



**UNIVERSITE HASSIBA BENBOUALI DE CHLEF**

**Faculté de Technologie**

**Département d'Electronique**

## **MEMOIRE DE MASTER**

Domaine : SCIENCES ET TECHNOLOGIES

Filière : TELECOMMUNICATIONS

Spécialité : SYSTEMES DES TELECOMMUNICATIONS

Design and performance measuring of an outdoor optical  
communication system using the OWC channel for a UAV  
network

Par

**FLITTI      Fouad**

**RETIBI      Amin**

Encadreur :

M. ADARDOUR H. Errachid

Maître de Conférence « A » à l'UHBC

Chlef, Juin 2024



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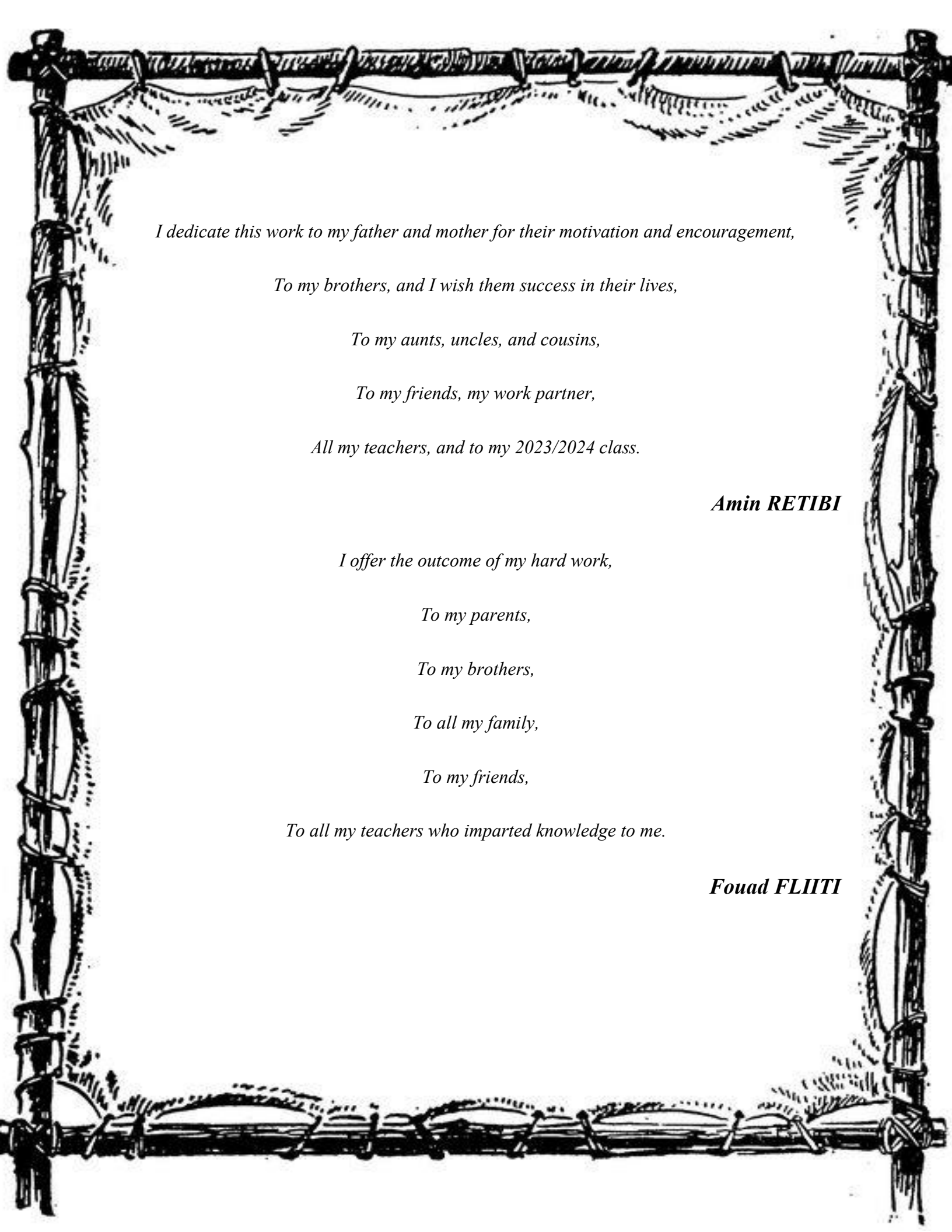
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*I dedicate this work to my father and mother for their motivation and encouragement,*

*To my brothers, and I wish them success in their lives,*

*To my aunts, uncles, and cousins,*

*To my friends, my work partner,*

*All my teachers, and to my 2023/2024 class.*

***Amin RETIBI***

*I offer the outcome of my hard work,*

*To my parents,*

*To my brothers,*

*To all my family,*

*To my friends,*

*To all my teachers who imparted knowledge to me.*

***Fouad FLIITI***



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## Abstract

Optical Wireless Communication (or OWC) and Free Space Optics (or FSO) are sophisticated methods for transmitting data at fast speeds and large bandwidths. However, these technologies encounter obstacles associated with atmospheric conditions (such as fog, rain, and haze) that might weaken signals. These situations can elevate bit error rates and diminish transmission distances. This project aims to analyze and create a design for an outdoor optical communication system that utilizes an OWC channel for a network of unmanned aerial vehicles (or UAVs) under different weather situations. What sets this research apart is the innovative use of adaptive techniques that utilize forward, backward, and bidirectional EDFA (or Erbium Doped Fiber Amplifier) topologies to adjust for these atmospheric conditions. To assess the performance of the proposed system, the Bit Error Rate (or BER) measure is set at  $1e-03$  to determine acceptable circumstances. In addition, the constellation diagram can provide us with a visual representation to analyze the system's performance.

**Keywords:** OWC, FSO, UAV, EDFA, atmospheric conditions, BER and constellation diagram.

## Résumé

La communication optique sans fil (ou OWC) et l'optique en espace libre (ou FSO) sont des méthodes sophistiquées de transmission de données à des vitesses rapides et à des largeurs de bande importantes. Toutefois, ces technologies se heurtent à des obstacles liés aux conditions atmosphériques (brouillard, pluie et brume) qui peuvent affaiblir les signaux. Ces situations peuvent augmenter le taux d'erreurs binaires et réduire les distances de transmission. Ce projet vise à analyser et à concevoir un système de communication optique extérieur qui utilise un canal OWC pour un réseau de véhicules aériens sans pilote (ou UAV) dans différentes situations météorologiques. Cette recherche se distingue par l'utilisation innovante de techniques adaptatives qui utilisent des topologies EDFA (ou amplificateur à fibre dopée à l'Erbium) vers l'avant, vers l'arrière et bidirectionnelles pour s'adapter à ces conditions atmosphériques. Pour évaluer les performances du système proposé, le taux d'erreur sur les bits (ou BER) est fixé à  $1e-03$  pour déterminer les circonstances acceptables. En outre, le diagramme de constellation peut nous fournir une représentation visuelle pour analyser les performances du système.

**Mots-clés :** OWC, FSO, UAV, EDFA, conditions atmosphériques, BER et diagramme de constellation.

## ملخص

تُعد الاتصالات اللاسلكية الضوئية (أو OWC) والبصريات الفضائية الحرة (أو FSO) من الطرق المتطورة لنقل البيانات بسرعات عالية ونطاق ترددي كبير. ومع ذلك، تواجه هذه التقنيات عقبات مرتبطة بالظروف الجوية (مثل الضباب والمطر والضباب) التي قد تضعف الإشارات. يمكن لهذه الحالات أن ترفع معدلات الخطأ في البتات وتقلل من مسافات الإرسال. يهدف هذا المشروع إلى تحليل وإنشاء تصميم لنظام اتصالات ضوئي خارجي يستخدم قناة OWC لشبكة من المركبات الجوية غير المأهولة (أو الطائرات بدون طيار) في ظل ظروف جوية مختلفة. ما يميز هذا البحث هو الاستخدام المبتكر للتقنيات التكيفية التي تستخدم طوبولوجيات EDFA (أو مضخم الألياف المخدرة بالإربيوم المخدرة) الأمامية والخلفية وثنائية الاتجاه للتكيف مع هذه الظروف الجوية. لتقييم أداء النظام المقترح، يتم تعيين مقياس معدل الخطأ في البت (أو BER) عند  $1e-03$  لتحديد الظروف المقبولة. بالإضافة إلى ذلك، يمكن أن يزودنا مخطط الكوكبة بتمثيل مرئي لتحليل أداء النظام.

