outdoor Wireless Communication Systems

Outdoor and indoor applications of optical wireless communication are equally viable. Technologies like Visible Light Communication (VLC) and Li-Fi (Light Fidelity) rely on light-emitting diodes (LEDs) to both illuminate and transport data rapidly in indoor systems. They make good use of the spectrum, are safe from electromagnetic interference, and are secure. The primary means of communication outdoors are based on Free Space Optical

(FSO) technology, which is used to create Line of Sight (LOS) links between FSO transceivers to deliver high speed broadband connectivity over metropolitan and last-mile networks. Both methods can be used in conjunction with existing RF infrastructure, and both are useful for providing communications where wired networks are not feasible [30–40].

1.5 Scope of Optical Wireless Communication

With its vast unlicensed optical spectrum, abundant available bandwidth, minimal electromagnetic interference, and enhanced communication security, OWC has emerged as a very promising technology for the future generation of communication networks. In addition to its usage in broadband access networks, OWC has found applications in secure military networks, intelligent transportation systems, underwater communication, body area networks, and satellite communication. For the communication infrastructure of the future, it has the potential to be a technology that enables large capacity wireless networks. [34–40].

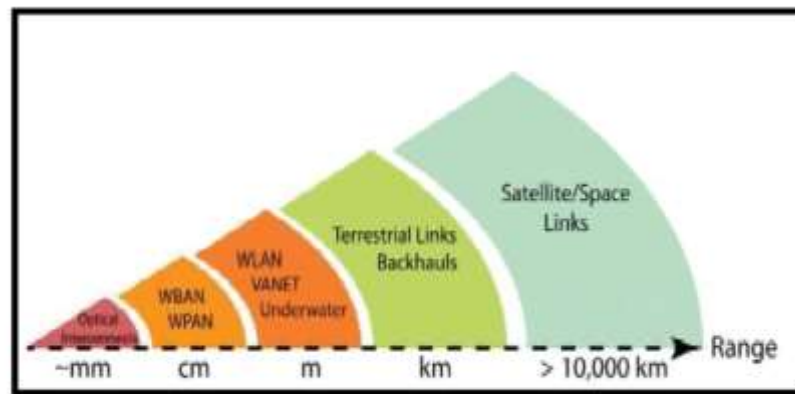


Figure 2. Categorization of Optical Wireless Communication Applications

1.6 Objectives of the Study

This review aims to examine the performance of short-haul optical links for broadband indoor and outdoor wireless communication. The study reviews the principles of Optical Wireless Communication, compares indoor and outdoor optical transmission techniques, analyses the major factors affecting link performance—including atmospheric turbulence, attenuation, scintillation, and propagation losses—and evaluates performance improvement techniques reported in the literature. Additionally, within the framework of upcoming 5G and 6G wireless networks, the article delves into the latest advancements, real-world uses, obstacles, and potential avenues for future study on short-haul optical communication systems.

2. FUNDAMENTALS OF OPTICAL WIRELESS COMMUNICATION (OWC)

2.1 Principle of Optical Wireless Communication

Optical Wireless Communication (OWC) is an alternative to traditional optical fibers that uses unguided light waves propagating over empty space to transmit data. Light intensity modulation, transmitted via the environment and detected by a photodetector, represents information. The use of OWC wavelengths of either infrared or visible or ultraviolet, along with its high bandwidth, low electromagnetic interference, secure transmission and licence-

free spectrum, is making it an attractive complement to conventional radio frequency (RF) communication systems [34–40].

2.2 Optical Spectrum Used in OWC

OWC uses various wavelengths of the optical spectrum for various applications. The near-infrared band (around 750-1600nm) is generally used in the outdoor Free Space Optical (FSO) communication due to its low atmospheric attenuation and the ability to use optical communication components. Systems that combine lighting and communication, such as Visible Light Communication (VLC) and Li-Fi, typically make use of the visible wavelength range (390-750 nm) inside. Alternately, special non-line-of-sight communication applications are being investigated with the use of ultraviolet wavelengths [34–40].

2.3 Components of Optical Wireless Links

Optical wireless communication systems generally include an optical transmitter, propagation channel in the atmosphere, or free space, and an optical receiver. The propagation channel propagates the optical beam in free space, and the transmitter converts the electrical information into optical signals. At the receiver, optical filters eliminate noise before a photodetector converts the light into electrical impulses and data recovery software processes the signal. Optical alignment, propagation circumstances, and receiver sensitivity all impact the link's overall performance. [9–10].

2.4 Optical Transmitters and Receivers

LEDs or Laser Diodes (LDs) are the most common types of transmitters. LEDs offer eye safety, low power consumption, wide beam coverage and dual lighting/communication applications, making them a desired solution for indoor communication. Because of the narrow beam divergence, the high optical power and the high modulation bandwidth, laser diodes are more appropriate for use in outdoor long-distance FSO communication. Avalanche photodiodes, or PIN photodiodes, are commonly employed in receivers because of their rapid response times and excellent sensitivity. The use of optical filters reduces the amount of background light and improves the signal-to-noise ratio. [3,9–11].

2.5 Optical Modulation Techniques

Numerous modulation strategies are available in OWC systems, each tailored to a specific use case. Most people utilize the simplest intensity modulation approach called On-Off Keying (OOK), which transmits a logical '1' and a '0' as the presence or absence of optical power. A technique that enables long-range optical links, Pulse Position Modulated (PPM) is more sensitive at the receiver and uses less power overall. In most practical systems, the optical intensity is modulated at the transmitter, and is directly detected at the receiver, which is easy to implement and highly reliable [9–10].

2.6 Indoor vs Outdoor Optical Communication

The difference between the indoor and outdoor optical communication systems is mainly from the following aspects: optical source, transmission medium and environment. For communication over short distances in enclosed areas, such as indoors, the typical system uses LEDs and visible light, and multipath reflections are significant, but atmospheric effects are not. Outside the laboratory, FSO systems use semiconductor laser diodes which operate at

wavelengths of 1310 nm or 1550 nm to create high-speed line-of-sight connections from a few hundred metres to a few kilometres. Fog, rain, beam divergence and scintillation are strongly affecting the outdoor links, which means that suitable mitigation methods should be developed to ensure reliable communications [11–13].

