High bit rate Free Space Optical link based on Pulse Position Modulation and DPSK

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Dedication:

With the blessing of Almighty ALLAH I completed MS EE DSSP Research work Thesis. I am thankful to my great Advisor Dr. Salman Abdul Ghafoor. He is beacon of ray for me. After that I am very thankful to my parents. Without my parents prayers I am un-complete. I am thankful to my family and friends, they supported me in my study duration.

Certificate of Originality

I hereby declare that this submission titled "High bit rate Free Space Optical link based on Pulse Position Modulation and DPSK" is my own work. To the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics, which has been acknowledged. I also verified the originality of contents through plagiarism software.

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Table of Contents

List of Abbreviations

ECC:	Error Correction Code
SOA:	Saturated Optical Amplifier
VLC:	Visible Light Communication
OOK:	On-Off Keying modulation
X-Coupler:	Cross Coupler
BER:	Bit Error Rate
ROP:	Received Optical Power
PRBSG:	Pseudo Random bit sequence generator
MZM:	Mach-Zehnder Modulator
OGPG:	Optical Guassian Pulse Generator
OA:	Optical Amplifier
PM:	Phase Modulator
FSO:	Free Space Optics
GOF:	Guassian Optical Filter
PS:	Power Splitter
PC:	Power Combiner
LPGF:	Low Pass Guassian Filter
PD-PIN:	Photo detector-PIN
MZI:	Mach-Zehnder Interferometer,
CW:	Continuous Wave
LASER:	Light Amplification by Stimulated Emission of Radiation
APD:	Avalanche Photodiode
LO:	Local oscillator
OWC:	Optical Wireless Communication
RF:	Radio Frequency
ROF:	Radio over Fiber

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Abstract:

Optical Wireless Communication (OWC), with its high bandwidth, easy deployment, no license requirements, protection from electromagnetic interference (EMI) and enhanced security, has emerged as a frontrunner for high-speed broadband, surpassing traditional radio frequency (RF) systems. Research presents a novel all-optical technique to transmit multiple channels of data over an optical link using DPSK and pulse position modulation (PPM) schemes. The combination of DPSK and PPM also makes eavesdropping and interception extremely difficult. Simulation results show that the technique achieves error-free transmission of the three channels at a data rate of 30 GHz, demonstrating better security and spectral efficiency than conventional methods. Furthermore, the study extends the application of this technique to inter-satellite links, enhancing link availability for small LEO satellites through integration with a GEO data relay satellite. As the demand for secure and high-speed communication escalates, this technique holds potential for practical deployment and seamless integration into emerging communication networks.

Chapter 1: Introduction to FSO system.

This chapter delves into the fundamentals of communication systems, with a particular emphasis on Optical Wireless communication.

1.1) What is Communication system:

The concept of communication systems can be described as comprehensive frameworks enabling information exchange between two entities. This information, encompassing voice, video, text, images, or any other data type, can be conveyed in either analog or digital form.

Communication systems facilitate the transmission of this information, referred to as signals, from one entity (transmitter) to another (receiver). These signals, carrying the intended information, can exist in either analog or digital formats. The chapter further explores the specific characteristics of Optical Wireless communication systems, highlighting their unique properties and applications.

1.2) Types of Communication Systems

Communication systems can be broadly categorized into two main types:

1.2.1) Optical Communication Systems: These systems utilize light pulses as carriers to transmit information. They offer several advantages, including high data rates, high bandwidth, and superior spectral efficiency. Additionally, they are less susceptible to electromagnetic interference and offer enhanced security, making them attractive choices for both commercial and academic applications.

1.2.2) Wireless Communication Systems: These established systems have been in use for decades and employ radio waves to transmit information. While widely used, they face limitations in terms of data rate, bandwidth, and spectral efficiency.

To address these limitations and cater to the growing demand for high-performance communication, several emerging technologies are gaining significant traction:

1.2.3) Optical Wireless Communication (OWC): This promising technology leverages light waves for wireless communication, offering high data rates and immunity to electromagnetic interference. OWC encompasses two primary categories:

> **a) FSO:** This technology transmits data through the open air (free space) using light pulses.
> **b) VLC:** This technology utilizes visible light for data transmission, enabling communication integration with lighting infrastructure.

1.2.4) Radio over Fiber (ROF) Communication: This hybrid technology combines the advantages of both RF and optical communication. It involves modulating an RF signal onto a light carrier for transmission over optical fibers. This approach offers the high capacity and security of optical fibers for long-distance transmission, while retaining the flexibility and ease of deployment of RF for last-mile connectivity.

For a detailed understanding of optical communication systems, refer to Figure 1.1, which depicts a generic block diagram showcasing the key components and their interactions.

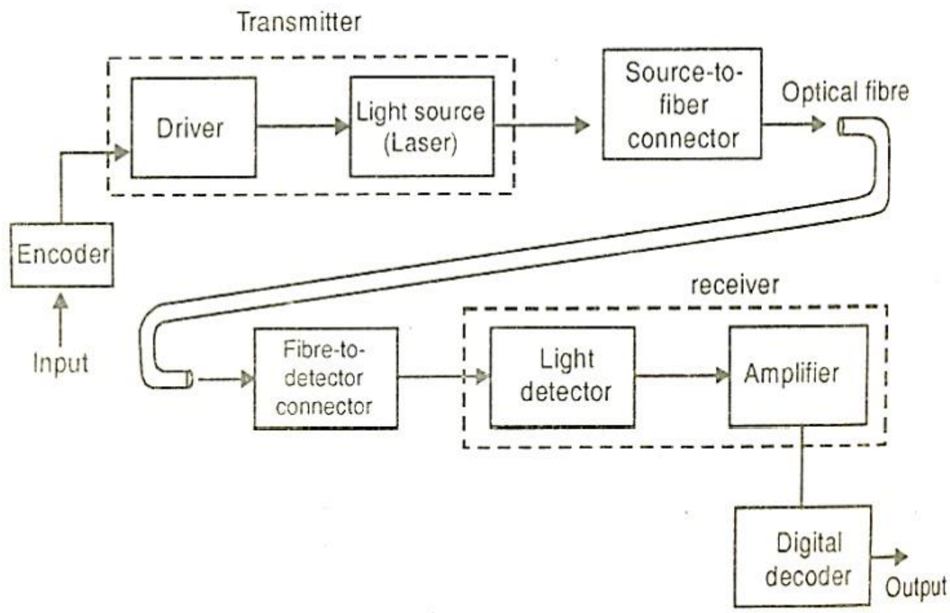

Figure.1.1: Generic block diagram of the optical fiber communication systems.

In contrast, Figure 1.2 illustrates the components and signal flow within a typical advanced digital wireless communication system. Figure 1.3 offers a visual representation of the ROF communication system, highlighting its key elements and functionalities.

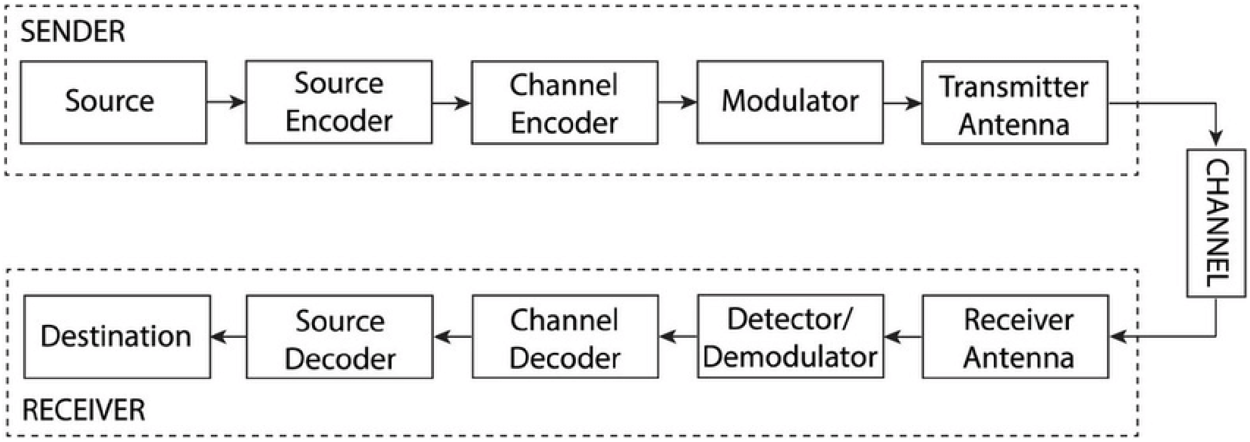

Figure.1.2: Brief Generic block diagram of advanced digital wireless communication system.

Besides this communication system is the radio over fiber (ROF). In the ROF communication basically use light to modulate the electrical signal (radio signal), then transmit it over the optical fiber channel to distribute the radio signal from central location to remote destinations.

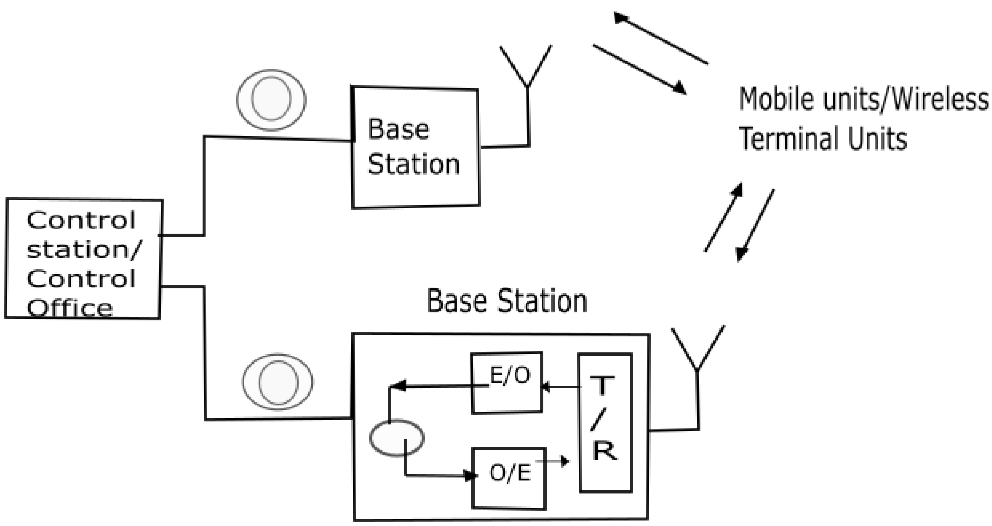

Figure.1.3: Generic block diagram of the ROF communication system.

1.3) Introduction to FSO:

Optical wireless communication (OWC) stands as a promising future technology in the ever-evolving landscape of communication systems. OWC encompasses two primary categories:

1.3.1) (FSO-channel)
1.3.2) (VLC)

We will study the free space optical (FSO-channel) communication systems in detail and will see the key parameters. The parameters that are demandable in academia and commercially. We will study why the OWC system is preferable compared to the other mentioned technologies.

(a) Why OWC: Addressing Data Traffic Bottlenecks

The ongoing advancements in 4G, 5G, and emerging 6G technologies fuel the rapid evolution of telecommunication. These advancements, encompassing applications like HD video streaming, multimedia services, high-definition television, internet protocol (IP) telephony, and ultra-broadband internet, contribute to a significant rise in the number of subscribers and, consequently, data traffic. Studies indicate that data traffic doubles every five years, posing a potential bottleneck in the coming decades [1].