**الكلمات المفتاحية:** OWC، FSO، FSO، الطائرات بدون طيار، EDFA، الظروف الجوية، BER ومخطط الكوكبة.

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AlGaAs	Aluminium and Gallium Arsenide
APD	Avalanche Photo Diode
BER	Bit Error Ratio
C2C	Chip-to-Chip
CO <sub>2</sub>	Carbon Dioxide
DBR	Distributed Bragg Reflector
DD	Direct Detection
DFB	Distributed Feed-Back
EAM	Electro-Absorption Modulator
EDFA	Erbium-Doped Fiber Amplifiers
FSO	Free Space Optics
GaAs	Gallium Arsenide
IEEE	Institute of Electrical and Electronics Engineers
IM	Intensity Modulation
InP	Indium Phosphor
IoT	Internet of Things
IP	Internet Protocol
IR	InfraRed
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
LEO	Low Earth Orbit
Li-Fi	Light-Fidelity
LOS	Line-Of-Sight
M2M	Machine to Machine
MIMO	Multiple-Input Multiple-Output
MZM	Mach-Zehnder Modulator
Nd-YAG	Neo dymium-doped Yttrium Aluminum Garnet
NLOS	Non-Line Of Sight
NRZ	No Return to Zero
OCC	Optical Camera Communication
OWC	Optical Wireless Communication
PD	Photo Diode
PIN	Positive Intrinsic Negative
PN	Positive-Negative
PON	Passive Optical Network

RF	Radio Frequency
RIN	Relative Intensity Noise
SDH	Synchronous Digital Hierarchy
SOA	Semi-conducteur Optical Amplifiers
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
TIA	Trans-Impedance Amplifier
UAV	Unmanned-Aerial-Vehicle
V2x	Vehicle-to-infrastructure
V2V	Vehicle-to-Vehicle
VL	Visible Light
VLC	Visible Light Communication
WBAN	Wireless Boday Area Network
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
Wi-Fi	Wireless-Fidelity
WPAN	Wireless Personal Area Network

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# **General introduction**

Wireless communications date back to the 19th century. This marked a massive advancement in transmitting voice and data without physical connections like cables or wires. This technical development utilizes electromagnetic signals like infrared, radio, and satellite waves. Contemporary wireless communication comprises various devices and technologies, such as cell phones, computers, tablets, laptops, Bluetooth technology, and printers.

Optical Wireless Communication (or OWC) transmits data by modulating light signals, usually within the infrared or visible light spectrum. OWC differs from typical Radio Frequency (or RF) communication because it utilizes optical signals for data transmission between devices. This technology is highly regarded for its ability to transmit large amounts of data, strong security measures, and resistance to electromagnetic interference. As a result, it is well-suited for a wide range of uses, such as indoor and outdoor wireless networks, underwater communication, and automotive communication systems.

Free Space Optics (or FSO) is a branch of OWC that focuses on transmitting light signals via the atmosphere for point-to-point communication. FSO systems employ lasers to establish a direct connection between two places, enabling data transmission across considerable distances without requiring physical connections. FSO is an appealing option for connecting the final stretch of a network, establishing communication networks in metropolitan areas, and filling in gaps in fiber optic infrastructure.

OWC and FSO encounter obstacles that must be addressed to guarantee a dependable connection. The presence of particles such as water vapour and carbon dioxide in the atmosphere decreases signal strength due to absorption. Additionally, the scattering of signals by air molecules and aerosols results in signal dispersion and attenuation. Atmospheric scintillation, caused by fast changes in the refractive index, results in variations in the intensity of the light signal. Inclement weather situations such as precipitation, fog, and atmospheric haze, along with physical impediments such as structures and vegetation, also affect signals' dependability. Some mitigation strategies involve the utilization of optimal wavelengths, high-efficiency transmission systems, adaptive optics, and resilient signal processing algorithms.

Following this concise exposition of OWC technology, this work presents a study and development of an outdoor optical communication system that utilizes an OWC channel for a network of UAVs capable of operating in different weather situations.

The research is structured into three chapters. The initial chapter offers a comprehensive overview of OWC technology. The second chapter systematically introduces the optoelectronic

components of the OWC system in a specific order. The study's results are discussed in the third chapter. The document comprises a comprehensive introduction, a conclusive summary, many viewpoints, and a bibliography.

## **CHAPTER 1**

# **OWC technologies**

## 1.1. Introduction

Wireless communications first appeared in the 19th century and have existed for several centuries. These technologies made voice and data communication without cables or wires possible. Data is transferred using electromagnetic signals, such as satellite waves, radio frequencies, and infrared, rather than a physical link. The term "wireless communication technology" covers various gadgets and systems, including printers, computers, tablets, laptops, smartphones, and Bluetooth [1]. An overview of OWC (Optical Wireless Communication) technology is given in this chapter.

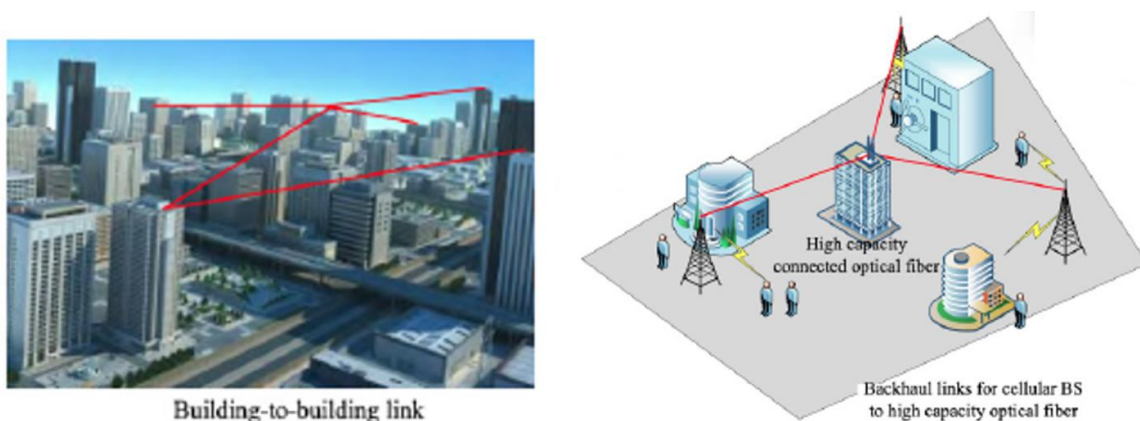
## 1.2. OWC Technologies

Wireless communication methods that use optical carriers in the visible, ultraviolet, or infrared regions of the electromagnetic spectrum are called optical wireless communications, or OWCs. OWC's primary technologies are:

- FSO stands for Free Space Optical Communication.
- Communication using Visible Light (VLC).
- Optical camera communications (OCC).
- A light-based wireless network is commonly known as Light Fidelity (Li-Fi).

### 1.2.1. Free space optical communication

FSO is an optical communication method that uses light propagation in open spaces to transfer data for computer networks and telecoms wirelessly. Numerous commercial solutions are available, and the FSO can now carry data at several Gbps speeds over several km distances [1], see Figure 1.1. The links usually function inside optical communication windows, which are wavelength regions between 780 and 1600 nm.



**Figure 1.1.** FSOs network architectures [2].

The atmospheric channel's use as a propagation medium is the primary technological challenge of FSO technology. Due to atmospheric turbulence and its sensitivity to weather, its dependability gradually diminishes. However, there is ongoing research on numerous RF-derived approaches and techniques, including cooperative diversity, channel coding, and multi-entry and multi-output communication (or MIMO). These are being explored with the aim of developing new solutions for RF/FSO hybrid systems to increase performance [1].

### 1.2.2. Visible light communication

A wireless technique called visible light communication (or VLC) allows data to be transmitted quickly using visible light, see Figure 1.2. The intensity of a light source is adjusted to transmit this data. A photodiode device receives the signal and converts it into formats that end users can easily read and consume. This visible light data transfer technique ranges from 400 to 800 THz (375 to 780 nm) [3]. For short-distance signal transfer at 10 kbit/s or DELs up to 500 Mbit/s [4]. VLC needs to be a solution that satisfies information and communication technology (or IoT) requirements while enhancing standard RF systems [5].

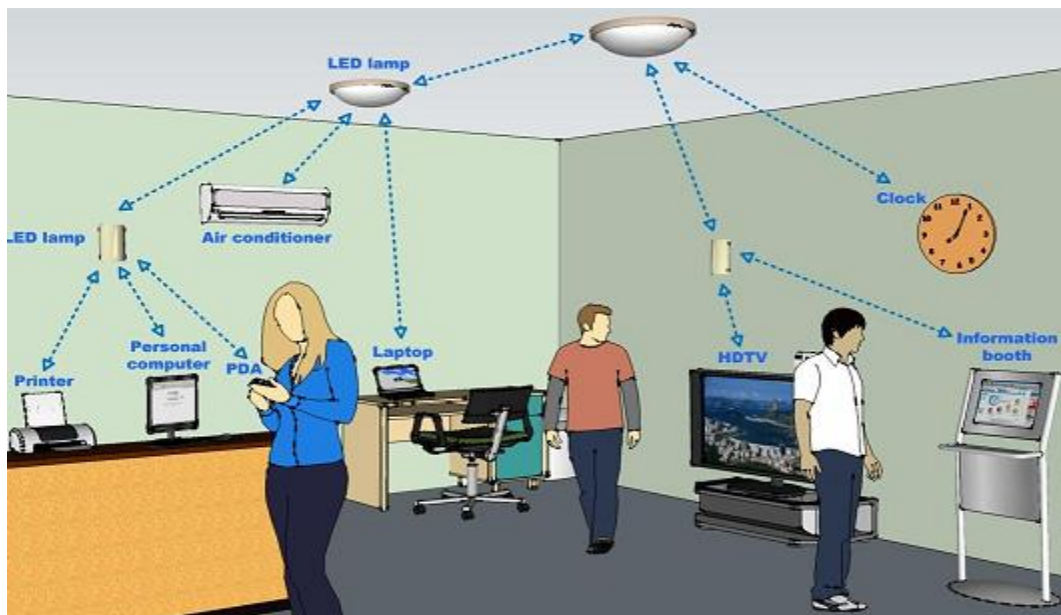
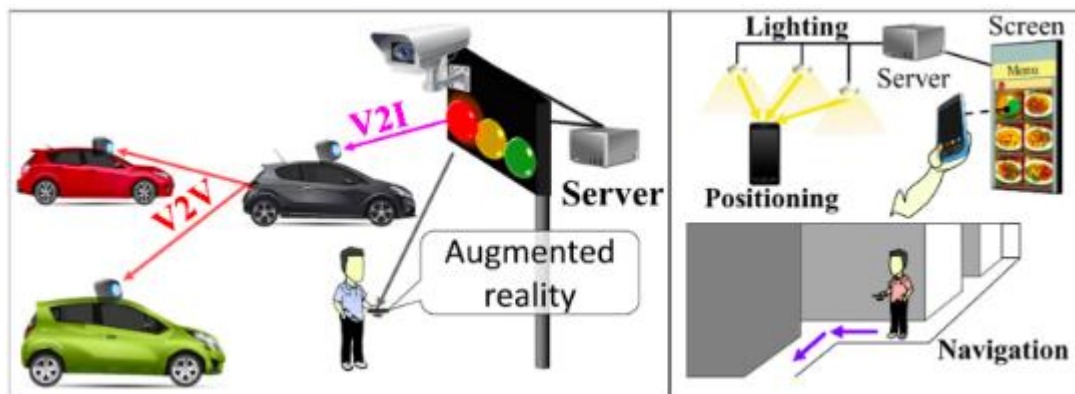