3. SHORT HAUL OPTICAL LINK ARCHITECTURE

3.1 Concept of Short Haul Optical Links

Short haul optical links are free space optical communication systems intended to deliver high speed broadband data transmission over relatively short distances, usually meters to a few kilometers. They offer an alternative to expensive fibreoptics for last mile systems, campus, metropolitan area networks (MANs) and temporary communications. Because of its excellent security, low installation cost, huge bandwidth, and availability of license-free spectrum, short distance optical connections (SHOPS) are quickly replacing or supplementing more conventional radio frequency (RF) communication technologies. [1–5].

3.2 Point-to-Point Optical Communication

The most common setup for short-haul optical communications is the point-to-point configuration. An optical transmitter and receiver are positioned such that they form a direct line-of-sight connection in this arrangement. The data is first modified with an intensity modulator before being transmitted through the atmospheric channel. A photodetector is used in a direct detection system to capture the received optical beam after it has been focused through an optical lens or telescope and filtered to eliminate background radiation. Among the many advantages of this design are its protocol openness, fast data speeds, and dependable communication free of electromagnetic interference. [1,6–9].

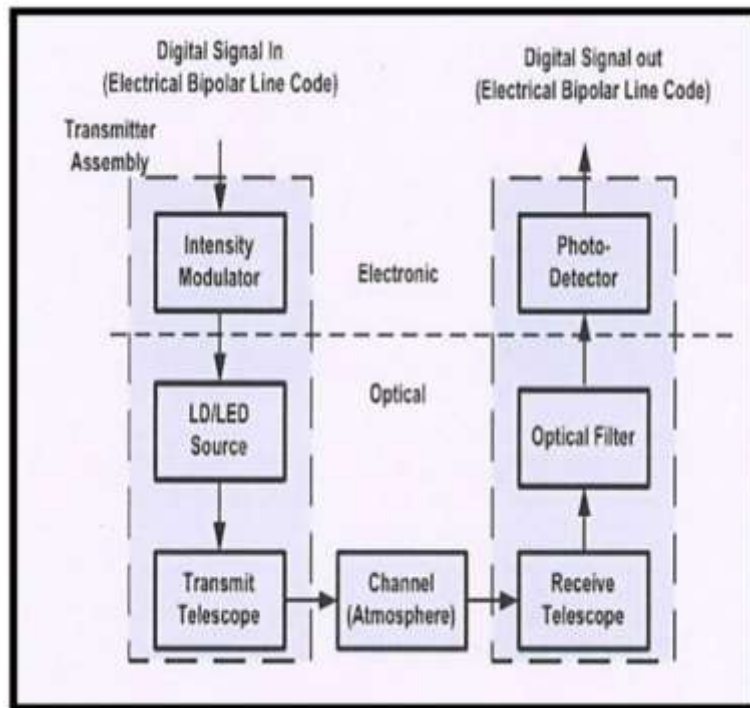


Figure: Short Haul Free Space Optical Link

3.3 Indoor Optical Link Architecture

For Visible Light Communication (VLC) and Li-Fi systems, the main optical transmitter used in indoor optical communication systems is Light Emitting Diodes (LEDs). In enclosed places like buildings, hospitals, and workplaces, LEDs are utilized not only to light up the area, but also to modulate digital data. Either the optical signal travels down the line of sight (LOS) or it is reflected off of various surfaces and then sent on to the receiver. Due to their high sensitivity and fast response time, PIN photodiodes are usually used as receivers. In contrast, for indoor optical links, the transmission power is relatively small, the transmission distance is short, there is little atmospheric attenuation and it is very suitable for secure broadband communication [10–12].

3.4 Outdoor Free Space Optical (FSO) Architecture

Semiconductor laser diode technology can be employed to create outdoor Free Space Optical (FSO) links with a transmission distance of up to several kilometres and at wavelengths primarily in the range 1310 nm and 1550 nm, to create broadband communication channels. Each component of the system works together: the transmitter houses a laser source, intensity modulator, beam collimator, and transmitting telescope; the receiver consists of a receiving telescope, optical filter, photodetector, and signal processing circuit. Fog, rain, haze, turbulence, scintillation, and beam wander are some of the atmospheric conditions that might impact the communication system's performance while the optical beam travels through the channel during propagation. In order to ensure dependable high-speed transmission, precise alignment and the utilization of efficient optical components are paramount. [6–13].

3.5 LOS and Non-LOS Optical Links

The optical wireless communication systems can work based on Line-of-Sight (LOS) propagation or Non-Line-of-Sight (NLOS) propagation. LOS communication means that the communication path is an optical path and is recommended in outdoor FSO systems, the reason being that it produces minimum attenuation and maximum received optical power. Using reflected (or scattered) or diffused optical signals, NLOS communication tends to be more typical in indoor environments where alignment is not always possible. While the NLOS system gives more flexibility and has a larger coverage area, it also has more path loss, multipath propagation, and lower transmission efficiency than a LOS system. Application needs, ambient factors, and intended communication performance dictate which of the two architectures is chosen. [9–13].

4. OUTDOOR FREE SPACE OPTICAL COMMUNICATION SYSTEMS

4.1 Free Space Optical (FSO) Communication

Optical wireless technology known as Free Space Optical (FSO) uses extremely narrow laser beams to transmit data over the air. Although free space optical networking (FSO) shares many similarities with optical communication, including a high bandwidth, license-free operation, protocol transparency, and resistance to electromagnetic interference (EMR), the communication medium in FSO is free space itself. FSO has been found to be a promising approach for last mile applications, metropolitan area networks (MANs), enterprise networks

and for temporary broadband connections in situations where laying optical fibre is expensive or impractical [1–6].