Meeting the ever-increasing demand for data requires delivering high data rates and reliability to end users, while maintaining low latency. However, the current radio frequency (RF) spectrum faces limitations due to congestion, hindering wireless traffic growth [3].

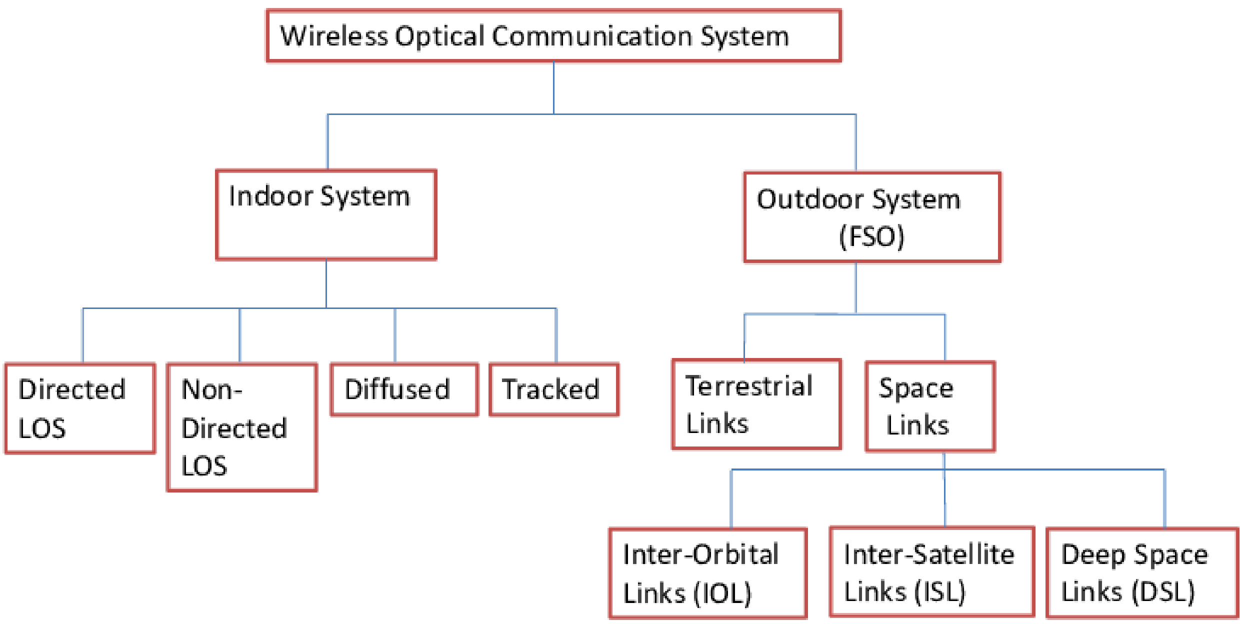

Figure.1.4: Optical wireless communication (OWC) system classification diagram.

OWC facilitates communication between nodes (source and destination) using light pulses transmitted through the free space channel (air). Data is encoded onto an optical signal at the transmitter and sent to the receiver. Notably, OWC data rates in the IR region can rival those of optical fiber communication [4-7].

It is important to acknowledge that the free space channel is inherently turbulent, meaning it is susceptible to impairments like fog, rain, storms, sunlight, dust particles, and smog. The collective impact of these factors is quantified by the scintillation index in FSO communication, which serves as an indicator of the severity of intensity fluctuations.

1.4) Comparison between OWC-link and RF-Link

The comparison table of the FSO channel and RF-Link can be found in reference [8]. Notably, OWC communication presents several advantages over traditional RF systems. With an optical frequency bandwidth in the terahertz (THz) range, OWC exceeds the typical RF carrier bandwidth by a factor of 105 [74-75]. The physical architecture of optical systems is significantly smaller, with a size of 0.3 m compared to the 1.5 m required for RF satellite antennas [76]. A common issue in the RF system is the interference caused by nearby carriers, because of the limited spectrum availability. On the other hand, OWC systems operate without spectrum licensing, eliminating the need for regulatory approvals and thereby reducing setup costs and development time [77]. The highly directional and narrowly divergent OWC laser beam renders interception exceptionally challenging, while the inability of FSO signals to penetrate walls provides an inherent defence against eavesdropping [78]. FSO's recent prominence in research stems from its potential to offer gigabit-capacity backhaul links at a fraction of the cost and deployment time associated with conventional RF or optical fiber systems [79,80]. It is expected to be the next breakthrough for fast internet access, offering unparalleled advantages over RF systems. Therefore, OWC emerges as a viable option to replace traditional RF-based communication systems. Table.1.1 summarizes the characteristics of optical wireless communication (OWC) systems and the RF communication systems.

Table.1.1: Comparison between OWC and RF Communication channel:

Parameters list	**OWC Link**	**VLC for indoor**	**Infra-red for indoor**	**RF**
Typical Data rate (R)	10Mbps-10Gbps	4Gbps(short link)	>1Gbps	<100Mbps
Component dimension	Small	Small	Small	Large
(Bandwidth-regulated)	N0	N0	N0	Yes
Power consumption	L0w medium	Low	L0w	(Medium)
Channel Security	High	High	High	L0w
interference EMI	N0	No	No	(Yes)
Network	Scalable	Scalable		N0n-Scalable

architecture				
Link performance effects	Intensity fluctuation	Multi-path	Multi-path	Multipath, fading, rain, interferences.
Distances	Medium long	Short	Short	Short-long
Coverages	(Narrow)	Narrow also wide	(Narrow also wide)	Mostly are wide
Path loss	High	Medium(high for NLOS)		High
Noise (signal degradation)	Sun + ambient light	Sun and ambient light	Sun + ambient light	Electronic/Electrical
Fog (attenuation)	37dB/km at 830nm	None		3dB/km at f=58GHz.
Mobility	None	Limited	Limited	Good
Standard	Developed	In-Progress (IEEE 802.15.7..)	Well developed	Matured
Services	communication	Illumination, communication, localization.	communication	Communication, and positioning.
Component Dimension	(Small)			(Large)

1.5) Optical Wireless Communication Significance:

Optical wireless communication (OWC), also known as FSO, has garnered significant attention in both commercial and research sectors due to its unique and appealing features:

a) Abundant Frequency Spectrum: Unlike radio frequency (RF) communication, OWC does not face limitations in the available frequency spectrum. RF communication operates within a constrained band of less than 10 GHz, while OWC harnesses a vast and readily available spectrum.

b) Immunity to Electromagnetic Interference (EMI): OWC communication is inherently resistant to electromagnetic interference, which can disrupt RF signals. This makes OWC ideal for use in environments prone to electrical noise, such as industrial settings or densely populated areas.

c) License-Free Operation: Unlike the RF spectrum, which requires licenses from national and international authorities like the Frequency Allocation Board (FAB) for specific bands, OWC operates in a license-free regime. This eliminates the need for lengthy application processes and associated costs, making OWC a more accessible and cost-effective solution.

d) Enhanced Bandwidth Capacity: OWC communication boasts significantly higher bandwidth capabilities compared to RF communication. It can offer up to 10,000 times more bandwidth, enabling the transmission of significantly larger data volumes.

e) Long-Range and High-Speed Communication: OWC systems offer high-speed communication capabilities with a versatile operational range. They can transmit data over distances ranging from nanometers to over 10,000 kilometers, while simultaneously delivering high data rates or symbol rates.

f) Solution for Future Communication Needs: OWC communication is considered a promising solution for meeting the ever-growing demand for higher capacity and high-density networks in the 5th and 6th generation of wireless technologies. It is expected to play a crucial role in supporting future advancements in various applications [9, 10, 11, 12, 13, 14, 15, 17, 18, 19-21].

1.6) Application of the FSO/OWC communication:

In the [22] the detail application of FSO communication is shared. The OWC communication is categorized into five classes based on their application.

a list of application of FSO communication in the cars, intuitions, indoor, outdoor, terrestrial, underwater and space can be found in the [23,24,25,26,27,28,29-31, 32,33,34, 35,36, 37, 38,39,40, 41,42]

1.7) Goal/Objective of the presented Research work:

The primary goal of this research is to develop and validate an innovative all-optical technique for secure and bandwidth-efficient Optical Wireless Communication (OWC). Leveraging the combination of modulation techniques, the proposed technique enhances security and spectral efficiency, making eavesdropping and interception extremely challenging. Additionally, the study aims to extend the application of this technique to inter-satellite links. Ultimately, the practical deployment and seamless integration of this technique into emerging communication networks are key objectives.

Chapter-2: Literature Review

2.1) Introduction:

Optical Wireless Communication (OWC) stands at the forefront of transformative technologies, harnessing light beams to transmit information across unguided channels, such as the Earth's atmosphere or free space. Diverging from traditional fiber optic communication, OWC offers several advantages, including a remarkably high bandwidth, easy deployment, allocation in unlicensed spectra, reduced power consumption (approximately half of RF), reduced size (approximately one-tenth of RF antenna diameter), and enhanced channel security **[72]**. This literature review investigates inter-satellite optical wireless communication (Is-OWC), a promising technology for space-based communication with crucial applications for the Internet of Things (IoT) and sixth-generation (6G) networks. We delve into the concept of Is-OWC, explore various satellite orbit types, and discuss the significance of the Ka-band for this communication method. Subsequently, we examine advanced modulation techniques and specialized approaches to optimize Is-OWC performance. Furthermore, we provide a comprehensive overview of recent techniques and hybrid solutions proposed in the literature to achieve optimal performance evaluation for Is-OWC systems. Finally, we summarize the advantages and challenges inherent to Is-OWC communication and showcase its diverse application potential, along with outlining its future prospects.

Like in the [44] the delay line interferometer is used and (DPSK) at the transmitter increase the system complexity. In the [45] pair of Mach-Zehnder modulator are used in the model which in turn increase the cost of the system. Whereas in the [50] the setup is fiber based and working on the DPSK modulation. The system suffer from the complexity and fiber non-linearity effects. Almost all approaches aforementioned which are working on the basis of optical wavelength shift keying modulation (OWSK) are using the optical fiber links. The optical fiber links suffers from various impairments like:

a) Non-linearity
e) Dispersion and electromagnetic interference (EMI).

The FSO channel got attraction in both the front and back-haul communication [51]. FSO channel are favorable as it require no license for spectrum availability, it has large bandwidth, smart hardware, less power consumption, and information can be sent securely, no problem of EMI, and the cost of FSO link is very fair in comparison to the optical fiber link [52][53].

The FSO link commonly suffer from the atmospheric turbulence that is called the intensity scintillation, represented by the scintillation index, it is like the multi-path fading in the wireless communication and is cause by the variation in the refractive index of atmosphere due to the temperature and pressure [52][54].

The turbulence and attenuation in the FSO links are addressed using the different models, like:

d) k-Model and gamma-gamma model is under research [55]. The intensity scintillation index of the atmosphere can be addressed in the best way if we use Gamma-Gamma model [56][57][58].