Figure 1.2. VLC system [6].

### 1.2.3. Optical camera communication

Wireless communications between optical sources and cameras (image sensors) are called optical camera communication, or OCC. Light-emitting diode data is received via camera image sensors. Because this technology can process images, it can be used in cameras of any kind and smartphones. Data rates between 10 bps and a few Mbps are possible with it. The covered distances vary between several and one hundred meters [7]. With this technology, cameras and

smartphone pocket lamps can function as transceivers and receivers without requiring a photodiode for direct-detection optical intensity modulation or changing the hardware configuration already in place. Specifically, cameras are employed as receivers, and Electro-Luminescent Diodes (or ELDs), or other light sources are utilized as transmitters (LASER diodes cannot be used). It is important to remember that infrared or ultraviolet light is examined in camera optical communication. Although the OCC's performance might be adequate indoors, its limited communication range, interference from surrounding light sources, and difficulty in detecting signals in direct sunlight—which stems from the lack of a specialized photodiode—make it impossible to use outside. This approach guarantees low-speed data transfer because the light beams from the camera flash can generate low frame rates. On the other hand, OCC can be used in various interior settings, including biomedical settings where portable skin patches are used to monitor bodily components [4], see Figure 1.3.



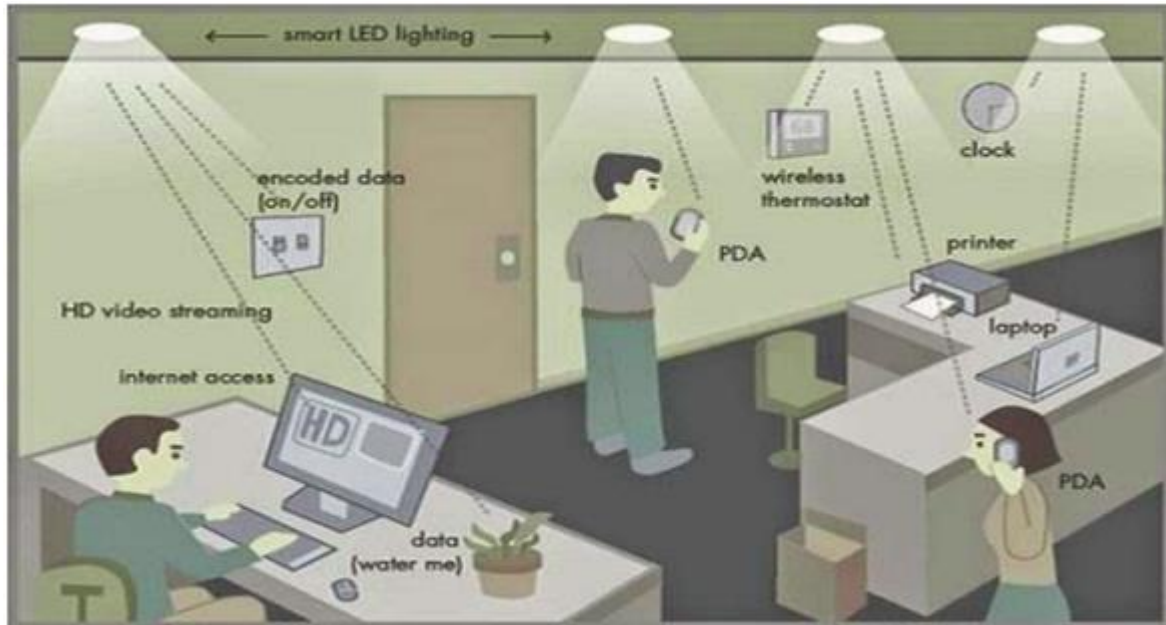
**Figure 1.3.** Example of promising OCC services [8].

#### 1.2.4. Light Fidelity

A wireless communication system called Light Fidelity (or Li-Fi) uses visible light with frequencies between 800 and 400 THz for violet and red light, respectively. Li-Fi uses the optical spectrum, or the part of the electromagnetic spectrum that is visible light, as opposed to Wi-Fi, which uses the radio portion. Li-Fi transmits data using amplitude modulation of the light source in a standardized and well-defined manner [2, 9].

LEDs have an operating speed of less than 1 microsecond, which allows them to be turned on and off quicker than the human eye can perceive. Binary coding facilitates data transmission through this unseen on/off activity. A digital "1" is transmitted while the LED is on, and a digital "0" is transmitted when the LED is off. Additionally, because these LEDs can be turned on and off fast, we have a great potential to send data through LED lights since there are no competing light frequencies, unlike radio frequencies used in Wi-Fi [2, 9].

Li-Fi is 80% more efficient than Wi-Fi, achieving up to 1 Gbps and even higher rates. Because the Li-Fi protocol layers are appropriate for wireless communication over short distances (up to 10 meters), Li-Fi varies from fiber optic. Because of this, Li-Fi has the advantage of enabling rapid wireless communication across small distances [2, 9], see Figure 1.4.



**Figure 1.4.** Li-Fi technology for connecting devices [10].

### 1.3. OWC link applied

Intensity modulation (or IM) during emission and Direct Detection (or DD) at reception form the foundation of optical transmission [11]. The fundamental band technique for IM/DD differs from radio communication in that frequency conversion is not carried out at the transmitter (electric-optical conversion) or receiver (optical-electric conversion) (see Figure 1.5).

The transmitter (see Figure 1.5) comprises a light source, an analog control circuit, and a modulator. Additionally, channel encoding/decoding blocks can be added before or after demodulation to detect and remedy mistakes. A modulator transforms Information bits into a signal  $s(t)$ . The restrictions for a system (or IM) are that  $s(t)$  is a genuine positive signal. The wave shape of this signal  $s(t)$  is then applied to a control circuit, which converts it into a current connected to the light flow (power emitted) radiated by the source, which is typically a Laser Diode (or LD) or an Electro-Luminescent Diode (or LED). Less directional LEDs are utilized for lower speeds in indoor OWC applications because they are less expensive and easier to use. In contrast, more directive LDs are used for high-speed point-to-point static communications

(e.g., outdoor FSO applications). This contrasts with LEDs, which are less directional and are utilized for lower data rates in indoor OWC applications because of their affordability and convenience. The optical signal is subsequently transferred across the channel to directly reach the receiver via Line of Sight (or LoS) or multiple reflections (or NLoS). It is also likely to experience noise problems from various sources.

The optical portion of the receiver's photodetectors transforms the light intensity carrying data into electrical signals for baseband processing (or DD). This thesis focuses on photodiodes, the most often used type of photodetectors, because of their low cost and high performance (sensitivity and reaction time) [7]. Other forms of photodetectors include phototransistors and image sensors. Thus, the photodiode sensitivity is a characteristic factor in converting the received optical signal into an electric current proportional to light intensity as a function of wavelength. A Trans-Impedance Amplifier (or TIA) changes the electric current into a voltage, which is then applied to the demodulator to provide the received information bits.