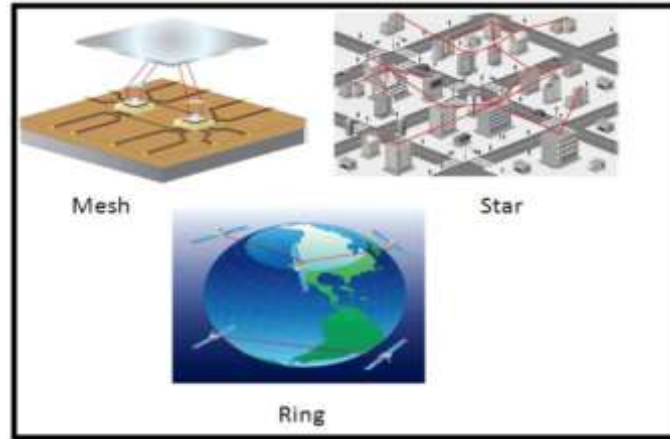


Figure: Applications of FSO Communication System

4.2 Atmospheric Propagation Characteristics

Atmospheric propagation channel parameters determine how well an outdoor FSO system works. The energy of the optical beam is diminished as it travels through the atmosphere owing to atmospheric absorption, scattering, and fluctuations in the refractive index. As both the transmitter's distance and the environmental variations rise, the propagation effects become more pronounced. The received optical power, signal-to-noise ratio (SNR), and dependability of optical communications are all impacted by atmospheric conditions since optical signals travel through an unguided medium. Therefore, in order to build trustworthy and effective outdoor optical communication systems, it is very necessary to characterize the atmosphere channel. [6–10].

4.3 Effects of Fog, Rain, and Smoke

One of the most significant factors in outdoor optical links is the weather. Dense fog is the most severe atmospheric condition because water droplets scatter optical beams and will cause significant attenuation in received optical signals, thus reducing the optical power received. In general, rain has less effect than fog because of the relatively large size and low concentration of rain drops that affect communication range, although when the rain is heavy enough, it can have a dramatic effect on communication. Likewise, smoke, dust, haze and suspended aerosols cause extra scattering and absorption losses which can compromise link availability and link quality. Therefore when designing an FSO system, the attenuation due to weather conditions should be taken into account, especially for long distance (LD) communication links [6–11].

4.4 Atmospheric Turbulence and Scintillation

When air temperature and pressure randomly change, it causes the refractive index of air to fluctuate, which in turn causes atmospheric turbulence. Scintillation is the random variation in the received optical beam's intensity caused by changes in the refractive index as an optical beam travels through turbulent layers. Commonly used to assess turbulence is the refractive index structural parameter (C_n^2), whereas the scintillation index is used to measure optical

fluctuations. The Rytov variance is another important characteristic statistical measure; it describes the turbulence strength and may be used effectively to evaluate the optical channel's features. The stronger the turbulence, the larger the value of the Rytov variance and the more degraded the signal [12–16].

4.5 Beam Wander and Beam Divergence

During propagation beam wander and beam divergence are also caused by turbulence in the atmosphere which manifests as scintillation. Beam wander is a random displacement of the centroid of the beam from large-scale turbulent eddies, while beam divergence is spreading of the optical beam over distance. In a long-distance line-of-sight communication system, these factors have a significant impact on the optical power received by the receiver and also increase the aiming errors. The experimental results show that when the atmospheric temperature rises, the variations in the refractive index increase, leading to a larger displacement of the beam and, ultimately, a lower efficiency of the receiver. Several options for mitigating these impairments have been explored such as aperture averaging, spatial diversity, adaptive optics, and accurate beam tracking [12–18].

4.6 BER Performance in Outdoor Optical Links

One of the most significant measures of the performance of an FSO system is the Bit Error Rate (BER). The received optical signal is affected by atmospheric attenuation, scintillation caused by turbulence, beam wander, and pointing errors, which all contribute to the increase in BER. It has been shown through simulation and experimental studies that longer operating wavelengths suffer comparatively smaller scintillation effects than the shorter wavelengths, and hence exhibit better BER performance, especially for the wavelength of 1550 nm. In addition, certain techniques like the aperture averaging, receiver diversity and partially coherent optical beams have been shown to give good reduction in intensity fluctuations, better S/N and a significant improvement in the communication reliability in weak, moderate and strong atmospheric turbulence [15–18].

5. INDOOR OPTICAL WIRELESS COMMUNICATION SYSTEMS

5.1 Visible Light Communication (VLC)

A novel optical wireless communication system called Visible Light Communication (VLC) uses light to illuminate the device and transmit digital information within the visible light spectrum (390 nm - 750 nm). To make use of the existing lighting infrastructure, VLC employs Light Emitting Diodes (LEDs) as optical transmitters. High data speeds, license-free operation, resistance to electromagnetic interference, and secure communication are just a few of the advantages of this technology. Therefore, VLC is quickly becoming a practical supplementary technology for indoor broadband connection in smart buildings, healthcare facilities, schools, and businesses. [1–5].

5.2 Li-Fi Technology

Light Fidelity (Li-Fi) is an advanced version of VLC whereby high-speed bidirectional wireless communication is possible via the visible light spectrum. The data is sent through by using the intensity of the LED lights that are rapidly changed at frequencies too high for humans to see. The use of optical frequencies, not radio frequencies, means light can provide

significantly higher bandwidth, greater network capacity, less interference and greater communication security. Li-Fi is believed to be a promising solution for the future 5G and 6G indoor wireless networks in areas with limited or undesirable RF communication [2–6].

5.3 LED Based Indoor Optical Links

High-brightness white LEDs are used as optical transmitters in the majority of indoor optical communication systems due to combining illumination and communications into a single device. The advantages of LEDs compared with laser diodes are increased beam coverage, reduced power consumption, increased eye safety, reduced cost, and ease of driving. The standard method of indoor communication systems relies on digitally modulating the optical intensity of the LED output. The optical signal emitted travels through the room and is captured by a receiver containing a photodetector. With their broad radiation pattern, LED-based systems ensure uniform coverage, which corresponds to short-range broadband communication [3–7].