2.2) Applications of OWC

OWC can be applied to various scenarios like terrestrial links, deep space connections, ground-to-satellite and inter-satellite links, remote sensing, astronomy research, military COMMIT operations, disaster emergencies, last-mile access, and wireless backhaul cellular networks. Satellite technology has revolutionized various fields, fostering advancements in several applications:

1. Weather Prediction: Observing Earth from space, weather satellites track climatic conditions and measure surface temperatures, enabling accurate forecasts and hurricane tracking.
2. Navigation Systems: Global positioning systems (GPS) utilize navigation satellites to precisely locate objects like airplanes, ships, and individuals worldwide.
3. Astronomical Exploration: Astronomical satellites, like Hubble, unveil the mysteries of the universe, capturing high-resolution images of distant stars, galaxies, and planets.
4. Mobile Communication: Beyond terrestrial cell towers, satellite phones enable communication from remote locations.
5. Television Broadcasting: Satellite television utilizes orbiting satellites to transmit programs directly to viewers, typically relying on geostationary satellites for constant reception.
6. Military Applications: Military satellites contribute to national security by providing vital communication, navigation capabilities, and intelligence gathering.
7. Internet Access: Satellite internet offers internet connectivity in areas with limited or no conventional infrastructure, though its speed might be less optimal.
8. Broadcasting Entertainment: Satellite radio, often used in vehicles, utilizes orbiting satellites to deliver audio content to listeners.

2.3) Is-OWC

Within this landscape, our exploration delves into the domain of IsOWC, where satellites, whether in LEO or GEO orbit, establish communication links. Geostationary Earth Orbit (GEO) satellites, strategically positioned above specific longitudes, facilitate information relay across vast regions. IsOWC can be utilized to extend this coverage to Low Earth Orbit (LEO) satellites, enhancing link availability to ground stations. IsOWC enables real-time data transmission from Earth observation satellites to ground stations, aiding weather forecasting, disaster management, and environmental monitoring. The OptiSystem software was used to simulate inter-satellite optical links between GEO and LEO orbit, covering 45,000 km, and achieved a BER of 10−6 [**81**]. This simulation also used physical techniques like MIMO and WDM. Other methods that use less bandwidth for data transmission over OWC are DPSK with dual polarization modulation and OSSB modulation [**82**]. The pulse position modulation (PPM) [83] is another method of delivering data without interference via multi-path. Optical wireless communications are anticipated to bring innovation to advanced networks as communication technologies continue to evolve and change. These future networks, such as 5G/Beyond 5G networks, use Low Earth Orbit (LEO) satellites and non-terrestrial networks like drones and High-Altitude Pseudo-Satellites (HAPS) to provide advanced services.

2.4) Key Challenges in IsOWC

While satellite communication can be affected by atmospheric conditions on Earth, Free-Space Optical (FSO) engineering leverages environmental windows to bypass such limitations. However, inter-satellite FSO connectivity faces challenges, particularly regarding link availability, which significantly impacts data transmission. This work explores various downstream and upstream communication challenges encountered by data designers in Is-OWC systems. Notably, the vacuum environment of satellite orbits eliminates the influence of weather disturbances, unlike ground-based communication. However, other factors, detailed in [92,137], present obstacles for Is-OWC communication. Here's a breakdown of some key issues:

Communication Delay: Delays vary based on satellite orbit, with higher delays for Geostationary Earth Orbit (GEO) and moderate delays for Low/Medium Earth Orbit (LEO/MEO) satellites. Optimizing network topology and selecting appropriate applications can help minimize these delays.

Network Design: Choosing the most suitable network topology (single, hybrid, or integrated) depends on the specific satellite specifications and the need for seamless protocol and payload handling across network segments.

Throughput: Higher data throughputs require utilizing higher frequency bands, often coupled with fiber links. Techniques like focused beams and dedicated ground stations can mitigate rain-induced fading effects. However, it's important to consider that not all applications, such as some IoT applications, require high throughput.

Link Availability: A trade-off exists between link availability and frequency band. Higher frequencies offer higher throughput but lower availability due to their sensitivity to atmospheric conditions. Tracking and switching systems also play a crucial role in link availability.

Cost: The overall cost of Is-OWC systems depends on the satellite's purpose, mission, and required bandwidth. Utilizing hybrid communication schemes can help reduce costs.

Spectral Efficiency: Employing advanced modulation and coding schemes along with newer division techniques is essential for maximizing spectral efficiency. Additionally, flexible frequency allocation and software-defined carrier technologies will be crucial in the future to accommodate new applications and optimize satellite efficiency.

Pointing Errors: Inaccuracies in aligning the laser beam with the receiver's beacon can lead to signal reception issues. This is partly due to the relative rotation between the transmitting and receiving terminals, and further exacerbated by the large distances involved in inter-satellite links.

Satellite Vibrations: Vibrations generated by various onboard components like thrusters, wheels, and solar panels can disrupt the Line-of-Sight (LOS) signal, introducing noise and impacting signal integrity.

Doppler Shift: The relative motion between transmitting and receiving satellites causes a shift in signal frequency due to the Doppler effect. This necessitates wide-range optical links and specialized components like lasers and filters (used in Local Oscillator systems) for achieving coherent communication. Minimizing Doppler shift requires careful consideration and potentially employing an optical phase lock loop in conjunction with the LO laser.

Background Noise: Various sources contribute to background noise in Is-OWC systems, including thermal noise, shot noise (originating in the preamplifier and signal circuit), and noise generated by the LO system itself. Additionally, stellar and cosmic radiation fluxes can introduce further background noise.

Acquisition, Tracking, and Pointing (ATP): Maintaining precise alignment between transmitting and receiving satellites, even amidst onboard vibrations, is a significant challenge in Is-OWC systems. Achieving this high level of pointing accuracy (micro-radian level) is crucial for successful communication.

Understanding and addressing these challenges is essential for optimizing the performance and reliability of Is-OWC systems, ultimately enabling them to fulfill their potential as a high-capacity, long-distance communication solution.

2.5) Security challenges in OWC

The presence of eavesdropping is attributed to the inherent openness of wireless propagation. There are various methodologies to enhance the security of OWC communication. User links may be vulnerable to drone-based interception because of the fast movement of LEO satellites in optical wireless communications. Mitigation options encompass the utilization of Direct Sequence Spread Spectrum (DSSS) and PLS approaches, as documented in references [84-86]. The attainment of confidentiality in satellite communication (SATCOM) systems necessitates making certain trade-offs. Efforts aimed at improving uplink confidentiality often require the reduction of transmit power, thereby affecting the integrity of the system. On the other hand, amplifying transmit power to enhance link reliability results in a higher likelihood of eavesdropping, as indicated by previous research [87]. Li et al. [88] assessed security performance, focusing on eavesdropping attacks and proposing a physical layer security-based SATCOM solution. Han et al [89] used relays with hopped beams to protect the Satellite Identification Number (SIN) from uplink jamming and downlink eavesdropping. Li et al.[90] investigated integrating AI and blockchain to improve data security in 6G, tackling eavesdropping and malicious message modification. Wang et al. [91] noted that satellite networks merging with terrestrial networks are vulnerable to security and eavesdropping issues. They presented MIMO antenna-aided PLS methods to improve security and reliability due to spectrum shortages using cognitive radio (CR) approaches. The approaches discussed above are complex and challenging to implement, which made us think of a new technique to send data that is more secure, uses less bandwidth, and is cheaper.

2.6) Modulations used in the FSO communication:

In the realm of Optical Wireless Communication (OWC), modulation schemes play a pivotal role in shaping how information is encoded and transmitted via light. These schemes determine the efficiency, robustness, and data rates achievable in optical communication links.

On-Off Keying (OOK) reigns supreme in FSO systems due to its simplicity and bandwidth efficiency. It leverages binary data, where "on" signifies a 1 and "off" signifies a 0, , respectively. However, OOK necessitates an adaptive threshold for optimal performance, unlike Detection (IM/DD) [140]. Combining OOK with line coding techniques further enhances its effectiveness. OOK NRZ offers a moderate signal-to-noise ratio (SNR) at a lower cost, while RZ exhibits superior sensitivity [139].

Despite its advantages, OOK suffers from limitations in spectral and energy efficiency. Additionally, it is susceptible to amplitude distortion, making power and energy crucial factors for FSO system design. Energy efficiency relates to data rate, while spectral efficiency relates to information rate.

To address OOK's shortcomings, alternative modulation techniques such as Pulse Position Modulation (PPM) and Multi-Pulse PPM (MPPM) are employed. Single-pulse PPM excels in energy efficiency but falls short in spectral efficiency [141]. To improve spectral efficiency, multiplied pulse PPM utilizes multiple laser sources and receivers, maximizing both energy and spectral efficiency [142]. Notably, PPM eliminates the need for the dynamic threshold required in OOK. Studies have shown that using half the available time slots with a laser source yields superior spectral and energy efficiency [143]. This energy efficiency makes PPM ideal for applications with high energy demands, such as deep-sea or space communication.

MPPM offers the benefit of improved PAPR compared to PPM, while PPM boasts superior average power performance [144, 146]. However, MPPM presents challenges in switching speed due to the high bandwidth of optical networks compared to electrical ones. Increasing switching speed incurs higher costs. Additionally, MPPM's reliance on binary convolutional codes poses demodulation difficulties at the receiver end. To mitigate this, a complex decoding method known as Soft Input and Soft Output (SISO) might be employed, further increasing network complexity [148].A variation of PPM, Differential Pulse Position Modulation (DPPM), transmits a data stream where each pulse is followed by an empty slot, enhancing bandwidth efficiency [149].While On-Off Keying (OOK) reigns supreme in FSO systems for its simplicity and bandwidth efficiency [150], alternative methods offer distinct advantages in specific scenarios. This section delves into (PWM), (DPIM), SIM, (OFDM), and Multi-Level Modulation techniques.

Compared to PPM at the same bit rate, PWM offers wider pulses, reducing inter-symbol interference (ISI) but sacrificing power efficiency [150]. Both PWM and PPM are synchronous, requiring synchronization between the modulator and demodulator. In contrast, DPIM, an asynchronous technique, transmits information using empty slots within the data stream [139]. This absence of fixed data stream lengths results in superior spectral efficiency [151]. However, DPIM faces challenges at the receiver, where empty slots can be misinterpreted as information, leading to errors.

SIM involves modulating information with an RF signal before converting it to an optical signal for intensity modulation [152]. While SIM boasts higher throughput and lower phase fluctuations compared to OOK, its power efficiency falls short [153]. OFDM, a prominent multiplexing technique, offers resistance to ISI by employing orthogonal subcarriers [154]. Researchers are exploring the integration of OFDM into optical wireless communication due to its impressive results in wireless communication. However, merging these techniques presents significant challenges due to their distinct domains (RF vs. optical) and inherent constraints (bipolar vs. unipolar nature and coherent vs. direct reception) [155]. Optical OFDM (OOFDM) offers benefits like long-distance transmission but necessitates a trade-off between distance and power loss [156].

These techniques aim to improve system capacity by transmitting multiple bits per symbol. M-ary Amplitude Shift Keying (M-ASK) exhibits lower sensitivity to distortion compared to OOK [157]. Additionally, various multi-level modulation schemes offer superior spectral efficiency compared to their binary counterparts [156]. However, these techniques are more susceptible to receiver sensitivity issues, particularly as dispersion parameters in FSO links increase.