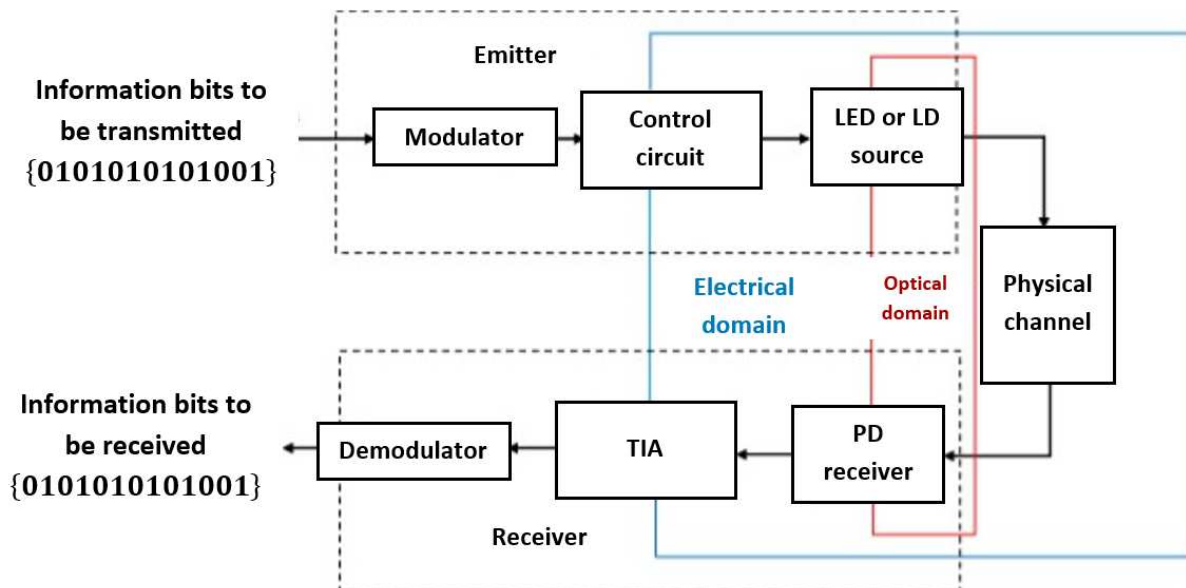
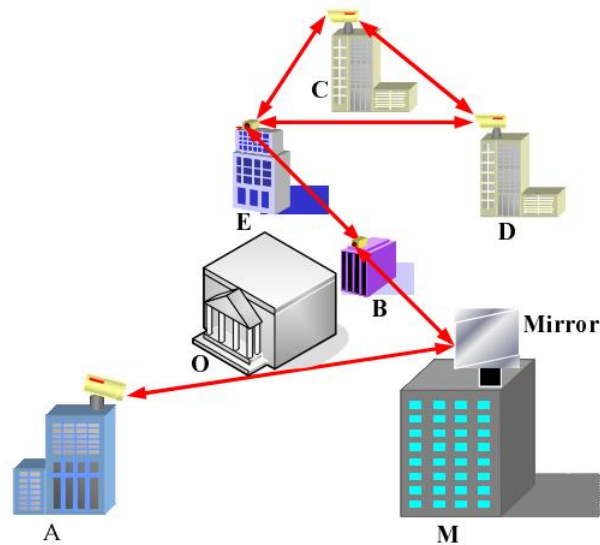


Figure 1.5. Simplified IM/DD transmission scheme [12].

#### 1.4. Topology between OWC nodes

However, location, distance, and meteorological factors play a significant role in determining the bandwidth and availability of each OWC link while constructing the OWC topology. For instance, we are given a collection of buildings to connect when designing the topology of an OWC network in a city center. Other buildings that might not be included in the topology must also be supplied and used in the physical topology, even though this series must contain the

original and terminal structures. This is because direct visibility is required for OWC links. Some buildings may be situated between buildings that have joined the OWC network, prohibiting the establishment of some potential OWC connections, even though those buildings cannot join the network. Like what Figure 1.6 shows.



**Figure 1.6.** Example of OWC network [13].

As illustrated in Figure 1.6, it is not possible to create a direct OWC link between (A) and (B) since buildings (A) and (B) are part of the OWC network and building (O) is not part of it, since building (O) blocks the line of sight between a and (B). Building (A) is required to use other buildings inside or outside (such as building M) in the OWC network to connect to building (B). As a result, each building can only be connected to a subset of buildings with a viewing line within a given maximum transmission range. Furthermore, unlike the topological control of radio frequency transmissions (e.g., IEEE 802.11) in wireless networks, which focuses on energy consumption, interference, and connectivity/mobility, the signal transmitted in the OWC system can only reach one specified receiver (as opposed to an omnidirectional antenna), so that OWC does not have any problems associated with the problem of hidden terminals. In reality, parallel OWC transmitters-receivers, for example, can be used between two OWC nodes to increase network capacity without significant costs or interference as in RF wireless networks, as shown in Figure 1.7. Similarly, the repeaters can relate to the performance improvement of OWC networks. Regarding topology design, the distinct features of OWC networks need to be considered when creating the physical and logical topology; algorithms created for WDM or RF wireless network topology design are not directly applicable to the effective processing and modeling of OWC networks [13].

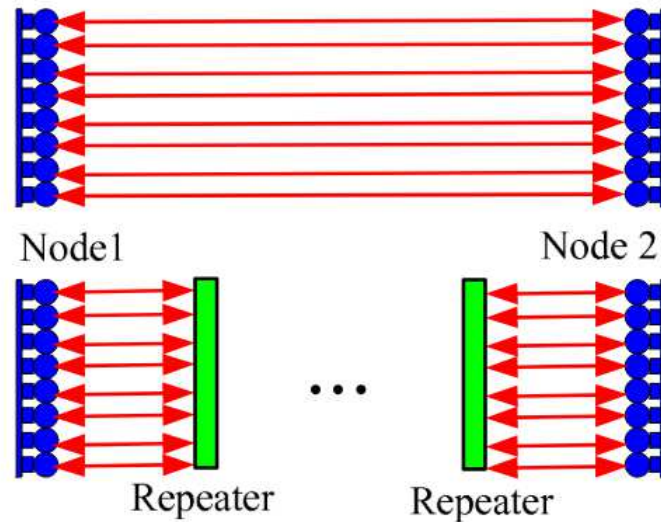


Figure 1.7. Space reuse in OWC networks [13].

### 1.5. OWC system applications

OWC has many potential applications [2, 4]. Figure 1.8 displays a visual depiction of potential OWC application platforms. Potential application platforms include airports, petrochemical plants, smart homes and cities, railway stations, healthcare facilities, data centers, transportation systems, and underwater communication networks.

These systems can be improved by implementing differential communication mechanisms, such as Machine-to-Machine (or M2M), Device-to-Device (or D2D), and Chip-to-Chip (or C2C). As the Internet of Things (IoT) advances, these strategies could be beneficial as millions of smart devices become networked [2]. OWC can be more effective in environments such as hospitals, healthcare facilities, petrochemical industries, etc., where RF emissions can disrupt sensitive equipment. Military submarines, which can create internal communications in a silent mode, serve as a reliable communications method for OWC.

Before implementing OWC technologies, evaluating the communication distance as a critical element is essential. The applications of OWC can be classified into ultra-short range, medium-range, long-range, and ultra-long-range, depending on the communication distance, as depicted in Figure 1.8. The numbers represent the categories [2, 4]. As shown in Figure 1.9, the OWC applications range from short-range C2C communications at a few micrometers to long-range inter-satellite and deep space links spanning several hundred kilometers. Here are a few examples :



Figure 1.8. Potential applications of OWC [2].