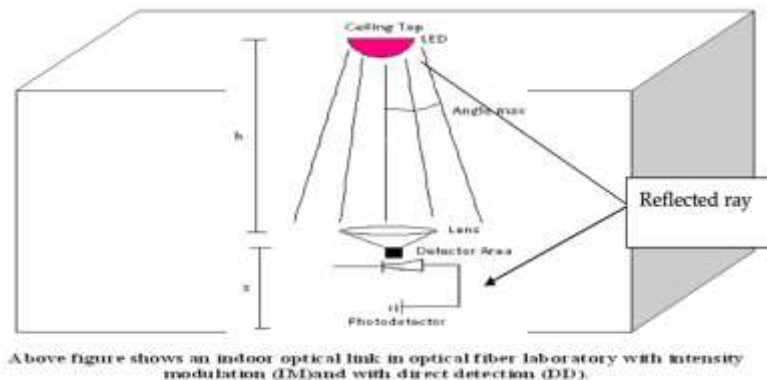


Figure: Indoor Optical Communication System

5.4 Impulse Response of Indoor Optical Channels

The impulse response of the optical propagation channel is a key factor in the performance of an indoor optical communication system. Optical signals can be transmitted directly to the receiver (direct line of sight), or they can be reflected from many different walls, ceilings, floors, and other objects, which leads to multipath propagation. The channel response is affected by a number of factors that have to do with the receiver-transmitter distance, the angle of incidence, the transmitter's optical power distribution, the detector's area, the qualities of its optical filter, and its field of view. Therefore, it is essential to improve the communication efficiency of indoor optical networks by designing suitable channels to decrease intersymbol interference. [5–8].

5.5 Indoor Optical Communication using LEDs

Inside optical communication systems, the usual method is Intensity Modulation with Direct Detection (IM/DD), which involves adjusting the LED's brightness according to the data that has to be communicated. The simplicity and compatibility of the modulation method known as Amplitude Shift Keying (ASK) with LED driver circuits make it a popular choice for usage in experimental systems. A PIN photodiode is part of the receive side, which amplifies, filters, and demodulates the received information after converting it from an optical signal to

an electrical signal. Optical filters are a great way to lower the signal-to-noise ratio and combat ambient light interference. Indoor line-of-sight communications, picture transmission, and high-speed local area networking are three areas where these systems really shine. [6–10].

5.6 Performance Analysis of Indoor Optical Systems

When testing an optical communication system inside, typical metrics include received optical power, Signal-to-noise ratio (SNR), Bit Error Rate (BER), communication range, and data transmission rate. Tests on a smaller scale have demonstrated that the LED communication system reliably transmits high-speed broadband data over short distances without compromising light quality. A high-performance communication system that incorporates smart lighting can be constructed using them in conjunction with a PIN photodiode receiver, provided that there is line-of-sight. The indoor optical wireless system is expected to play a significant role in future smart buildings and next-generation wireless communication systems because of its secure communication capabilities, low power consumption, and high bandwidth. [6–11].

6. PERFORMANCE PARAMETERS OF OPTICAL LINKS

Optical wireless communication systems' reliability, efficiency, and data throughput are impacted by a number of transmission and channel characteristics. Aperture averaging, receiver diversity, received optical power, atmospheric attenuation, scintillation, and signal-to-noise ratio (SNR) are some of the most important performance indicators for an indoor/outdoor optical link. These parameters are useful to evaluate the quality and strength of an optical communication system with different environmental conditions.

6.1 Signal-to-Noise Ratio (SNR)

The Signal-to-Noise Ratio (SNR) is a crucial statistic for evaluating the quality of an optical link. What this means is that the received power is proportional to the overall noise power at the receiver. The higher the SNR, the more reliable the communication, the further distance the communication can be achieved, and the smaller the error probability. For outdoor optical links, the received optical power is decreased by atmospheric attenuation, scintillation, fog and beam divergence which also reduces the SNR. The SNR in an indoor system tends to be relatively higher due to the fact that there is no atmospheric noise whereas there can be ambient noise due to illumination or multipath reflections. A few common ways to increase the signal-to-noise ratio (SNR) are to make the receiver more sensitive, to use optical filters, and to make the receiver aperture larger. [1–8].

6.2 Bit Error Rate (BER) Analysis

Bit Error Rate (BER) is one of the most popular metrics used to measure the performance and indicates the probability that a bit of data is received incorrectly while being transmitted. BER is dependent on the optical power received, detector sensitivity, modulation scheme, atmospheric turbulence and receiver noise. When the received signal strength is weak, signal strength variations cause the probability of bit error to increase. It has been shown by simulation and experimental work that BER degrades drastically in strong turbulence, but in strong turbulence, BER improves drastically with the use of some of the various methods of

turbulence attenuation, which are mostly referred to as aperture averaging and receiver diversity. The reportings of longer wavelengths (1550 nm) showing a lower BER compared to shorter wavelengths are due to a reduction in scintillation effects [9–14].

$$\text{BER} = Q(\sqrt{2E_b/N_0})$$

where E_b = energy per transmitted bit, N_0 = noise power spectral density, and $Q(\cdot)$ is the Gaussian Q-function.

6.3 Link Budget Analysis

The optical signal's power before and after propagation across the optical link can be compared using a link budget study. Beam divergence, air attenuation, aiming inaccuracy, losses in optical components, and receiver characteristics are all part of it. If the designer can accurately estimate the link budget, they can maximize the communication range while maintaining the appropriate BER performance. The received optical power can be expressed as:

$$P_r = P_t H(0)$$

where P_r = received optical power, P_t = transmitted optical power and $H(0)$ = channel DC gain [6–10].

6.4 Aperture Averaging Technique

Aperture averaging is a good solution for reducing scintillation caused by the atmosphere in outdoor FSO systems. It is based on the idea of increasing the aperture diameter of the receiver to spatially average out fast fluctuations in intensity due to small-scale atmospheric turbulence. This will substantially minimize scintillation-induced signal fading and enhance the reliability of communications. The aperture averaging factor is a measure of the effectiveness of aperture averaging:

$$A(D) = \sigma_{I^2}(D) / \sigma_{I^2}(0)$$

where $\sigma_{I^2}(D)$ is the scintillation variance for receiver aperture diameter D , and $\sigma_{I^2}(0)$ represents the variance for a point receiver. According to simulation and experimental findings, increasing the receiver's aperture diameter considerably improves the SNR and BER for moderate and heavy turbulence. [12–18].