An analog modulation technique also utilized with light sources, PAM employs pulse amplitude for signal modulation. It offers bandwidth efficiency compared to other schemes like PPM and OOK but presents higher complexity [159]. Studies have shown that increasing the number of bits in LPPM leads to a negative impact on Bit Error Rate (BER) while MPPM exhibits the opposite trend. Additionally, LPPM exhibits decreasing average power with increasing bits but a ballooning bandwidth, while M-PAM displays the opposite behavior [159]. Therefore, the choice between these techniques hinges on specific requirements, such as prioritizing power efficiency over bandwidth.

This category encompasses modulation schemes that utilize the phase of the signal for modulation. Binary Phase Shift Keying (BPSK) employs two phases (0° and 180°) for modulation. BPSK, commonly used in devices with limited range like Bluetooth, offers lower power consumption compared to Quadrature Phase Shift Keying (QPSK), which uses four phases and modulates two bits at a time, resulting in higher capacity but lower power efficiency for a specific signal-to-noise ratio [143]. As the number of phases increases in PSK schemes, so does the bandwidth efficiency, but so does the power requirement. This trade-off is crucial when selecting the appropriate modulation technique for FSO applications.

Beyond the previously discussed methods, Differential Phase-Shift Keying (DPSK) offers an alternative approach. Unlike traditional PSK schemes, DPSK modulates the signal's phase relative to the preceding symbol, mitigating certain drawbacks inherent in QPSK and PSK [160]. This technique demonstrably reduces the impact of various signal-degrading effects [160].

DPSK shares similarities with (DQPSK), exhibiting comparable performance. However, DQPSK transmits two bits per symbol, resulting in double the data rate and superior spectral efficiency compared to DPSK, albeit at the expense of slightly higher power consumption [160].

Carrier-less Amplitude and Phase Modulation (CAP) presents another modulation technique with advantages for FSO systems. Similar to QAM, CAP modulates two carrier signals; however, CAP combines and filters these signals before transmission, contrasting the separate modulation employed in QAM. Studies have shown that CAP offers improved energy efficiency compared to PAM, while also being more cost-effective [161].

In conclusion, this exploration has delved into a wider range of modulation techniques applicable to FSO systems, highlighting their unique characteristics and potential benefits. Table II summarizes the various qualities associated with each discussed modulation scheme. Understanding these diverse techniques empowers informed selection based on specific application requirements. Table 2.1 gives a brief overview of the modulation schemes we have explored.

Table 2.1: Modulation schemes for OWC

Modulation Schemes	References	Qualities in FSO
OOK	139,140	This technique (high sensitivity, moderate SNR) offers low cost, easy implementation, and moderate power efficiency.
PPM	142,143,139	This synchronous method boasts higher power efficiency than MPPM and eliminates the need for dynamic thresholding.
MPPM	145,139	This technique features improved PAPR, low peak power, and high spectral efficiency.
DPPM	148,139	This method surpasses MPPM in spectral efficiency and offers improved power efficiency as compared to PPM.
PWM	150	This synchronous approach exhibits higher average width and spectral efficiency compared to PPM, providing a better response to ISI but with lower power efficiency.
DPIM	139,140,141	This method eliminates synchronization requirements and offers a wider bandwidth compared to PPM and PWM,

		but it poses challenges in demodulation.
SIM	152,139,153	This method offers higher throughput than OOK, reduced phase fluctuation, and increased capacity, although it exhibits lower power efficiency and incurs slightly higher costs.
OOFDM	154	This method boasts high resistance to ISI and excellent range, but presents difficulties in combining signals.
M-ASK	153	This approach exhibits lower sensitivity compared to OOK.
PAM	157	This method prioritizes spectral efficiency over implementation complexity and offers moderate power efficiency.
MPAM	159	This approach surpasses PAM in spectral efficiency, though it requires dynamic thresholding at the receiver.
QAM	151,157	This method offers increased intensity, exceeding both power and spectral efficiency compared to PAM.
BPSK	139,142	This method demonstrates superior power efficiency compared to QPSK.
QPSK	160,139	This method prioritizes high capacity and spectral efficiency at the expense of power efficiency.
DPSK	160,159	This method offers larger capacity compared to DQPSK but suffers from a lower data rate and reduced spectral efficiency.
DQPSK	160	This method prioritizes high data rate and bandwidth efficiency, sacrificing power efficiency.
CAP	161	This method excels in energy efficiency compared to PAM, while maintaining simplicity and affordability in its implementation.

2.6.1) Advanced Modulation Techniques for Is-OWC Systems

The chosen modulation technique significantly impacts an Is-OWC system's reliability, energy efficiency, and ability to efficiently utilize the available spectrum. Recent research highlights how the propagation medium in Is-OWC systems heavily influences other key parameter selections. Consequently, bandwidth-efficient modulation approaches play a crucial role in system design.

Visible Light Communication (VLC) research has explored various line coding and modulation techniques. On-Off Keying (OOK) is often considered due to its simplicity, energy efficiency, and cost-effectiveness. However, OOK offers limited data rates and suffers from pulse width widening effects. While Pulse Amplitude Modulation (PAM), like PAM-4 and PAM-8, is being investigated to improve spectral efficiency, it comes at the cost of reduced receiver sensitivity. Similarly, pulse width modulation (PWM), commonly used for LED dimming, offers limited data rates. Both OOK and PPM are single-carrier pulsed modulation techniques that may require time-domain equalization in Free-Space Optical (FSO) systems with severe channel impairments.

Researchers are increasingly exploring advanced modulation formats like Carrier Suppressed Return-To-Zero (CSRZ), Duobinary Return-To-Zero (RZ), and modified DRZ to address the limitations of PPM in terms of bandwidth inefficiency and complexity. However, these formats still struggle to support data rates exceeding 40 Gbps.

The ever-growing demand for data necessitates high-capacity FSO systems. Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) are frequently encountered modulation formats in FSO. While DPSK offers two phase shifts (0 and π), DQPSK offers four (0, $\pm\pi/2$). However, DPSK relies on consecutive bits for reception, leading to error propagation. Conversely, DQPSK suffers from significant background noise interference.

Multi-level modulations hold promise for achieving high speeds while extending FSO distances. but suffer from non-linear distortions due to high Peak-To-Average-Power Ratio (PAPR). Quadrature Amplitude Modulation (QAM)-based FSO systems offer good immunity to noise and efficient bandwidth usage. However, QAM is less power-efficient compared to QPSK. Various QAM variations exist, ranging from 8-QAM to 256-QAM. 256-QAM has the narrowest spectrum due to each symbol carrying 8 bits.

To achieve high speeds, researchers are exploring various dimensions like space, time, frequency, polarization, and modulation quadrature. Polarization division multiplexing (PDM) leverages the polarization dimension to improve spectral efficiency and double user capacity. Combining PDM with other modulations like OFDM, QAM, or QPSK can further enhance optical transmission capacity. PDM effectively reduces the symbol rate compared to single-polarization transmission, enabling the use of lower-speed electronics in high-speed systems.

2.7 Techniques to address the scintillation noise/index:

In the literature different techniques have been suggested to address the scintillation noise. We know the OWC channel is almost terrestrial. These techniques include:

a) Time delayed diversity like in the [59]
b) For overcoming the atmospheric fluctuation (fading effect) many techniques are applied like in the [60][61] Multiple transmitter and receivers are used (spatial diversity)
c) For improving link performance like in the [62-66] Multiple Receivers are used.
d) While for improving the FSO-Link performance like in the [67][68] Multiple Transmitters also preferred.
e) Whereas for addressing the intensity fluctuation in the FSO-Link like in the [69,70] Lenses of large aperture are preferred.

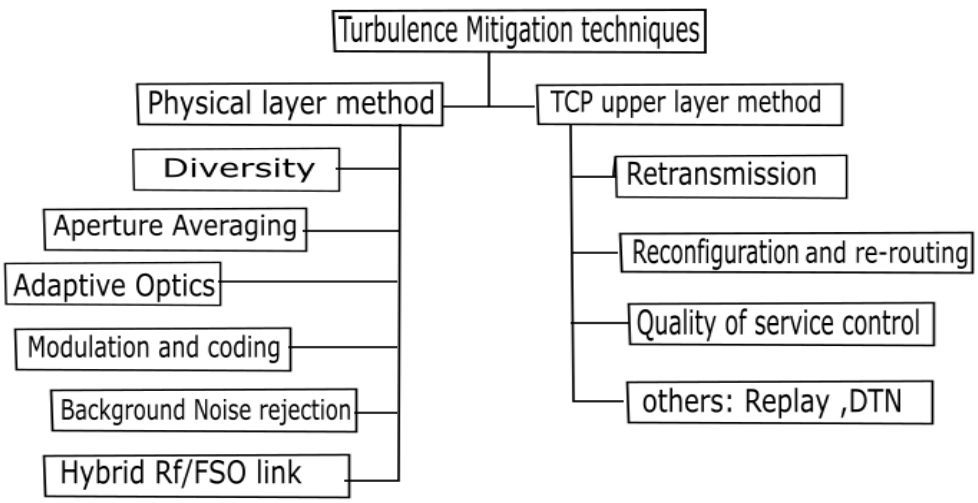

Figure.2.2: Techniques/Mechanism used for the mitigation of atmospheric turbulence. [71]

2.8 Channel Models for OWC:

Table.2.2 briefly explains the FSO-model used in the different FSO channel with required coding and detection techniques applied.

Table.2.2: OWC-Channel models used with modulation and detection technique:

S.No	Coding	Modulation techniques	Channel model	Channel detection techniques	Paper References
1.	Convolutional (add	On-Off Keying	gamma-gamma	Direct detection	[174]

	redundancy)			Method	
2.	-	On-Off Keying	(Log-Normal)	ML detection (with CSI)	[175]
3.	-	On-Off Keying	(Gamma-gamma, Log normal)	(ML sequence detection) with MLSD	[176]
4.	Turbo code	On-Off Keying and PPM	--	Direct Detection (DD)	[177]
5.	-	On-Off Keying	K	Direct detection (DD)	[178]
6.	-	On-Off Keying	K and IK	Direct detection (DD)	[179]
7.	-	On-Off Keying	Modified Rician	Coherent Detection (DD)	[180]
8.	Reed Soloman	PPM, DPSK modulation	Log normal and negative exponential	Direct Detection (DD)	[181]
9.	-	PP Modulation	(Gamma-gamma)	Direct Detection (DD)	[182]
10.	Space time trellis code	On-Off Keying	(negative exponential with K)	Direct detection (DD)	[183]
11.	(BICM)-Bit interleaved coded and multi-level coding	(PPM modulation)	(Poisson)	Direct detection(DD)	[184]
12.	LDPC, OFDM coding	On-Off Keying, QAM,BPSK,QPSK	(Gamma-gamma)	Direct detection (DD)	[185]
13.	-	PPM along with dual pulse PPM	(negative exponential)	Direct detection (DD)	[186]
14.	-	DPPM and OOK	Log normal	Direct detection (DD)	[187]

15.	Reed soloman	PPM	Poisson	Direct detection (DD)	[188]
16.	-	SIM DPSK	(Gamma-gamma)	Direct detection (DD)	[189]
17.	-	SIM BPSK	K	Direct detection (DD)	[192]
18.	Block code, convolutional code , and turbo code.	On-Off Keying	(Log normal)	Direct Detection (DD)	[193]
19.	code division multiple access (CDMA) and Turbo coded	SIM-PSK	Gamma-gamma	Direct Detection (DD)	[194]
20.	(Convolutional code)	PP-Modulation	(gamma-gamma)	Iterative Ietection (ID)	[195]
21.	LDPC	On-Off Keying	(gamma-gamma)	VBLAST-ZF detection	[196]
22.	-	PP-Modulation	(gamma-gamma)	VBLAST-ZF detection	[197]
23.	-	. (DPP Mand PWM)	Gaussian	Direct detection (DD)	[198]
24.	Hybrid channel (LDPC code) and adaptive code.	BPSK scheme	Kim Model and gamma-gamma with Hybrid RF and FSO	ML-Detection (ML-D)	[199]
25.	Interleaved concatenated code (ICC) convolutional and reed Solomon)	Binary PPM	Gaussian model	Iterative detection (ID)	[200]

Chapter-3: OWC-Link Components

This chapter covers the components that are used generally in the OWC channel. Which type of transmitter and receivers are preferred in optical communication. The types of the receiver used in the optical communication. The parameters values used for transmitter and receiver.