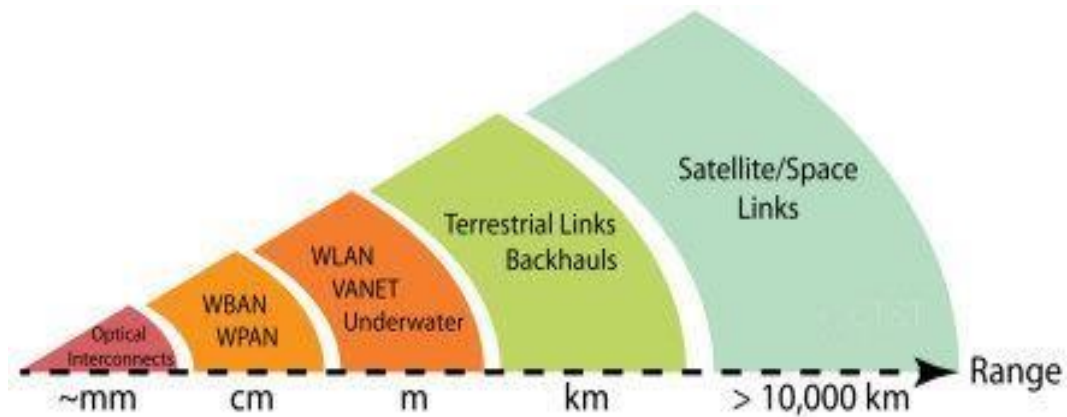


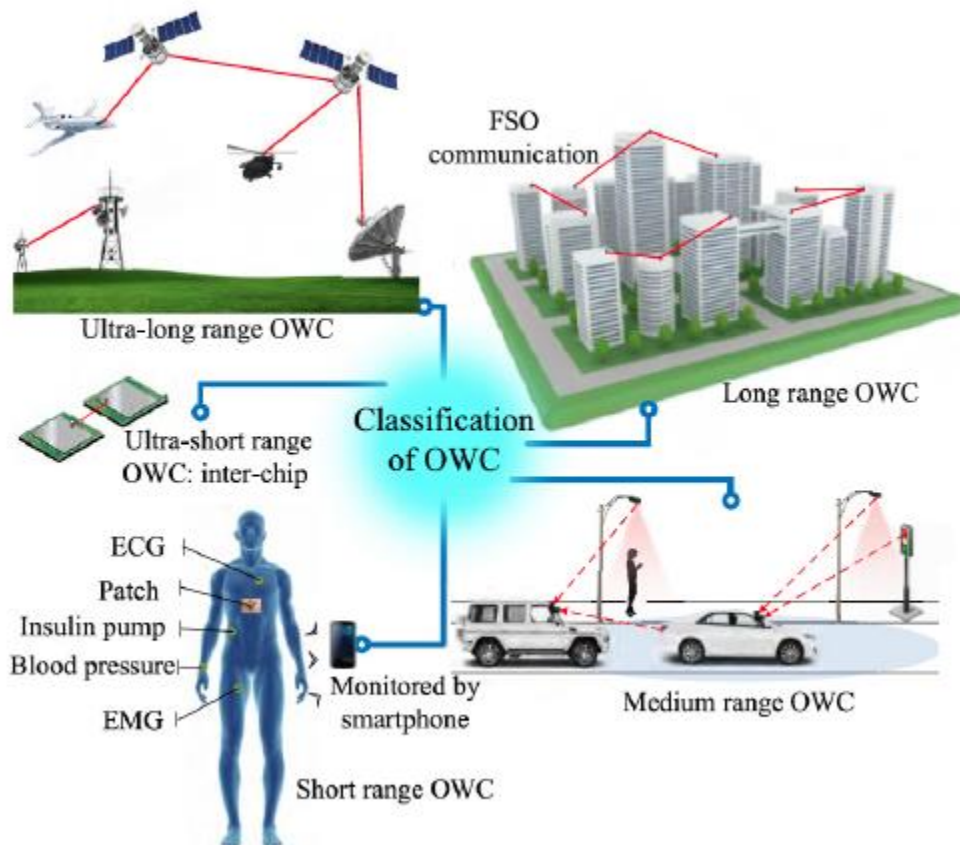
Figure 1.9. Classification of OWC applications according to the distance over which transmission occurs [14].

- Ultra-short-range optical wireless communication (OWC) applications are gaining importance due to the increasing significance of optical interconnects. Despite their bulkiness and tendency to create bottlenecks in system design, copper-based electrical connections are commonly employed due to their high bandwidth and low latency [15]. Optical waveguides in optical connections can be used to communicate

between two devices, providing a more flexible and lightweight option than traditional electrical wires (see Figure 1.10).

- Short-range optical wireless communication (OWC) is commonly used in applications such as Wireless Body Area Networks (or WBAN) and Wireless Personal Area Networks (or WPAN). These applications include communication at distances of tens of centimeters [16, 17]. Using WBANs, many sensors and detectors can be integrated inside the body to monitor various health metrics, such as blood pressure and heart rate. WBANs utilizing RF transmissions may not be the optimal option for hospitals due to the vulnerability of the equipment to RF radiation. By incorporating Visible Light (or VL) sensors into wearable technology or clothing, OWC-based WBANs enable the collection of vital signs on a smartphone. The fundamental concept of the IoT is that all devices close to an individual are interconnected through a WPAN (see Figure 1.10).
- Medium-range OWC is often utilized for transmitting data over moderate distances, with one frequent application being Wireless Local Area Networks (WLANs). Historically, RF wireless communications have been used. However, as previously stated, the RF spectrum is nearly depleted, making OWC a potential alternative. It is possible to achieve inter-building wireless connectivity by using LEDs for lighting and communication by creating a WLAN using OWC. VLC can also be utilized in outdoor settings, including traffic lights, street lighting, advertising displays, and car headlights/tail lights. This can result in the establishment of Vehicle-to-infrastructure (or V2x) and Vehicle-to-Vehicle (or V2V) communications (see Figure 1.10).
- Long-range OWC can be utilized to establish a connection between two WLANs at extended distances. FSO (or Free Space Optics) networks provide substantial data transfer capacity, with data speeds reaching the terabits per second range. Additionally, these networks are highly flexible and can be easily adjusted or reconfigured. Long-range OWC links can serve as backhaul connections to overcome the limitations of conventional coaxial cables. Currently, free-space optical connections are also utilized for aerospace purposes [18] (see Figure 1.10).
- Free-space optical networks are highly effective for long-range applications spanning several thousand kilometers, such as ground-to-satellite and inter-satellite communications. Multiple free-space inter-satellite optical communications have

been examined, demonstrating the promise of OWC for long-range FSO applications [16, 17] (see Figure 1.10).



**Figure 1.10.** Applications of OWC as a function of communication distance [2].

## 1.6. Advantages and disadvantages of OWC

### 1.6.1. Advantages of OWC

This sub-section enumerates the primary benefits of OWC:

- The laser beam's exceptional directivity and narrowness ensure excellent secrecy.
- A license is not required for the microwave frequency band, as it operates at a frequency of 350 THz without causing any interference with radio communications.
- The running costs are significantly lower, amounting to only one-fifth of the expenses associated with fiber optics. This is achieved without the need to install and upkeep a costly cable infrastructure.
- Efficient network installation requires few node installation devices, making it suitable for temporary backup or high-capacity connections.

- This protocol enables the seamless transmission of data or circuit services and may be integrated into any existing protocol. It ensures transparency in the transmission process.
- The information capacity is high, reaching up to 10 Gb/s, while commercial wireless laser technology can achieve a maximum speed of 2.5 Gb/s.

Essentially, this system's primary advantages are its ability to maintain anonymity, absence of licensing requirements, affordability, quick implementation, protocol transparency, and high data transfer capacity [19, 20].

### **1.6.2. Drawbacks of OWC**

This subsection lists the main drawbacks of the OWC:

- Weather conditions impact the quality of communication, as variables like precipitation, fog, and clouds weaken and disperse the optical signal.
- The range of communication is restricted by atmospheric attenuation, scintillation effects caused by turbulence, technological limitations, and equipment alignment.
- The connection can only be established when there is a direct line of sight between the transmitter and receiver. Optical signals cannot reflect or rebound like radio waves.
- Various external variables can disrupt the connection, including obstructions obstructing the line of sight, interference from artificial lighting, fluctuations in temperature and humidity, and mechanical vibrations.

OWC is susceptible to air conditions, distance/alignment issues, absence of line-of-sight, and environmental disturbances. As a result, mitigation strategies are necessary to ensure a dependable connection [21, 22].

### **1.7. Attenuation in an OWC channel**

Attenuation in an OWC channel is the decrease in the intensity of the optical signal as it travels through the transmission medium. Below are a few crucial aspects of attenuation in this particular channel:

- **Atmospheric Absorption:** The atmosphere contains particles and molecules that can absorb specific wavelengths of optical light as it travels through the air. Gases such

as water vapor, carbon dioxide, or ozone can absorb particular wavelengths, leading to a notable decrease in signal strength.

- Rayleigh scattering and diffusion occur when particles in the atmosphere, such as air molecules and aerosols, disperse light in different directions. Rayleigh scattering, the primary type in the optical range, is directly proportional to the frequency of light raised to the fourth power. It causes signal dispersion, resulting in attenuation.
- Atmospheric scintillation results from swift fluctuations in the refractive index of air induced by atmospheric turbulence. These variations cause quick changes in the intensity of the optical light, which can result in fluctuations in signal power at the receiver.
- Rain effect: Raindrops can absorb and disperse optical light, further weakening the signal. OWC systems can face significant challenges when it comes to rain, primarily because of the heightened levels of absorption and dispersion it induces.
- The obstruction effect occurs when objects such as buildings, trees, or other structures block the direct path between the transmitter and receiver, causing a decrease in signal strength. Moreover, interference from external light sources, such as street lighting or vehicle headlights, can disrupt optical transmission.

Several strategies can be utilized to reduce the impact of attenuation in OWC channels. These include employing specific wavelengths optimized for the task, designing highly efficient transmission systems, using adaptive optics to counteract the effects of atmospheric turbulence, and implementing robust signal processing algorithms to minimize the impact of scintillation and distortion [23-25].

### **1.8. Current status of OWC systems implemented on an aircraft**

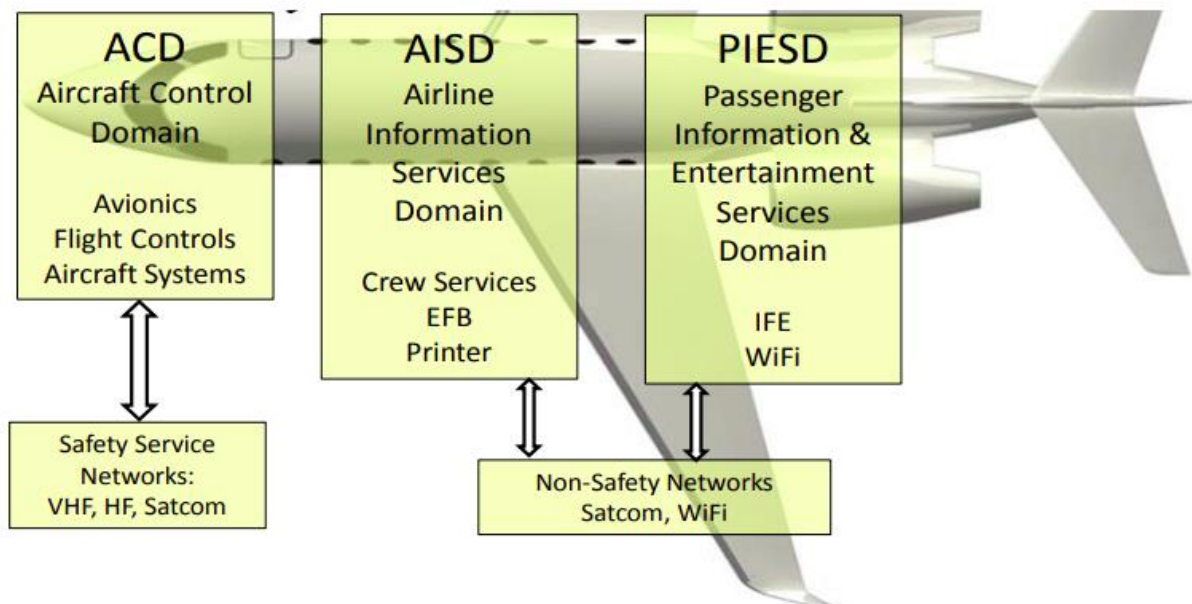
The OWC systems installed on board an aircraft are the latest technology, methodologies, and practices for exploiting optical communication technology within the aviation environment. This involves creating, implementing, and utilizing OWC systems for multiple applications, such as in-flight entertainment, cabin connectivity, aircraft-to-ground communication, secure data transmission, obstacle avoidance, and inter-vehicle communication. The state-of-the-art encompasses the most recent progress in optical transceiver technology, signal processing techniques, adaptive optics, and integration with current avionics systems. These developments aim to enhance aviation applications' performance, reliability, and safety.