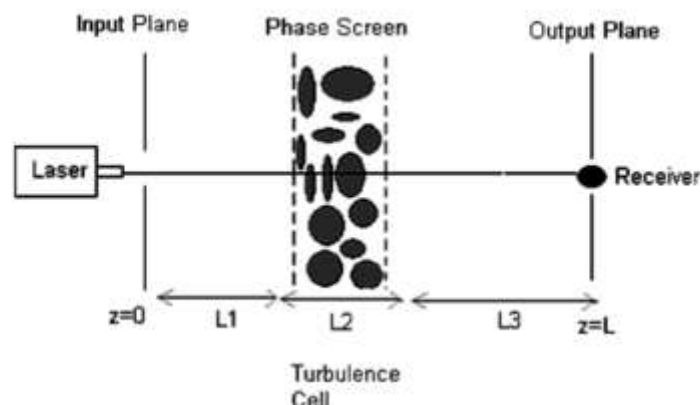


Figure: Simulated Optical Channel Propagation Geometry

6.5 Receiver Diversity Technique

A receiver with multiple receiving apertures is called a receiver diversity. These signals are used to minimize fading and beam wander and scintillation effects, and to increase the reliability of communication in the case of severe atmosphere turbulence [13–18].

6.6 Impact of Wavelength on Link Performance

Optical wireless communication performance is greatly affected by operating wavelength. It has been proven that 1550 nm has lower scintillation phenomenon and superior BER than 780 nm in the atmosphere. It also provides higher transmission power with compliance to eye-safety requirements and is the most desirable wavelength of choice for outdoor FSO systems. Most of the indoor systems use visible wavelengths emitted by white LEDs for simultaneous illumination and communication [14–18].

7. COMPARATIVE ANALYSIS: RF VS OPTICAL WIRELESS COMMUNICATION

Radio Frequency (RF) communication has been the foundation of wireless network for over several decades due to its wide coverage, mobility support and well-established infrastructure. But the exponential increase in wireless data, multimedia services, and Internet connected devices has been straining the limited RF bandwidth. While the RF system performance has been greatly affected by the use of advanced technologies like Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO) and millimetre-wave communication, the capacity of the spectrum and bandwidth still limit the data rate that can be achieved [19–29].

Optical Wireless Communication (OWC), which mainly includes Free Space Optical (FSO) and Visible Light Communication (VLC), is a promising complementary technique to RF systems. OWC uses either infrared, visible or ultraviolet light for wireless transmission, which means that it can use an enormous unlicensed optical spectrum. High spectral efficiency is made possible by these optical communication systems, allowing for data speeds of many gigabits and even terabits per second in the future. Better communication security, fewer interference, and immunity to electromagnetic interference (EMI) are all possible outcomes of spatially confining optical beams of good quality [30–40].

When using optical wireless systems, it is crucial to precisely align the transmitter and receiver. This is particularly true for outdoor FSO applications, as atmospheric turbulence, fog, rain, and beam wander can all impact communication performance. In contrast to fiber-optic communication, optical wireless communication (OWC) offers a number of benefits when it comes to short-haul broadband connection: it can be deployed quickly, the installation is cheaper than for fibre-optic communication, it does not require any licence and it has a higher communication capacity. Another interesting application of indoor VLC systems is the capability to simultaneously receive light and data reception, which can contribute to the energy efficiency of the light system and decrease network congestion for indoor networks [34–40].

As a result, optical wireless communication is no longer viewed as an alternative to RF technology, but as a complementary technology that can solve the problem of spectrum

scarcity and satisfy the need for increasing bandwidth in the next generation of 5G/6G wireless communication.

Table 7.1 Comparative Analysis of RF and Optical Wireless Communication

Parameter	RF Communication	Optical Wireless Communication (OWC)
Operating Spectrum	Radio frequency bands	Infrared, Visible and Ultraviolet spectrum
Bandwidth Availability	Limited	Very High
Spectrum Licensing	Licensed spectrum required	Unlicensed optical spectrum
Data Rate	Moderate (Mbps–Gbps)	Very High (Gbps–Tbps)
Electromagnetic Interference (EMI)	Susceptible	Immune
Interference	High in dense deployments	Very Low due to narrow optical beams
Security	Moderate	High because of directional transmission
Power Consumption	Comparatively higher	Lower for short-haul communication
Deployment Cost	Moderate	Low for last-mile and indoor installations
Propagation Medium	Radio waves	Free-space optical beam
Weather Sensitivity	Low	Higher (fog, rain, turbulence affect FSO)
Typical Applications	Cellular networks, Wi-Fi, satellite communication	FSO, VLC, Li-Fi, LAN interconnection, smart buildings

8. EXPERIMENTAL AND SIMULATION STUDIES

The theoretical simulation of optical wireless communication systems and experimental testing have been widely studied for such short-haul systems. These studies offer significant information about the behaviour of optical links under various weather conditions and ascertain how well the various mitigation methods function in enhancing the reliability of optical communications. Free Space Optical (FSO) communication systems have been thoroughly studied in MATLAB simulations and controlled lab experiments for the effects of turbulence, scintillation, beam wander, and aperture averaging.

8.1 Simulation of Atmospheric Turbulence

The atmospheric turbulence was simulated by the statistical channel models developed by Kolmogorov theory of turbulence. We were able to study the propagation of optical beams in light, moderate, and intense turbulence using turbulence phase screens, which depicted random variations of the atmospheric refractive index. The behaviour of the channel was evaluated by analysing important turbulence parameters: the refractive index structure parameter (C_n^2), Rytov variance, scintillation index, and beam displacement. It was found that optical link performance is significantly reduced due to higher signal fluctuations and fading when the turbulence intensity is increased for the simulations performed in this study [12–18].

8.2 MATLAB Based Optical Link Analysis

Using the simulation tools in MATLAB, we examined various performance characteristics for various working wavelengths, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), scintillation index, and aperture averaging factor. At the 780 nm, 980 nm, 1310 nm, and 1550 nm wavelengths, coherent and partly coherent optical beams were evaluated. It was observed from the simulation results, that the scintillation effect was found to be lower for longer wavelengths and the communication performance was better, as compared to the shorter wavelengths under same atmospheric conditions [14–18].