3.1) Optical sources used in the literature:

Different types of sources are used in the literature to generate the optical pulses for the OWC-Communication both for FSO-Communication and for visible light communication (VLC).

The LASER in use are Semi-conductor LASER. They are:

3.1.1) DFB DBR LASER

For OWC communication systems, also known as FSO systems, leverage single-mode lasers due to their advantageous properties. These lasers emit light with only a single transverse electromagnetic field mode and a single longitudinal cavity mode. An example of such a laser is the DFB (Distributed Feedback) laser, which boasts a remarkably narrow linewidth of less than 0.1 nm [171, 172]. This narrow linewidth translates to a capability for high-data-rate modulation due to the concentrated energy emission of these sources.

3.2. Optical detectors used in the literature:

When reaching the receiver end, the optical signal is converted into an electrical signal using photodetectors. Two commonly employed types are:

3.2.1. PIN Photodiodes: These detectors offer lower gain and sensitivity compared to avalanche photodiodes (APDs). However, they are generally more affordable and readily available commercially. PIN photodiodes are widely used in optical communication systems due to their favorable characteristics, including good quantum efficiency, compact size, excellent sensitivity, suitable construction materials, and fast response times [173].

3.2.2. Avalanche Photodiodes (APDs): APDs provide superior sensitivity compared to PIN photodiodes, offering a gain improvement of 4 to 7 dB. These detectors strike a balance between cost and performance, making them commercially viable for various applications.

3.3. Optical Receivers in FSO/OWC Systems

FSO and OWC communication systems utilize two main types of optical receivers:

3.3.1. Coherent (Heterodyne) Receivers: These complex and expensive receivers employ a locally generated optical field that is mixed with the received signal from the transmitter. The combined signal is then detected, leading to increased receiver complexity and cost. Coherent receivers are primarily used when the optical carrier is modulated using amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM) schemes.

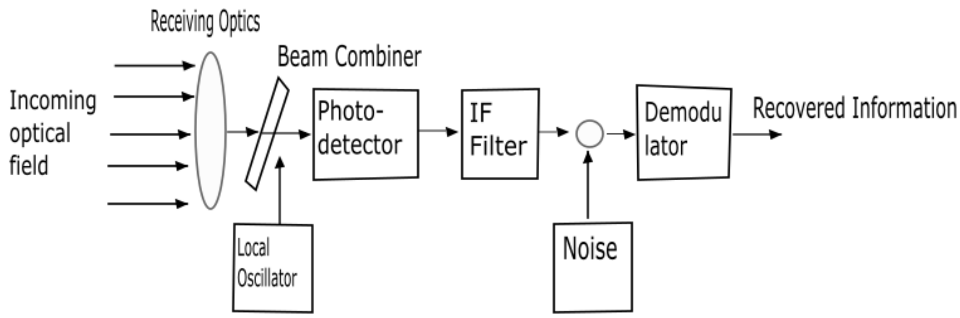

Figure.3.1: Generic block diagram of coherent detection in optical communication.

3.3.2. Incoherent (Non-coherent/Direct) Receivers:

These simpler and more cost-effective receivers, also known as direct or power (intensity) detection receivers, do not require a local oscillator. This straightforward approach makes them easier to implement and manage in FSO/OWC systems.

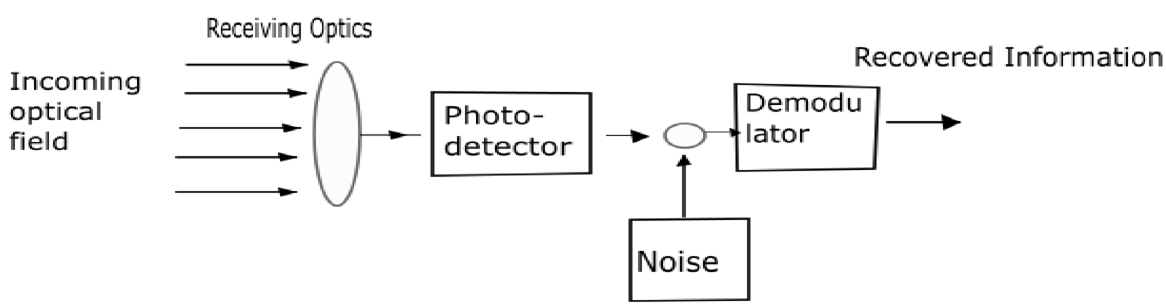

Figure.3.2: Generic block diagram of direct detection in optical receiver.

3.4. Noise at the receiver end:

Several types of noise can corrupt the optical modulated signal during transmission and reception. These can be categorized as follows:

3.4.1) Photodetector-Induced Noise: This noise originates from the receiver's circuitry and arises due to the movement of electrical charges through resistors.

3.4.2) Thermal Noise: This electronic noise originates from the random thermal motion of electrons within the receiver's circuitry.

3.4.3) Background Light Noise: This unwanted light, distinct from the transmitted signal, enters the receiver and adds noise to the received signal. It can be likened to ambient light interfering with the desired signal.

3.4.4) Shot Noise (Quantum Noise): This inherent noise stems from the statistical nature of the photon conversion process when the optical signal is converted into an electrical signal at the receiver.

3.4.5) Dark Current Noise: This noise originates from the leakage current within the photodiode's P-N junction at the receiver, even when no optical signal is present.

3.5) Free Space Optical Communication Link Briefly Explain:

The FSO channel can be easily understandable pictorially as:

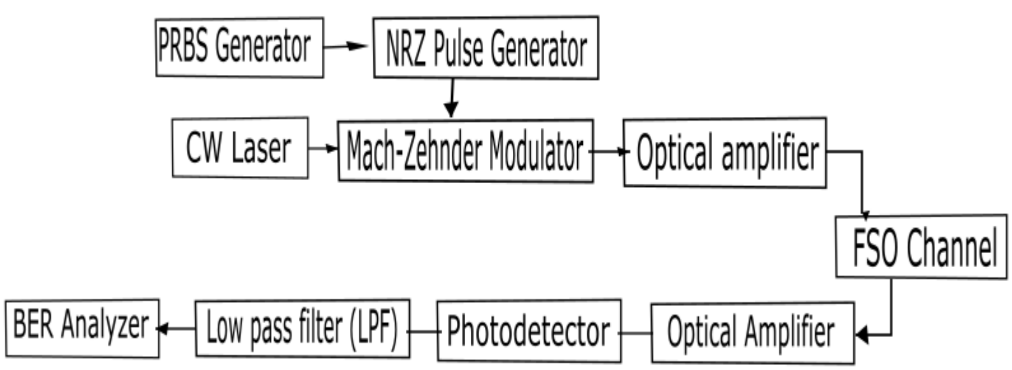

Figure.3.3: Generic block diagram of the FSO-channel showing components.

The figure.3.3 briefly explain the steps that are needed for the basic FSO-communication. The modulated data is sent over the free space. Following the figure.3.3

a) Continuous Wave (CW) Laser: This powerful laser serves as the source of light pulses for long-range FSO communication, exceeding 10,000 kilometers. It can also support high data rates of up to 40 Gbps.

b) Pseudo-Random Bit Sequence (PRBS) Generator: This component generates the digital data to be transmitted in the form of a sequence of 0s and 1s, typically at a rate of N Gbps.

c) Non-Return to Zero (NRZ) Pulse Generator: This component converts the digital data from the PRBS generator into an electrical signal suitable for driving the Mach-Zehnder Modulator (MZM-Modulator).

d) Mach-Zehnder Modulator (MZM-Modulator): This optical modulator manipulates the incoming laser light by altering its frequency, amplitude, phase, or polarization. The electro-optic effect within the MZM-Modulator, where the material's optical properties change upon application of an electric field, enables this modulation. The MZM-Modulator features two branches where the desired variations are introduced.

e) Optical Amplifier: This component amplifies the modulated optical signal before it is transmitted through the free space channel. The gain is typically expressed in decibels (dB), with a common value of 20 dB applied to the signal before transmission.

f) Free Space Channel: The amplified modulated signal travels through the free space medium (air). However, various environmental factors, such as smog, rain, dust particles, sunlight, and storms, can affect the signal. These impairments are collectively represented by the scintillation index, which can vary in severity. The signal is then received by the receiver.

g) Optical Amplifier: At the receiver end, the received signal is amplified again using an optical amplifier, typically providing up to 20 dB of gain and having a noise figure of 4 dB.

h) Photodetector: This device converts the received optical signal back into an electrical signal for further electronic processing.

i) Low-Pass Filter (LPF): The converted electrical signal is passed through a low-pass filter with a specific bandwidth. This filter eliminates unwanted noise and harmonics from the signal, extracting the desired information transmitted from the source.

j) Bit Error Rate (BER) Analyzer: This tool evaluates the quality, strength, and reliability of the received signal by measuring the bit error rate (BER). It indicates whether the received signal is reliable and has good quality.

3.6) Modulation techniques:

The MZ-Modulator works on the two modulation mechanisms.

3.6.1) Direct Modulation:

This straightforward approach directly modifies the continuous wave (CW) light emitted by a laser source. However, it suffers from several drawbacks, including laser resonance frequency chirp, pulse spreading, turn-on delay, clipping, and limited modulation depth due to the need to avoid completely shutting off the laser. These limitations can lead to information loss. Despite these downsides, direct modulation remains popular due to its simplicity and robustness.

3.6.2) Indirect/External Modulation:

The indirect approach, on which the MZ-Modulator primarily relies, involves modifying the transmission characteristics of an externally generated light source. By separating light generation and modulation, this method offers several advantages. It boasts a wider bandwidth, reaching up to 60 GHz, while delivering superior quality compared to its direct counterpart. However, it comes at the cost of higher complexity and expense.

External modulation offers several benefits over direct modulation, including a larger extinction ratio, broader bandwidth, superior spectral purity, the ability to handle higher power levels, and the elimination of the degrading effects associated with direct modulation, such as laser line width instability.