An airplane system refers to any electronic system placed aboard an airplane. These may encompass flight deck and cabin systems. The aviation industry has established aircraft data network domains [17] in response to the growing utilization of airplane data networks.

The three domains are aircraft control, airline information services, and passenger information and entertainment services.

The domains are depicted in Figure 1.11. Occasionally, a domain is explicitly established for devices owned by passengers.

The metal structure of the aircraft is a significant factor in the challenges faced by on-board RF systems. The typical commercial airplane, with dimensions of approximately 30 meters in length and 5 meters in width, has a passenger capacity ranging from 150 to 220 individuals. This high passenger density can introduce interference through the Doppler effect and masking. However, the aircraft's metal structure also plays a role, significantly deviating the radio properties within the airplane from commonly employed RF propagation models. This unique environment necessitates specialized RF propagation models for accurate analysis [26, 27].



**Figure 1.11.** Aircraft information domains [28].

## 1.9. Conclusion

In conclusion, the OWC technologies provide a favorable method for transmitting data wirelessly, offering advantages such as increased data transfer capacity, minimal delay, and improved security. However, there are still obstacles to overcome, like air attenuation, restricted range, and line-of-sight limitations. Nevertheless, researchers are constantly exploring

mitigating measures such as adaptive optics, error-correcting codes, and improved wavelength selection to tackle these problems. Nevertheless, the utilization of OWC systems in diverse sectors, ranging from in-flight entertainment to inter-satellite communications, showcases the adaptability and promise of this technology. Continued research and development endeavors will enhance the precision of OWC technologies, expand their usage, and enhance their efficiency in many settings. OWC's ongoing development can completely transform wireless communications by providing quicker, more secure, and more dependable data transfer across various applications. The following chapter presents the optoelectronic components used in the proposed system.

## **CHAPTER 2**

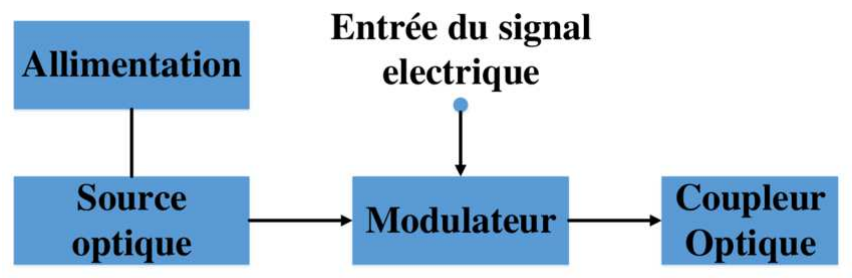
# **Optoelectronic components for a OWC system**

## **2.1. Introduction**

Optical wireless communication operates by transmitting information in the form of light through a wireless optical link between two points. Through a wireless optical channel, data is transmitted from one location to another. A transmitter converts the information from an electrical signal into an optical signal and then sends it across an optical wireless channel. Subsequently, the signal is subjected to the inverse procedure of converting from optical to electrical form at a receiver. This chapter provides a detailed explanation of the constituent parts of both a transmitter and a receiver, highlighting the complexity and depth of our understanding.

## **2.2. Optoelectronic transmitters**

The transmission device is implemented in an optical connection utilizing several components, such as the optical source and modulator. It aims to transmit an optical signal to the transmission medium, where the data is stored (see Figure 2.1) [29].



**Figure 2.1.** Structure of an optical transmitter [30].

In wireless optical transmission systems, optical transmitters must meet specific criteria. This device's advantages include its compact size, ability to operate at room temperature, use of semiconductor circuit control, capability to modulate high-frequency light emissions, narrow radiation spectrum, high output power, and long service life. Semiconductor devices classified into light-emitting and laser diodes are the light transmission elements that fulfill these requirements [29].

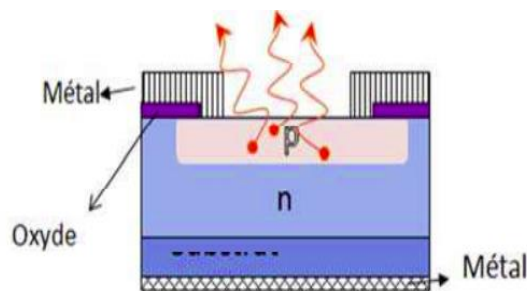
## **2.3. Optical source**

Optoelectronic sources are active components in optical telecommunications. The conversion of electrical signals to optical signals, also known as electrophotonic conversion, occurs through optical sources such as Laser Diodes (or LDs) and Light-Emitting Diodes (or LEDs). These sources rely on forward-polarized PN junctions, where the emission of light results from the

recombination of electron-hole pairs. Within the realm of optical telecommunications, wider bandwidths require using sources with narrower spectra [31].

### **2.3.1. Light-Emitting Diodes (or LEDs)**

An LED is an optoelectronic device that emits light when an electric current is applied. A heavily doped PN junction in a semiconductor generates monochromatic or polychromatic radiation by the radiative recombination of charge carriers (see Figure 2.2). LEDs are commonly employed for illumination, particularly in flat panel displays such as LCD backlights or Organic LED (or OLED) TVs.



**Figure 2.2.** Basic structure of an LED.

#### **a. LED features**

LEDs are cost-effective, user-friendly, less rapid, exclusively multimodal, and generate a broader beam. Due to their lower concentration and power, they provide challenges in fiber coupling and are limited to usage with multimode fibers (i.e. for short-distance applications).

The light spectrum emitted by LED is characterized by a beam that spreads widely and an optical spectrum that covers a wide range of wavelengths. The width of this spectrum is within the usual range ( $\Delta\lambda = 50 - 60 \text{ nm}$ ). As a result, their usage is restricted to lines that are short in distance and have low speeds, specifically below 622 Mbit/s (see Figure 2.3).

Emission direction: Light-emitting diodes can be classified into two types based on the direction in which they emit light:

- These objects radiate light in a direction that is at a right angle to the plane of the junction.
- Alternatively, there are lateral light-emitting diodes that produce light in a plane that is parallel to the junction (see Figure 2.4).

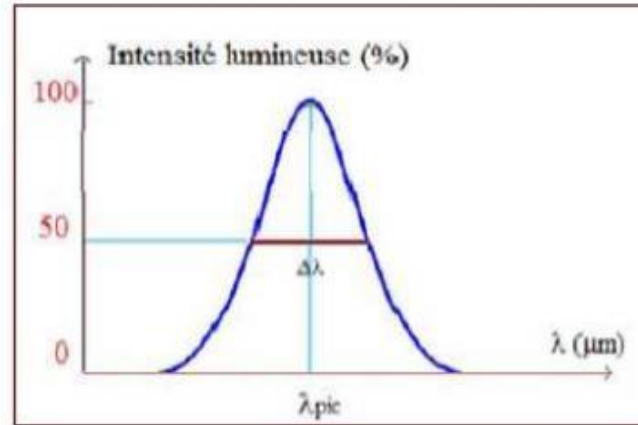


Figure 2.3. Emission spectrum of an LED.

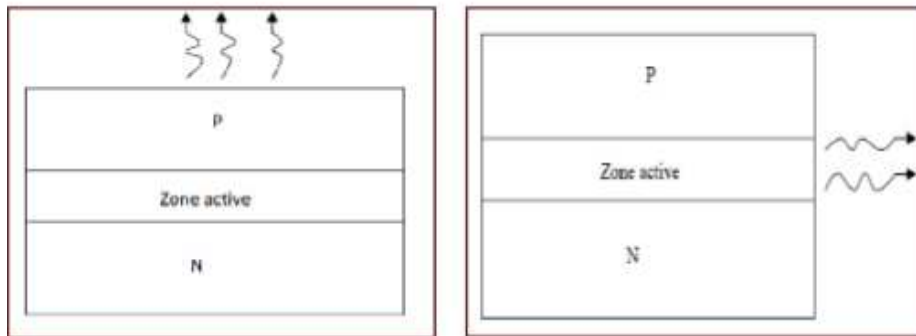


Figure 2.4. Emission modes of an LED.

**b. LED types**

The LED family can be categorized into multiple groups. The most commonly utilized diodes in optical telecommunications are surface emitters, edge emitters, and super-luminescent diodes. Light-emitting diodes emit light across the complete range of colors the human eye can see. The values in Table 2.1 represent the typical characteristics observed in diodes often used in commercial applications.