8.3 Experimental Test Bed for Optical Communication

To confirm the theoretical predictions, a laboratory-scale experimental test bed was built to study optical beam propagation through controlled atmospheric turbulence. The system comprised semiconductor laser sources, LED transmitters, photodiode receivers, optical lenses, mirrors, beam steering and computer-controlled measurement instruments. Artificial thermal turbulence was produced to reproduce outdoor atmospheric conditions and the beam wander, refractive index variations, scintillation effects and BER performances were measured in detail. The experimental setup allowed a good match between theoretical predictions and measured results [15–18].

8.4 Performance Improvement using Aperture Averaging

The different mitigation techniques studied here were found to be of considerable effectiveness in reducing the scintillations in the atmosphere, namely aperture averaging. Received optical power, signal-to-noise ratio (SNR), and bit error rate (BER) all declined as receiver aperture diameter grew, while spatial averaging of intensity variations grew. Experiments and simulations both showed that scintillation under moderate and heavy turbulence decreased as the receiver aperture size increased. Using partially coherent beams also enhanced the aperture averaging's effectiveness compared to conventional coherent optical beams. [15–18].

8.5 Results under Weak and Strong Turbulence

In both the simulation and experimental studies, it was consistently found that performance of the optical link is greatly dependent on its operating wavelength. The scintillation indices and the BER performance were better for the longer wavelengths, especially the 1550 nm wavelengths than for the 780 nm wavelengths. When the atmospheric turbulence is strong, the partially coherent optical beam has more advantages than the coherent optical beam, can

reduce the intensity fluctuation, and enhance the reliability of communication. Beam wander and scintillation were also reduced with increasing receiver aperture diameter, leading to considerable increases in system performance. The results presented herein validate the capability of the three technologies (longer wavelengths and FFT aperture averaging and receiver diversity) to increase the reliability and availability of outdoor short-haul OWC systems under poor atmospheric conditions [15–18].

9. APPLICATIONS OF SHORT HAUL OPTICAL LINKS

Due to the fast advancements in Optical Wireless Communication (OWC), short-haul optical links have become widely used in various applications that require dependable, secure, and high-speed wireless communication. Their capacity to provide broadband connectivity using unlicensed optical spectrum makes them strong contenders to augment the traditional radio frequency (RF) communication system.

9.1 Smart Homes and Smart Buildings

Additionally, intelligent buildings and smart houses that use Li-Fi and Visible Light Communication (VLC) also make advantage of short-haul optical communications. Internet of Things (IoT) devices, smart lighting control, home automation, and secure indoor networking can all benefit from LED-based lighting systems that simultaneously transmit light and high-speed wireless data. They have immunity to electromagnetic interference, and are therefore ideal for use in hospitals, aircraft cabins, and industrial environments where RF communication might be limited [30–40].

9.2 Military and Secure Communication

Military and defense applications necessitating a high level of security can also make advantage of short-haul optical communications, thanks to the extremely directed character of optical beams. Because they are difficult to intercept outside of the transmission line, Free Space Optical (FSO) systems are considered the most effective method for secure command and control networks, surveillance systems, border communication, and tactical combat communication. They are also immune to electromagnetic interference, which makes them even more reliable to operate in hostile environments [34–40].

9.3 LAN-to-LAN Connectivity

High speed LAN-to-LAN connectivity applications are one of the most popular uses for FSO technology. Short-haul optical links enable cost-effective building-to-building, campus-to-campus, enterprise-to-enterprise and metro-area network-to-network interconnection without physical fibre deployment. In addition to reducing installation time and infrastructure costs, these connections make high-speed data transfer, multimedia communication, video conferencing, and Internet access possible. [6–13].

9.4 Vehicular Communication

More and more research into ITS and V2V communication has focused on optical wireless technology. You may quickly communicate traffic, collision warning, and navigational data by using your vehicle's LED headlights, taillights, and traffic signals as communication transmitters. The use of these applications in smart cities will help achieve better road safety and efficient traffic management in the future smart cities [30–40].

9.5 Underwater Optical Communication

An attractive substitute for acoustic communication for short-range underwater applications is Underwater Optical Wireless Communication (UOWC). Underwater sensor networks, ROVs, maritime exploration, environmental monitoring, and defense operations can all benefit from its significantly improved data rates and communication latency. Optical communication is also affected by absorption and scattering at low frequency, but is very effective over short distances [36–38].

9.6 5G and Beyond Networks

Optical links are short-haul ones that are an important enabler for future 5G and beyond (6G) communication networks, as they offer a huge bandwidth in the optical spectrum. To alleviate spectrum congestion, FSO and VLC technologies can be employed in conjunction with RF technology to provide ultrahigh speed backhaul, indoor broadband access, and last mile connection. They will be crucial in addressing the ever-increasing need for high-capacity wireless communications and will be integrated with intelligent networking, IoT, cloud and next generation wireless infrastructure [26–40].

10. CHALLENGES AND LIMITATIONS

While optical wireless communication (OWC) has numerous advantages, it is not yet widely used due to environmental and technological concerns, particularly with outdoor free space optical (FSO) communication systems. The properties of the optical propagation channel and the severe alignment requirements between the transmitter and receiver are the main causes of these limitations.

10.1 Atmospheric Attenuation

Atmospheric attenuation is a major issue for optical communication in outdoor settings. The received optical strength and communication range are both reduced when optical signals are absorbed and scattered by environmental conditions such as fog, haze, rain, smoke, and dust. Because the size of the fog droplets is comparable to the wavelength of the optical signals, thick fog significantly weakens the signal compared to the other types of fog. [6–12].

10.2 Line-of-Sight (LOS) Dependency

An LOS channel connecting the sender and receiver is typically required for short-haul optical communication systems. Any communication barrier, such as a building site, plants, moving objects, temporary obstacles, etc., will cause the communication to fail. Optical wireless communication has limited flexibility due to the extremely stringent need of line-of-sight (LOS) in extremely dynamic contexts like wireless optical communication. [9–13].