Table.3.1: Basic characteristics of LASER diodes.

S.No	**List of Parameters**	**Properties**
1.	LASER's materials	compounds are III-V
2.	Recommended Emission Wavelength	800nm to 1500 nm
3.	Mostly used Output Power	1mW to 100 mW
4.	Preferred Linewidth	0.1nm to 5 nm
5.	Modulation Bandwidth of LASER	Many GHz

Chapter-4: Proposed Model, Methodology, Results and Discussion

This chapter proposes the hybrid DPSK-PPM Modulation technique for Secure and Spectrally Efficient Multi-Channel Optical Wireless Communication. It also covers the **methodology**, **results** and **Discussion** part. The related figures, plots, and eye-diagram covered in this chapter will justify the proposed model for Optical Wireless Communication. Besides this it includes the possible application scenario of the proposed model and is concluded with the summary of the proposed model.

4.1) Proposed Model Basic Properties:

4.1.1) Software for simulation of the proposed Model:

Research employes Optisystem 20 software, a commercial tool commonly used for simulating optical fiber and wireless communication systems for research and development purposes. Terrestrial OWC links are susceptible to atmospheric turbulence, which varies in intensity depending on weather conditions. The severity of turbulence is quantified by the scintillation index, with higher values indicating stronger turbulence.

To mitigate the effects of turbulence and ensure smooth data transmission, various channel models are employed. This study utilized the Gamma-Gamma model, which effectively counteracts atmospheric turbulence in terrestrial links while assuming no turbulence in space. This model is well-suited due to its ability to accurately represent the characteristics of terrestrial FSO channels.

Electromagnetic Spectrum band Showing OWC frequencies band:

The electromagnetic spectrum encompasses various frequency bands, including those used for OWC. Optical wireless communication, also known as FSO, transmits data through unguided media using optical carriers within the visible light, infrared, and ultraviolet regions. OWC systems typically operate between 350 nm and 1550 nm, a range characterized by low absorption and attenuation. Additionally, these wavelengths are safe for human eyes.

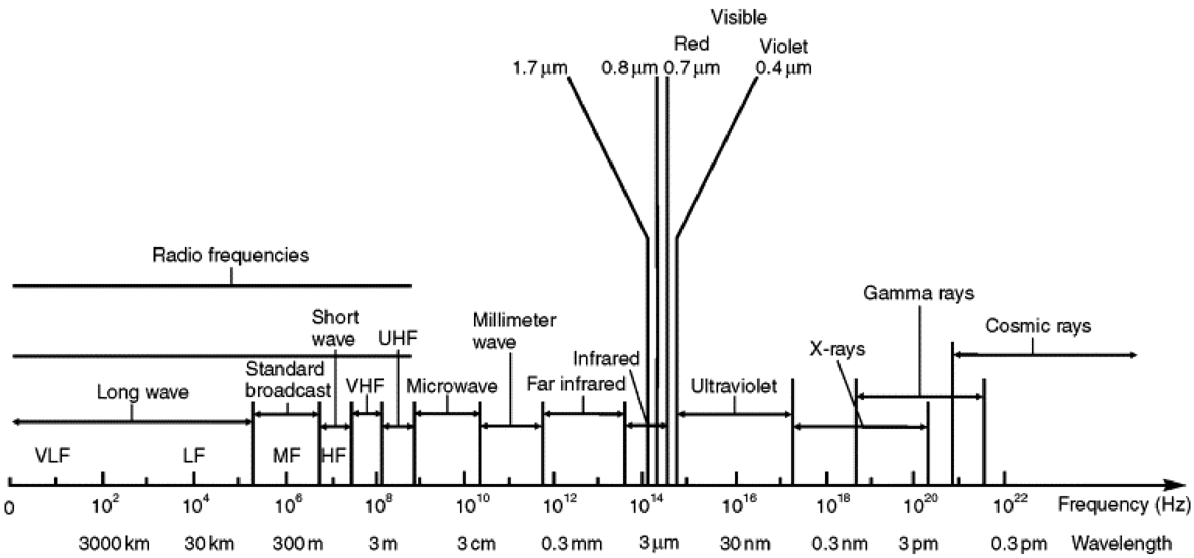

Figure.4.1: Radio frequency (RF) Spectrum showing OWC region.

4.2) Proposed Model operation Principle and Methodology:

The detailed setup of our proposed technique is shown in Figure 4.2. Our approach utilizes an optical pulsed laser source with a center wavelength of 1552 nm. The laser emits Gaussian-shaped pulses with a width of 12 ps and 10 GHz frequency. These pulses carry the data of three channels from the optical ground station (OGS). Each data symbol consists of 3 data bits. Optical Differential Phase Shift Keying (DPSK) modulation is employed for encoding data of channel one. Initially, pseudorandom bit sequence (PRBS) generator generates the bitstream, which is then fed to a DPSK encoder. In the DPSK encoder, the PRBS data is combined with a one-bit delay through an XOR gateway before converting it into NRZ format. The DPSK-encoded electrical signal then modulates a Mach-Zehnder (MZ) modulator, resulting in an optical DPSK signal. Hence, the optical DPSK signal efficiently encodes data bits of channel-1 in the phase of the optical carrier [166].

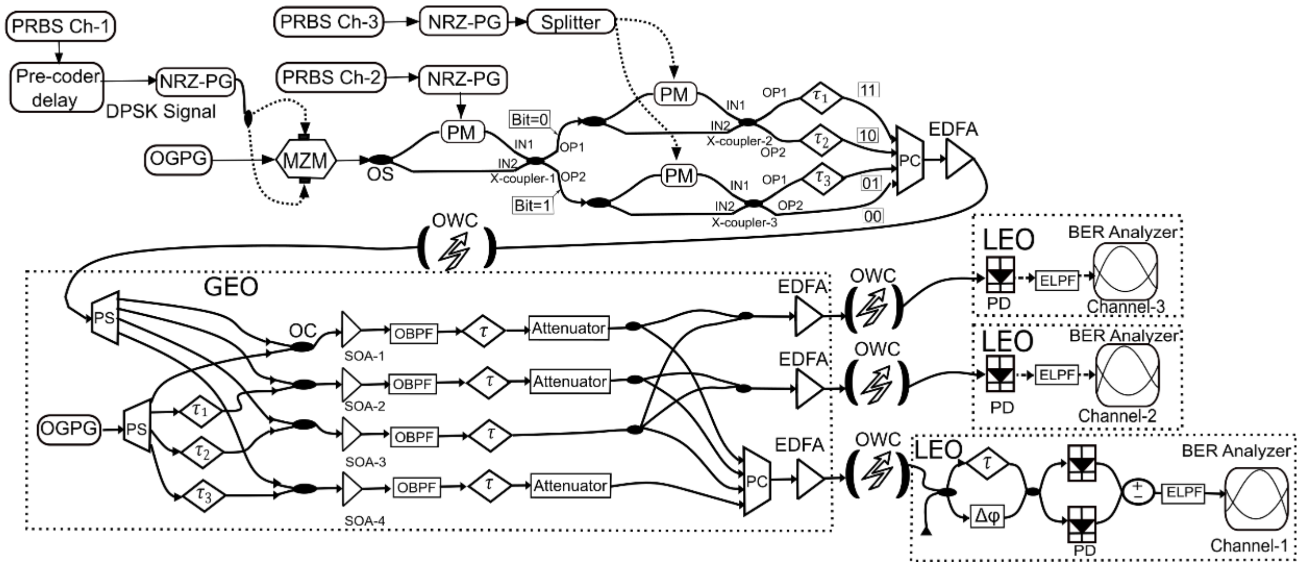

Figure.4.2. Hybrid PPM-DPSK technique designed in Optisystem. EDFA: Erbium doped fiber amplifier, PM: Phase modulator, PC: Power combiner, OC: Optical coupler, OS: Optical splitter, PS: Power splitter, PD: Photodetector, OBPF: Optical band pass filter, φ shift: Phase shift, OGPG: Optical Gaussian pulse generator, ELPF: Electrical low pass filter

This optical signal is then transmitted through a Mach-Zehnder Interferometer (MZI) structure. Within the interferometer, one of the branches incorporates a phase modulator (PM) that receives its electrical input from channel-2 having a bandwidth of 10 GHz. The data for channel two is produced by a PRBS generator that controls an NRZ electrical pulse generator (NRZ-PG). The phase of the optical signal is rotated by 90 degrees by the PM for a high electrical data value (representing one bit), while it does not change the phase for zero bits. A 3dB X-coupler having two input and two output ports is placed at the end of the MZI [167].

The X-coupler has a transfer matrix that can be written as:

$$\begin{bmatrix} OP_1 \\ OP_2 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \begin{bmatrix} IN_1 \\ IN_2 \end{bmatrix}$$

The transfer matrix determines the optical signal at output. If the signal's phase changes by 90 degrees, it will come out of port OP1 of X-coupler-1. If the signal's phase stays the same, it will come out of port OP2. In this way, the path of the optical signal depends on the data bits of channel one.

Following the first MZI, two additional MZIs are used, with their PMs simultaneously receiving electrical data pulses from channel three. Similar to the previous MZI, the PM from channel two decides which port of the X-couplers the optical signal will go through. If the PM gets one bit, the signal will go through port OP1. If the PM gets a zero bit, the signal will go through port OP2. This means that the four outputs of X-coupler-2 and X-coupler-3 will get an optical pulse for each time period, based on the bits the PMs of the three MZIs receive.

We use variable delay lines to create pulse position modulation (PPM) for four different pairs of bits on the output paths. Each 2-bit symbol is used to control the position of a pulse within a fixed time frame. The pulse for the bit pair “00” has no delay. The pulse for the bit pair “01” has the smallest delay (t1), which is more than the optical signal’s pulse width (12 ps). The pulse for the bit pair “11” has the largest delay (t3), which is less than the optical signal’s time period (100 ps). The pulse for the bit pair “10” has a delay (t2) that has a value between t1 and t3. We use a 4x1 power combiner to join the four outputs. The power combiner’s output is boosted by an EDFA amplifier before it goes over the optical wireless channel (OWC) from the OGS. We use the Gamma-Gamma channel model [166] to simulate this channel.

At the GEO satellite relay, it is split into four different paths employing a power splitter. Subsequently, an optical pump signal, like the pulsed laser source at the ground station but with a different optical wavelength of 1550nm will be employed to demodulate received DPSK-PPM signal and get data channels.

We delay the four signals generated from the local pump source using same delays as the ones at the transmitter side. This means that there is always one pump pulse for each PPM pulse time interval, as input to SOA shown in Figure 4.3. Each of the four paths will randomly combine with four received signals and experience four-wave mixing (FWM) using SOAs. We pick the pump power and the wavelength difference between the pump and signal pulses to make one sideband on each side of the signal and pump spectrum [79]. We used bandpass filters at 1548.4 nm after each SOA to choose the sidebands that are made by FWM.