Materials	Radiation	Wavelength
InAs	Ultraviolet	315 nm
InP	Infrared	910 nm
AlGaAs	Red, Infrared	660 nm, 1000 nm
GaAs	Yellow	590 nm
GaP	Green	560 nm
SiC	Blue	470 nm

Table 2.1. LED types.

### **c. LED applications**

- LED rear illumination is used for cars, bicycles, road signs, and railway signs;
- Infrared lights for surveillance cameras that are not visible to the naked eye;
- Status indicators for different devices, such as warning lights and car dashboards;
- Electronic screens used for measuring instruments, calculators, and timekeeping equipment;
- Motion detectors, namely optical mice, are used [32].

### **2.3.2. Laser Diode (or LD)**

Since the early days of fiber optics, semiconductor transmitters have been the favored choice for telecommunications. This is because they are compact compared to the fiber core, it is relatively simple to modulate the emitted light by directly controlling the current, have a narrow optical spectrum, and consume minimal energy. Laser diodes are the optimal choice for optical telecommunications due to their superior ability to connect with fiber efficiently. The term LASER is an abbreviation for Light Amplification by Stimulated Emission of Radiation. Contrary to the light-emitting diode, which emits light without any external stimulation [33].

Lasers primarily have three essential components: an active medium, a pumping mechanism, and an optical resonator. Figure 2.5 depicts a laser setup.

- The amplifier medium is composed of the atoms to be stimulated. It can be a liquid or a semiconductor, with GaAs being a common example of a semiconductor medium.
- Pumping source: The source stimulates the atoms in the amplifying medium (population inversion) by introducing energy. The source might be either electrical or luminous, namely optical.
- An optical resonator, also known as an optical cavity, consists of two types of mirrors: a total reflector that reflects all incoming photons and a partially reflecting mirror that enables a small percentage (1% to 10%) of photons to pass through, creating the laser beam while reflecting the remaining radiation [33].

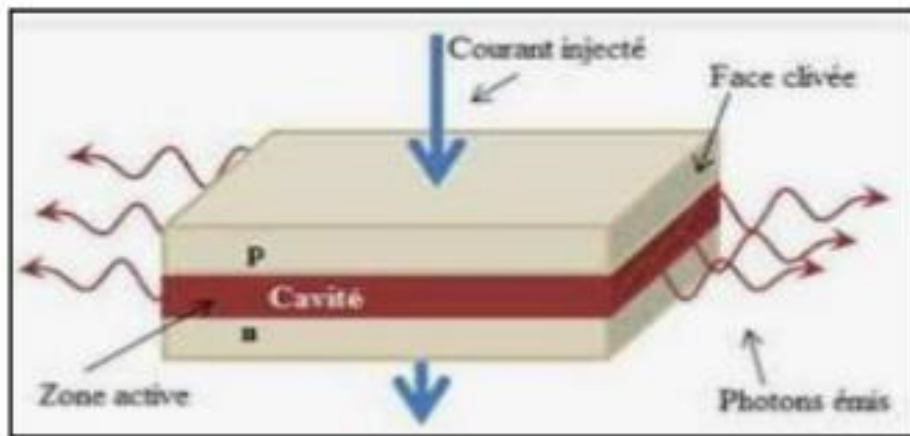


Figure 2.5. Laser diode structure [32].

### a. LD features

The laser diode is a device that emits coherent light through the process of stimulated emission.

Monochromatic refers to something that consists of or displays only one color. A thin beam of monochromatic light with a limited width of electromagnetic radiation.

Precisely guided: In this scenario, a focused stream of light will serve as the illumination source. Initiating a launch through an optical fiber is straightforward.

Coherent: A monochromatic light emitted by a broadband LED. The approach or threshold of a laser diode is a crucial characteristic.

The laser diode must be operated at a power level lower than the minimum requirement. If the light's energy is lower than its threshold, the emission will be less than its maximum energy [34].

The junction current determines the power of a laser diode (see Figure 2.6). Indeed, the fluctuation in the luminosity due to the current indicates the presence of residual light. Stimulated emission occurs when the current surpasses the threshold, causing all injected carriers to undergo a stimulated combination [35].

Laser noise: The technology used in semi-conductor lasers involves an optical frequency generator that is not perfect and is influenced by noise in both amplitude and frequency. The variability of this noise constrains the efficiency of every optical communication system. The noise is caused by spontaneous emission in a laser diode [35]. The RIN (or Relative Intensity Noise) measures the amplitude or intensity of noises at a specific frequency. It quantifies the level of noise between spectral densities and power fluctuations.

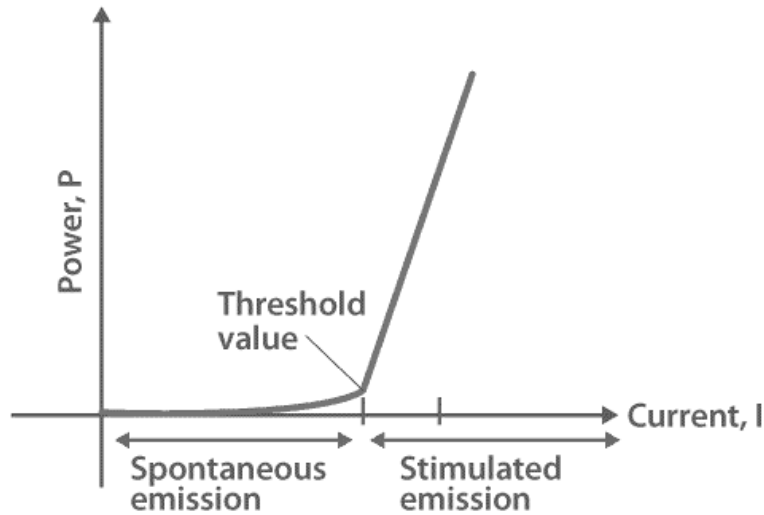


Figure 2.6. Power-Current characteristics of an LD [34].

**b. LD types**

Multiple potential variations of lasers exist:

- Solid-state lasers, which are the most potent, utilize crystals, ceramics, or glass that are doped with different atoms as the light-amplifying medium. One example is neodymium-doped YAG lasers.
- Liquid lasers utilize an organic dye as the emission medium.
- Gas lasers utilize a gas as the medium for generating photons. This gas is enclosed within an insulating glass, quartz, or ceramic tube. Some examples of lasers are helium-neon and CO<sub>2</sub> lasers.
- Semiconductor lasers utilize semiconductors, specifically gallium arsenide (GaAs), as their primary materials.

Type of laser	Environment laser	Color	Applications
Diode laser	Semiconductor	Red (780 nm), Infrared IR (1300 ,1550 nm)	DVD Playing Telecommunications
CO <sub>2</sub>	Gas mixture	Infrared IR (1060 nm)	Internal and external surgery, material welding
Nd-YAG	Solide	Infrared IR (1060 nm)	Internal and external surgery, material welding

Table 2.2. LD types [32].

## **2.4. Optical modulator**

Typically, an ongoing optical signal is modified based on the data, data rate, and chosen modulation type for transmission in optical transmission systems. Alternatively, it is feasible to modulate the optical signal directly at its origin by manipulating the pump current of the laser diode. We shall outline two techniques for modifying an optical signal.

The modulator is a device used to alter the characteristics of the optical wave, such as its amplitude and phase. Two techniques for modulating optical waves are direct modulation and external modulation.

Direct modulation involves altering the polarization current injected into the optical source. This procedure is straightforward and cost-effective.

External modulation involves combining the optical signal from the source with another optical signal from a local oscillator using an optical modulator. There exist two categories of optical modulators: Electro-Absorption Modulators (or EAM) and Mach-Zehnder Modulators (or MZM) [31, 36].

## **2.5. Modulation Types**

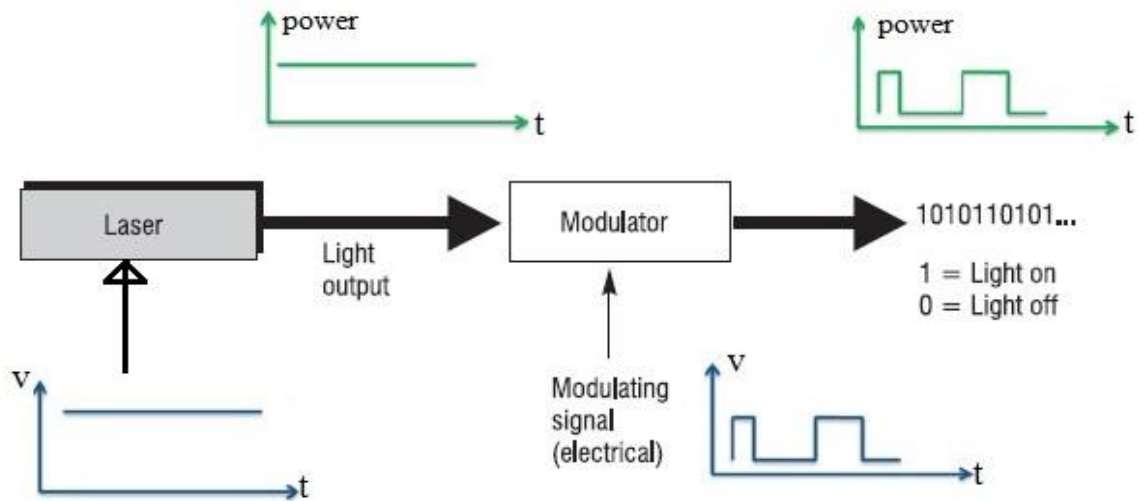
### **2.5.1. Direct modulation**

Direct modulation is a method used in optical communication to encode information directly onto the optical carrier signal by modulating the light source, usually a semiconductor laser diode. This technique directly applies an electrical signal to the laser diode, altering its output intensity, frequency, or phase.