10.3 Beam Alignment Problems

For dependable communications, it is essential that the sender and receiver be in perfect alignment. Loss of optical power at the receiver can occur from as little as a little misalignment due to things like aiming mistakes, mechanical vibrations, thermal expansion, or even a little construction movement. When dealing with longer propagation distances, the alignment challenges are exacerbated by atmospheric turbulence-induced beam wander and divergence. [12–18].

10.4 Ambient Light Noise

Indoor optical wireless communication system is influenced by ambient light from sun, fluorescent lamps and other artificial lighting sources. An increase in bit error rate (BER) and a decrease in signal-to-noise ratio (SNR) could result from this undesired optical radiation's noise at the photodetector. Optical filters and appropriate modulation techniques typically mitigate these effects. [6–10].

10.5 Fog and Atmospheric Turbulence

Circular variations in the air's refractive index brought on by turbulence in the atmosphere lead to scintillation, beam broadening, beam wander, and intensity fading. The impact of these effects becomes more profound for moderate and strong turbulence, and they cause poor reliability of communication and higher BER. While the use of aperture averaging and receiver diversity techniques reduces turbulence effects on a system, complete mitigation is still difficult [12–18].

10.6 Installation Complexity and Limited Mobility

Optical wireless systems are more sensitive to installation, alignment and maintenance than are RF communication systems and must be done precisely and regularly to achieve stable operation. Fixed transmitter–receiver alignment requires user immobility, limiting use of FSO systems in high mobility communication scenarios. Hence, optical wireless is not considered as a substitute for conventional RF systems, especially in the case of seamless mobility and omnidirectional coverage [6–13].

11. FUTURE SCOPE AND EMERGING TRENDS

The next generation wireless communication systems will be expected to have an important role for Optical Wireless Communication (OWC). Rapidly, short-haul optical links are becoming capable of much more than just being used for broad-band applications, as technological breakthroughs in photonic devices, intelligent communication algorithms, and high-speed optical components continue to extend the usefulness of these components. Improving communication reliability, expanding communication capacity, and integrating optical technologies into new wireless networks are the primary areas of future study.

11.1 Integration with 5G/6G Systems

When combined with optical wireless communication, 5G and 6G wireless networks are expected to assist in meeting the ever-increasing demands for extremely fast internet connections. There are a few potential alternatives to the current indoor RF lines, such as Li-Fi, Visible Light Communication (VLC) to augment them, and Free Space Optical (FSO) communication to provide high-speed wireless fronthaul and backhaul links. Applications with very high data rates and low latency should be enabled by this hybrid deployment, which should also boost spectrum efficiency and reduce the problem of spectrum congestion. [30–40].

11.2 Hybrid RF–FSO Communication

To address the limitations of each individual technology, a new trend in communication networks is the use of hybrid systems based on radio frequency-free space optical (RF-FSO). In ideal weather, optical links can provide multi-gigabit communication, while in bad weather, RF links can deliver communications through thick fog and severe turbulence. With



the intelligent switching of RF and optical channels, the reliability, availability, and service continuity in a broadband communication system can be significantly enhanced [30–40].

11.3 AI-Based Adaptive Optical Systems

The use of Artificial Intelligence (AI) and machine learning techniques will improve the performance of optical wireless communication by allowing the adaptive channel estimation, automatic beam alignment, predictive compensation of atmospheric effects, and intelligent management of resources. AI-based control systems can automatically track environmental factors and dynamically adjust parameters like transmitter power, receiver alignment, and modulation to ensure optimal communication performance and minimize (BER) Bit Error Rate [15–18].

11.4 Terahertz Optical Communication

When designing future systems for extremely high-capacity communication, terahertz (THz) and optical wireless should be top priorities. Existing wireless technology cannot compare to the terahertz frequencies, which provide enormous bandwidth. Integrating THz and optical backhaul networks will pave the way for ultra-low latency communication, massive IoT connection, and rapid wireless access in the future, all of which are anticipated to have a positive impact on industrial automation and smart cities. [26–40].

11.5 Quantum Optical Networking

Research into secure communication, also known as quantum optical communication, is quickly becoming into an exciting area for the future generation of communication networks. It is theoretically impossible to break the security of quantum optical networking by using quantum key distribution (QKD) of information via the quantum state of light. Future research on quantum photonics, integrated optical devices and secure free space communication are predicted to bring about great improvements in optical wireless communication applications to defence, financial systems, satellite communication and critical infrastructure protection, although this is in the experimental phase at the present time. [34–40].

12. CONCLUSION

The need for reliable, high-speed wireless broadband is always increasing, and one potential solution is optical wireless communication, or OWC. By capitalizing on the expansive unlicensed optical spectrum, OWC circumvents numerous constraints imposed by conventional Radio Frequency (RF) communication, including electromagnetic interference, small bandwidth, and scarce spectrum. In the field of various OWC technologies, short-haul optical links have been proved to have large potential to provide secure, high capacity, cost effective indoor and outdoor communication.

This article has covered the fundamentals of short-haul optical wireless communication systems, including their design, architecture, performance attributes, uses, and difficulties. Visible Light Communication (VLC) and Li-Fi are two examples of indoor technologies that are well-suited to smart homes, hospitals, schools, and other intelligent buildings because they use LED technology to both brighten the space and transfer data wirelessly. Although factors such as atmospheric attenuation, turbulence, and alignment requirements can impact



the performance of outdoor Free Space Optical (FSO) communication, it is still a viable option for establishing broadband backhaul, last-mile links, enterprise networking, and secure military communication.

Additionally, the review illustrates the potential for considerable enhancement of system performance using mitigation techniques, such as using an aperture average, receiver diversity and the choice of operating wavelengths. It is well known from experimental results and simulations that longer wavelengths, especially 1550nm, have less scintillation and better Bit Error Rate (BER) in atmospheric turbulence. Moreover, the use of partially coherent optical beams and larger optical receiver apertures can help minimize signal fading and enhance the reliability of the optical communication system.