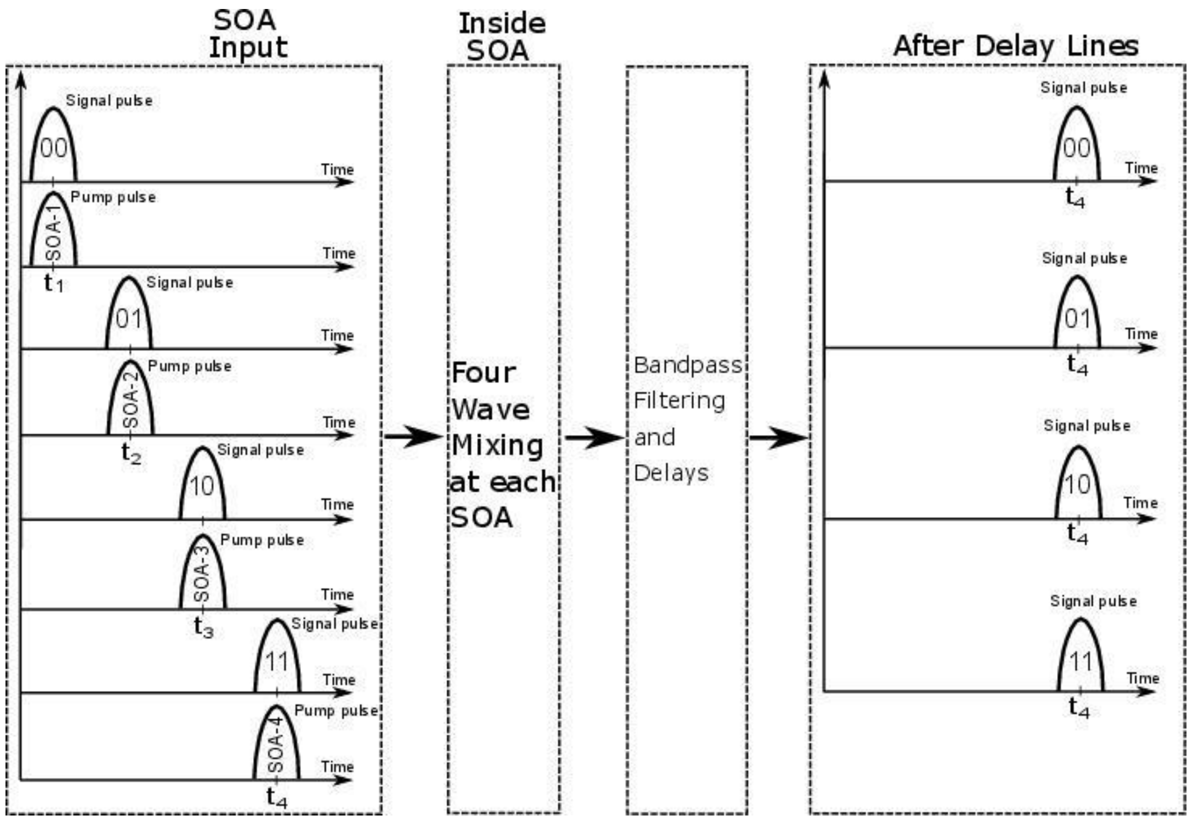

Figure.4.3: Explanation of Pulse Position demodulation using pump pulse.

As previously discussed, each PPM pulse represents two bits of data from channel two and channel three simultaneously, as shown in Figure 4.3. So, based on the bits we get, we can see a different FWM sideband after the OBPF. For example, if we have “11”, it is trasmitted with a time delay t3. This pulse will only combine with the pump pulse going into SOA-3, which has the same delay. The FWM sideband we get after SOA-3 is filtered, delayed, and then split equally between the photodetectors of channel two and three.

Therefore, a PPM pulse for an “11" bit pair will split into two OOK pulses, with each pulse signifying a "1" bit. Time delays at the output of all the OBPFs are introduced to align the pulses in all the paths. Similarly, the "10" bit pair is transmitted with latency t2. On the receiver side, this pulse will only combine with the local pulse at SOA-2 experiencing the same latency. Hence, the FWM sideband will be solely generated at SOA-2. After passing through a filter and delay, the output is fed solely to the photodetector corresponding to channel one. Thus, channel one receives a pulse signifying a "1" bit, and channel two receives no pulse signifying a "0" bit. Subsequently, the pulse is passed through a delay and attenuator to match with the pulses in other paths. Following the procedure, a pulse signifying the "01" bits will be fed solely to the photodetector of channel three. For "00" bits, overlap will not occur inside SOA due to lack of any received pulse , no pulse at the output of the OBPFs. Therefore, both receivers count this absence of an optical pulse as a "0" bit. This conversion method basically transforms the received PPM signal into two OOK signals. After OOK signals are detected by photodetectors, they are passed through a low-pass filter to noise. The signal is then fed to bit error rate (BER) analyzer for computation using eye diagrams, as explained in the subsequent section.

In accordance with the findings in [168], when the received signal and local pump signal are fed to a semiconductor optical amplifier (SOA), idler signals are produced with wavelengths dependent on the spacing between the signals. The number of idle signals produced in SOA depends primarily on the received and pump signal powers and their wavelength difference [168]. The efficiency of four-wave mixing (FWM) is inversely proportional to the wavelength spacing between the parent signals. Hence, we carefully adjust the signal strength and wavelength spacing to generate only one idler on each side.

The combined signal is transmitted over the IsOWC channel to the third LEO satellite equipped with a DPSK receiver. The incoming optical DPSK signal is demodulated using balanced detection method, which exploits the relative phase changes between consecutive bits. A bit delay introduced by the Mach-Zehnder Delay-Interferometer (MZDI) provides a reference signal, cancelling out the phase information added during modulation. The photodiodes convert the remaining intensity difference, indicative of the phase change between bits, into electrical currents. The DPSK decoder compares the current difference at bit transitions to determine if a data bit has flipped, thereby recovering the original data stream. The process effectively removes the bit-delay signal and decodes the transmitted information [169,170]. Hence, we successfully receive and decode the data bits from three channels on LEO satellites.

The parameters used in the simulation include the characteristics of the optical pulsed laser source, such as the centre wavelength, pulse width, and repetition rate. Similar values are used for both links, covering aperture diameter, input power, attenuation rates, sequence length, samples per bit, pointing error angles, optical efficiency, dark current, and Mach-Zehnder modulator extinction ratio. The proposed model uses some key simulation parameters, which are shown in Table 4.1.

Table.4.1: List of Parameters values applied in the proposed Model:

Parameter Details	Value
Bit rate per channel	10Gbps
Number of bits transmitted	512 Bits
Center wavelength of Gaussian pulse generators-1	1550nm
Center wavelength of Gaussian pulse generator-2	1554nm
Pulse width of the Gaussian pulse generator	25Ps
Noise figure of optical amplifier	4 dB
Gain of optical amplifier	20 dB
RX Aperture diameter	20 cm
Beam divergence of TX	2 mrad
FSO attenuation	2 dB/km
Bandwidth of each Gaussian optical filters at RX and Tx Side	50 GHz
Cut-off frequency of electrical low pass filters at RX side	Bit rate Hz
Length of FSO channel	1 km
Index refraction structure of FSO	5e-015 m^-2/3
Attenuation in FSO channel	2dB/km
TX aperture diameter	5cm
Optical amplifier gain	20 dB
Range of FSO link	1 Km
Responsivity of PINs	0.9 A/W
Modulation BW of PINs photodetector	2 GHz
Symbols per second	10G symbols/sec
Extinction ratio of MZ Modulator	30dB

4.3) Results and Discussion of proposed Model:

As previously stated, the proposed methodology has the capability to transmit data from three distinct channels through a single optical wireless communication (OWC) link. The individual channel's data rate is 10 Gbps, resulting in a cumulative transmission of 30 Gbps through a single pulsed laser source of 10 GHz. Evaluation of the technique's performance has been conducted by analyzing the BER of each distinct channel for various IsOWC link lengths. The OWC channel is characterized by the widely adopted Gamma-Gamma model, in which the refractive index is selected as 5×e 15 to accurately depict the turbulence of the medium. Additionally, attenuation in the channel is maintained at 0 dB/km due to negligible turbulence in space. As previously described, the receiver employed FWM to convert the received PPM signal into On-Off Keying (OOK) signals representing channels 2 and 3, respectively. Figure 4(a-d) depicts the optical spectrum seen at the output of four SOAs, respectively. The spectral graphs indicate that the PPM and pump signals are both located at 1552 nm and 1550nm wavelengths, respectively. The occurrence of four-wave mixing (FWM) leads to the generation of two sidebands, specifically at 1548 nm and 1554 nm wavelengths. In [168], non-linear shifts generated by SOAs cause a minor wavelength shift in the sidebands. The sideband near the pump wavelength is selected using OBPFs with a 20 GHz bandwidth and centered at 1548.4 nm; an eye diagram of the received hybrid DPSK-PPM signal is displayed in Fig. 4(e). The eye diagram reveals that the optical pulses are located across four distinct positions within a single bit period. Each point in this context represents a binary pair of bits. Upon reception of the hybrid-PPM signal, the pair of bits is then divided into two on-off keying (OOK)data streams, as elaborated in the preceding section. Figures 4(f), 4(g) and 4(h) illustrate the eye diagrams of the resultant signals Channel-1, Channel-2, and Channel-3 produced at the output of electrical low-pass filters, respectively. The minor variations in intensity caused by the turbulence present in the optical wireless communication (OWC) channel can be clearly visualized in these eye diagrams. The plots depicted in Figure 4.4 were derived from an optical wireless communication (OWC) channel with a length of 40,000 km. This configuration yielded a bit error rate (BER) of around 10–8.

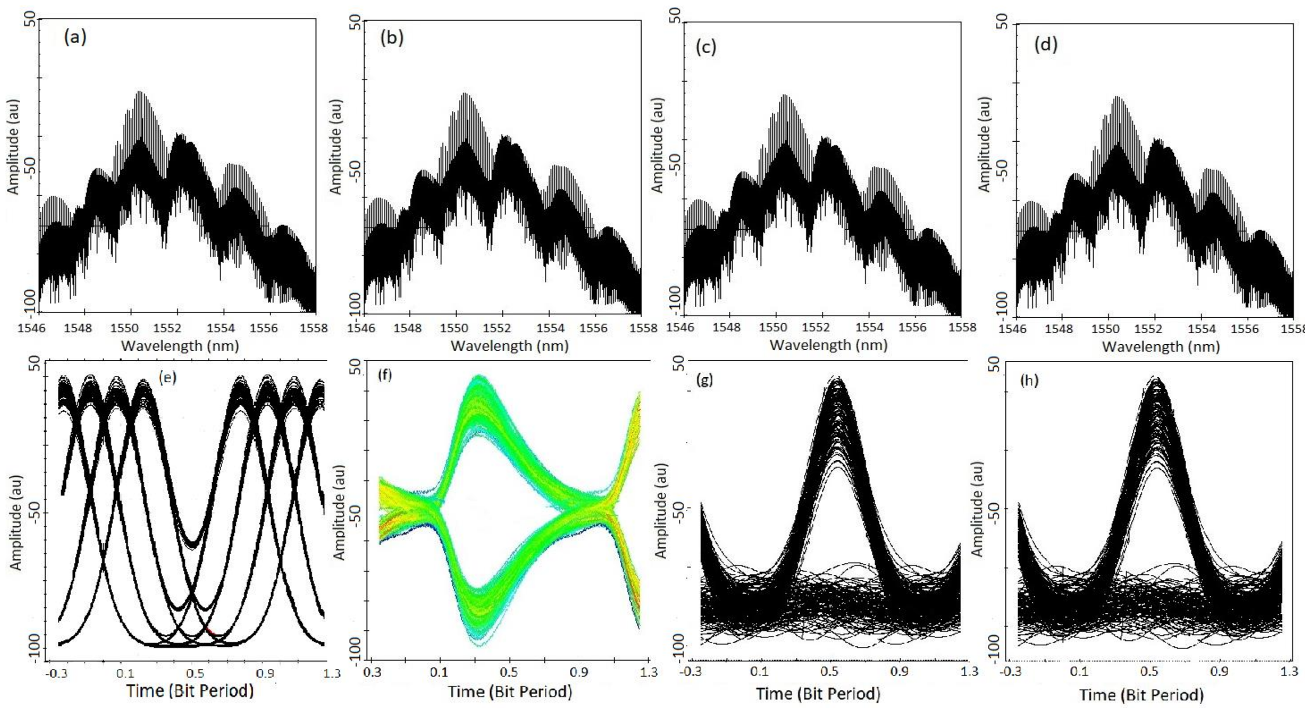

Figure.4.4: Optical spectra of the signals at the output of (a) SOA-1, (b) SOA-2, (c) SOA-3 and (d) SOA-4. (e) Eye diagram of the PPM signal after demodulation. Eye diagrams of the OOK signals for (f) Channel-1, (g) Channel-2 and (h) Channel-3, respectively.