Considering the potential for SI, AI, Hybrid RF-FSO, and Next Generation 5G/6G Communication Systems to contribute to short-haul optical links in future ultra-high-speed wireless communication networks, optical links are poised to become an increasingly vital component of the overall system. Optical Wireless Communication is a technology that has a great potential to enable future broadband communication networks as it offers secure, energy efficient and high-capacity connectivity.

REFERENCES

1. A. G. Bell, "Selenium and the photophone," *Nature*, pp. 500–503, Sept. 1880.
2. "Photophone by Alexander Graham Bell and Charles Sumner Tainter," *The Alexander Graham Bell Family Papers*, Library of Congress, Apr. 1880.
3. M. K. Carson, *Alexander Graham Bell: Giving Voice to the World*. New York, NY, USA: Sterling Publishing Co., 2007.
4. D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, U.K.: Cambridge University Press, 2005.
5. J. Foerster, "Ultra-Wideband Technology for Short-Range, High-Rate Wireless Communications," Intel Labs, 2001.
6. *IEEE Communications Magazine*, "100 Years of Communications Progress," vol. 22, no. 5, May 1984.
7. L. N. Binh, *Advanced Digital Optical Communications*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2008.
8. B. Leiner et al., "A Brief History of the Internet," Internet Society, May 1997. [Online]. Available: <http://www.isoc.org/internet-history/brief.html>
9. M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, 2nd ed. New York, NY, USA: Wiley, 2005.
10. W. C. Jakes, *Microwave Mobile Communications*. New York, NY, USA: Wiley, 1974.
11. Cisco Systems, "Cisco Unified Communications Overview," Cisco Documentation. [Online]. Available: <http://www.cisco.com>
12. A. M. Mousa, "Prospective of Fifth Generation Mobile Communications," *International Journal of Next-Generation Networks*, vol. 4, no. 3, pp. 7–24, Sept. 2012.



13. B. Bing, High-Speed Wireless ATM and LANs. Norwood, MA, USA: Artech House, 2000.
14. R. M. Gagliardi and S. Karp, Optical Communications. New York, NY, USA: John Wiley & Sons, 1976.
15. J. E. Katz, Handbook of Mobile Communication Studies. Cambridge, MA, USA: MIT Press, 2008.
16. S. Baines, "The Next Billion Mobile Users," 2005. [Online]. Available: <http://networks.silicon.com/mobile>
17. M. Castells, The Internet Galaxy: Reflections on the Internet, Business and Society. Oxford, U.K.: Oxford University Press, 2001.
18. M. Castells, J. L. Qiu, M. Fernández-Ardèvol, and A. Sey, Mobile Communication and Society: A Global Perspective. Cambridge, MA, USA: MIT Press, 2007.
19. I. F. Akyildiz and J. M. Jornet, "The Terahertz Band: Next Frontier for Wireless Communications," Physical Communication, vol. 12, pp. 16–32, 2014.
20. S. Cherry, "Edholm's Law of Bandwidth," IEEE Spectrum, vol. 41, no. 7, pp. 58–60, Jul. 2004.
21. T. Komine and M. Nakagawa, "Fundamental Analysis for Visible-Light Communication System Using LED Lights," IEEE Transactions on Consumer Electronics, vol. 50, no. 1, pp. 100–107, Feb. 2004.
22. Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical Wireless Communications: System and Channel Modelling with MATLAB®, 2nd ed. Boca Raton, FL, USA: CRC Press, 2019.
23. M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, Optical Wireless Communications: An Emerging Technology. Cham, Switzerland: Springer, 2016.
24. H. Willebrand and B. S. Ghuman, Free Space Optics: Enabling Optical Connectivity in Today's Networks. Indianapolis, IN, USA: Sams Publishing, 2002.
25. L. C. Andrews and R. L. Phillips, Laser Beam Propagation through Random Media, 2nd ed. Bellingham, WA, USA: SPIE Press, 2005.
26. L. C. Andrews, R. L. Phillips, and C. Y. Hopen, Laser Beam Scintillation with Applications. Bellingham, WA, USA: SPIE Press, 2001.
27. M. A. Khalighi and M. Uysal, "Survey on Free Space Optical Communication: A Communication Theory Perspective," IEEE Communications Surveys & Tutorials, vol. 16, no. 4, pp. 2231–2258, Fourth Quarter, 2014.
28. H. Henniger and O. Wilfert, "An Introduction to Free-space Optical Communications," Radioengineering, vol. 19, no. 2, pp. 203–212, Jun. 2010.
29. H. Kaushal and G. Kaddoum, "Optical Communication in Space: Challenges and Mitigation Techniques," IEEE Communications Surveys & Tutorials, vol. 19, no. 1, pp. 57–96, First Quarter, 2017.
30. H. Haas, "LiFi is a Paradigm-Shifting 5G Technology," Reviews in Physics, vol. 3, pp. 26–31, Nov. 2018.



31. H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?," *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1533–1544, Mar. 2016.
32. D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED Based Indoor Visible Light Communications: State of the Art," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1649–1678, Third Quarter, 2015.
33. S. Arnon, *Visible Light Communication*. Cambridge, U.K.: Cambridge University Press, 2015.
34. J. M. Kahn and J. R. Barry, "Wireless Infrared Communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.
35. Z. Ghassemlooy, W. O. Popoola, and S. Rajbhandari, *Visible Light Communications: Theory and Applications*. Boca Raton, FL, USA: CRC Press, 2017.
36. H. Kaushal and G. Kaddoum, "Underwater Optical Wireless Communication," *IEEE Access*, vol. 4, pp. 1518–1547, 2016.
37. S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 72–82, Mar. 2012.
38. I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz Band: Next Frontier for Wireless Communications," *Physical Communication*, vol. 12, pp. 16–32, Sept. 2014.
39. H. Elgala, R. Mesleh, and H. Haas, "Indoor Optical Wireless Communication: Potential and State-of-the-Art," *IEEE Communications Magazine*, vol. 49, no. 9, pp. 56–62, Sept. 2011.
40. IEEE Communications Society, "Best Readings in Optical Wireless Communications." [Online]. Available: <https://www.comsoc.org/publications/best-readings/optical-wireless-communications>