To evaluate how the IsOWC link length affects the performance, we plotted the BER against the link length for all three channels, as shown in Fig 4.5. The plots demonstrate that the suggested method functions effectively for long IsOWC link lengths, ensuring the system’s robustness. We can observe that for all lengths, Channel-1 has a comparably higher BER than Channels 2 and 3. This observation can be attributed to the modulation schemes used in these channels. DPSK having a non-coherent nature, is more sensitive to noise, getting much worse at longer links where noise accumulates. On the other hand, PPM offers better BER due to its lower noise sensitivity. PPM is inherently more robust against noise because it uses pulse timing rather than phase. Additionally, the BER performance is excellent for a range of pulse delay values. An

increase in the interval between pulses enhances performance due to the decreased inter-pulse interference that occurs between the pulses as they propagate through SOA [168]. In the context of PPM (pulse-position modulation), we chose a 12ps pulse width to achieve a broad range of time delay values, ensuring secure communication by minimizing vulnerability to eavesdropping. While we initially demonstrated one-way signal transmission, our proposed PPM modulation and demodulation technique can also be employed for transmitting downlink data from the optical pulsed source to the receiver. It is evident that our proposed technique does not require specialized error correction methods and may send data with ease across an IsOWC link of 40,000 km. Our cumulative data rate of 30 Gbps is higher than that of previous PPM-based investigations. If we lower the data rate, the link's length can be further extended. Thus, for our suggested method, there is a trade-off between achievable length and data throughput. We used the well-known commercial tool Optisystem to simulate the link that considers the majority of the essential characteristics of the OWC channel. No specialized optical or electronic components are used in our suggested method. Consequently, it's easy to implement hardware using readily available commercial equipment.

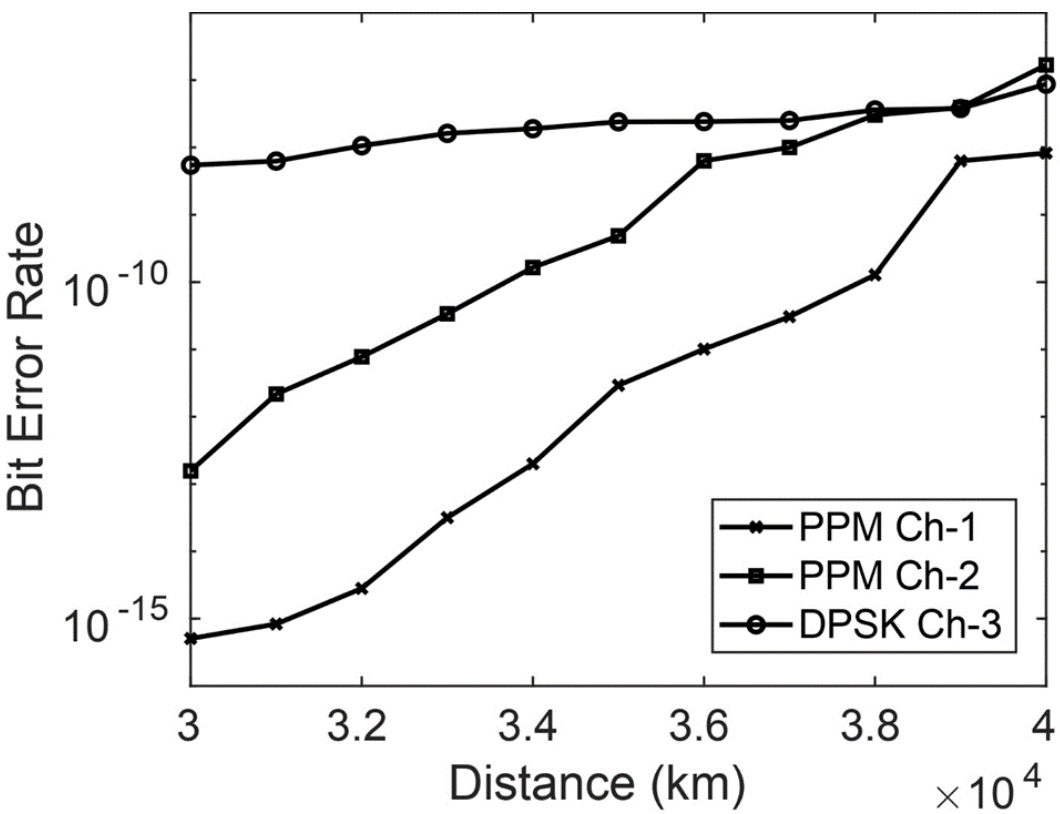

Figure. 4.5: log of BER versus link length for IsOWC Ch-1 (a), Ch-2 (b) and Ch-3 (c).

4.4) Application Scenario of proposed model:

LEO satellites are known for their intermittent connectivity with ground stations, featuring brief contacts separated by extended intervals. This intermittent nature, particularly concerning time-sensitive data, can pose a significant challenge [162]. Small satellites can communicate with ground stations more often by using a GEO relay satellite, which increases the availability of the link to the ground stations. Direct links between LEO satellites and ground stations are available for a small time span, limited by the distance between the two. Several GEO data relay satellites are already in operation, such as EDRS [163], LCRD [164], and LUCAS [165].

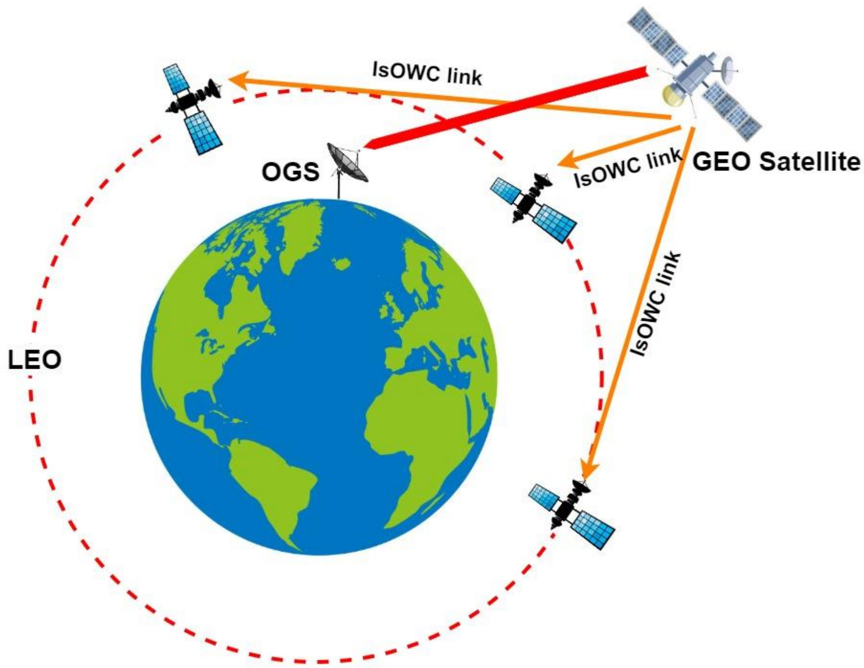

Figure.4.6: Application scenario of GEO-relaying between Optical ground station and LEO satellites employing IsOWC links.

The proposed hybrid PPM-DPSK technique can be utilized in the context of GEO data relaying to transmit multiple channels with improved security and bandwidth efficiency. Figure 4.6 above demonstrates a specific application scenario where the proposed technique can be utilized. A GEO satellite is used as a relay between an Optical Ground Station (OGS) and three LEO satellites. Transmitting three distinct channels through a single OWC link can enhance the efficiency of OWC systems by decreasing the number of optical transceivers required. A GEO satellite can provide coverage to a much larger area than a LEO satellite. This is because the GEO satellite is stationary in the sky, while the LEO satellite is constantly moving. This can be especially beneficial for small satellites and other platforms with limited resources.
Hence, the technique can be used in GEO relaying between Optical Ground Station (OGS) and LEO satellites, increasing link availability.

Chapter-5: Future Work and Conclusion

5.1 Conclusion:

An innovative approach for transmitting three data channels securely over one OWC link is presented, addressing the lower spectral efficiency and eavesdropping challenges associated with wireless communication. The hybrid approach, combining Differential Phase Shift Keying (DPSK), introduces phase-encoded security and PPM, enabling users to choose from various time delay values between PPM pulses. This dynamic variation enhances the security of OWC links against potential eavesdroppers, offering a flexible and adaptive security mechanism. Our proposed technique demonstrates a reduced power per channel compared to traditional techniques like On-Off Keying (OOK) and DPSK, as the data from three distinct channels is transmitted over one optical carrier. Moreover, the technique can facilitate uplink data transmission from OGS to multiple LEO satellites through a GEO data relay satellite, enhancing link availability. The proposed method can be implemented without any special components, which makes it a cost-effective and practical solution for network operators. This novel approach could enable more widespread wireless connectivity through networks using land and satellite optical connections. It has potential applications in underwater networks or providing high-speed internet to remote areas. As demand grows for secure, fast communication, this method is well-suited for real-world use.

5.2 Future Work:

To move beyond the current investigation of uplink performance with the hybrid DPSK-PPM modulation scheme, future research can explore three key areas. Firstly, system design optimization can involve investigating alternative coding and modulation techniques for improved efficiency and robustness, along with advanced signal processing algorithms for enhanced signal quality and mitigation of non-linear effects. Secondly, practical considerations necessitate evaluating the impact of real-world limitations like pointing accuracy and satellite size on performance, while developing solutions to address these limitations and ensure reliable deployment. Finally, exploration of advanced modulation techniques holds promise, with research avenues including implementing multilevel schemes for increased reach and data rates, and investigating the feasibility and potential benefits of employing 3D modulation techniques. By pursuing these future directions, this work paves the way for unlocking the full potential of Is-OWC technology for long-distance, high-capacity communication.

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