Direct modulation is a process that involves manipulating a signal directly to get the desired outcome:

- The electrical input signal refers to an electrical signal that carries information to be conveyed. This signal can be digital data or analog signals. It is then applied to a semiconductor laser diode.
- The modulation of light output involves manipulating the laser diode's parameters, such as its injection current or voltage, to control the emitted light's intensity, frequency, or phase.
- The transmission of the modulated optical signal involves sending the coded information across an optical communication system, such as optical fibers or free space, to the receiver.

Direct modulation transfers data by directly modifying the characteristics of a light source, often a laser diode, using an electrical signal that carries the information (see Figure 2.7) [37, 38].



**Figure 2.7.** Principal scheme of direct modulation [37].

Nevertheless, direct modulation is widely employed in diverse optical communication systems, such as fiber optic telecommunications, laser-based spectroscopy, and optical sensing applications. It provides benefits such as simplicity, cost-efficiency, and fast operation, making it suited for quick data transfer and modulation applications. Nevertheless, direct modulation can encounter drawbacks such as nonlinearity, chirp, and wavelength instability, necessitating compensatory techniques to achieve maximum performance in specific applications [37, 38].

### 2.5.2. External modulation

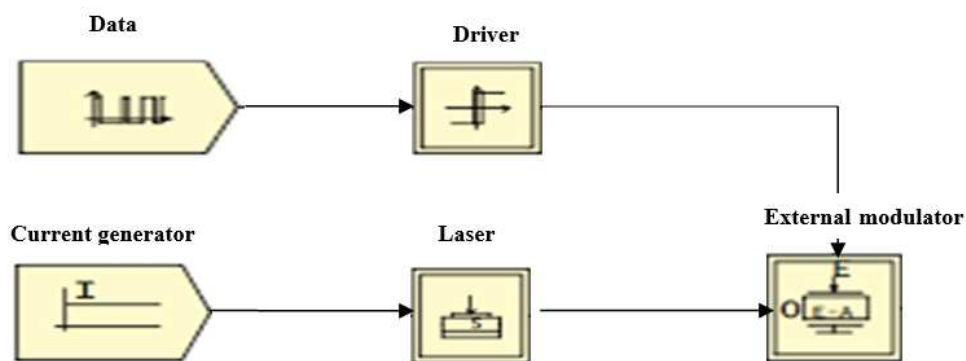
External modulation, often called an external modulation scheme, is a technique employed in optical communication systems to modify an optical signal after its generation, usually by a laser source, but before it is transmitted across the optical medium. This method entails utilizing an external modulator, such as an Electro-Absorbent modulator (or EAM) or Mach-Zehnder modulator (or MZM), to apply alterations to the optical signal.

External modulation is a process that involves the manipulation of a signal from an external source:

- Generating an optical signal involves using a laser source, such as a laser diode or semiconductor laser, which produces a coherent optical signal.

- An external modulator modifies the optical signal based on an external electrical or auditory input. The optical signal is directed to this device to apply the necessary adjustments.
- The modulation process involves the external modulator modifying the characteristics of the optical signal, such as its intensity, phase, frequency, or polarization, based on the input signal it receives.
- Transmission: The modulated optical signal is sent to the receiver, such as optical fibers or open space, over the optical communication system.

To summarize, external modulation involves utilizing an independent external device to modify an optical signal produced by a laser source based on an electrical or acoustic input signal before sending the modulated optical signal [37, 38], see Figure 2.8.



**Figure 2.8.** Synoptics of external modulation [35].

External modulation techniques are extensively employed in diverse optical communication applications, such as long-distance telephony, optical sensors, spectroscopy, and high-speed data transfer systems. They offer enhanced flexibility and control in the modulation process, allowing for the utilization of advanced modulation techniques to optimize system performance and achieve higher transmission capacities [37, 38].

### a. Mach-Zehnder modulator

The method employed to vary the intensity of a beam involves passing it via a Mach-Zehnder interferometer, where the phase difference between the two arms can be manipulated, as depicted in the accompanying diagram (see Figure 2.9).

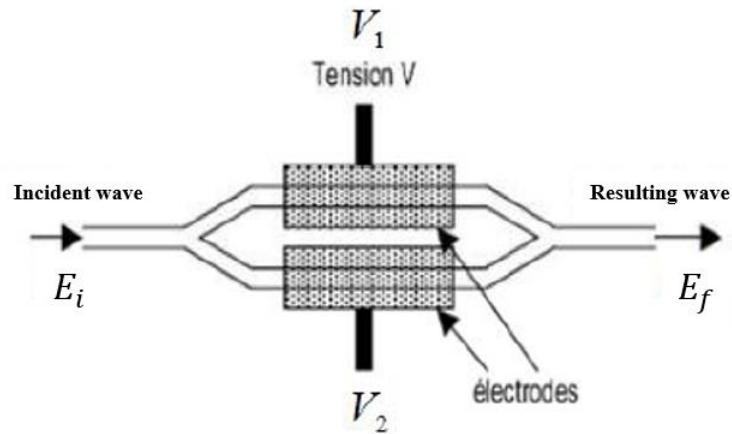


Figure 2.9. Principle design of MZM.

According to the provided Figure 2.9:

- $E_i$  represents the electric field of the incoming optical signal.
- $E_f$  represents the electric field of the output signal.
- $V_1$  and  $V_2$  represent the control voltages applied to the electro-optical cells.

The light is connected in two guides using a Y coupler. The two beams are subsequently merged back together at a second Y-shaped junction. The key to the Mach-Zehnder modulator's operation lies in the one or two electro-optic cells positioned on one of the arms of the interferometer. These cells impart a relative phase shift to the two signals, a crucial step in the modulation process. The disphase is then transformed into changes in the optical signal intensity through the interference between the disphased signals from both arms. Most Mach-Zehnder modulators available in the market are manufactured using a LiNbO<sub>3</sub> substrate, which enables a shallow loss (< 0.2 dB/cm) [39].

#### b. Electro-absorbent modulator

Electro-absorbing modulators operate by altering the absorption spectrum of a semiconductor when exposed to an electric field. An augmentation in the intensity of this electric field causes a displacement of the absorption threshold towards longer wavelengths, thus amplifying the absorption of light that traverses the semiconductor. The performance is contingent upon the choice of material.

Devices, including a quantum well guide, exhibit superior electro-absorption efficiency per unit length and broader bandwidth. However, they require a higher control voltage and are more susceptible to light polarization than devices that utilize solid material guides.

Electro-absorbing modulators alter the absorption of the semiconductor material in response to an electric field, hence modifying the intensity of the transmitted optical signal [40].

### **2.6. Optical transmitter parameters**

Essential characteristics of an optical transmitter:

- Emission area refers to the surface area of the emission window, measured in square meters.
- Emission power refers to the amount of power emitted by the emission surface, and it is often measured in units of dBm or mW. This power should be measured in an unobstructed environment and as proximate as feasible to the system's emission apertures.
- Beam divergence, also known as  $\theta$ , refers to the maximum angle between the beam's central axis, which has the highest power density, and the direction that corresponds to a lower power density of -3dB. The degree of deviation is quantified in milliradians (or mrad).
- The wavelength, denoted as  $\lambda$ , is derived from the central wavelength and the spectral range. The unit of measurement for this is the nanometer [41].

### **2.7. Optical amplifiers**

Attenuation limits the transmission of optical signals on an optical channel. Despite the little or higher attenuation of the optical channel, detecting a signal beyond a few hundred kilometers of propagation becomes unfeasible. To address this phenomenon, it is necessary to strategically position repeaters, particularly amplifiers, at regular intervals throughout the optical transmission chain. These repeaters serve the purpose of replenishing energy to the optical signal, ensuring its accurate detection.

In the past, optic transmission systems employed electronic repeaters to transform the optical signal into an electrical signal, amplify it, and then convert it back into an optical signal. This mechanism was intricate and significantly constrained the efficiency of the optical transmission line.

As a result, optical amplifiers were created to directly enhance the optical signal using physical phenomena that differ depending on the type of amplifier [36]:

- Erbium-Doped Fiber Amplifiers (or EDFA) are optical amplifiers that use erbium-doped fibers to amplify optical signals.

- Amplifiers that exhibit non-linear effects, such as Raman and Brillouin amplifiers.
- Semiconductor Optical Amplifiers (or SOA) use semiconductors to amplify optical signals.

### **2.7.1. Semiconductor optical amplifiers**

SOAs, or Semiconductor Optical Amplifiers, are small devices that enhance the strength of optical signals in communication networks. These devices are constructed using semiconductor materials intentionally contaminated with impurities to produce a medium that amplifies light. Their principle relies on stimulated photon emission, which allows for signal amplification. These devices provide a broad range of amplification frequencies, making them valuable for Wavelength-Division Multiplexing (or WDM) systems, and can be used in various applications. Despite their small size, these devices have drawbacks such as excessive noise levels and susceptibility to polarisation. However, the critical characteristics of SOA are outlined as follows:

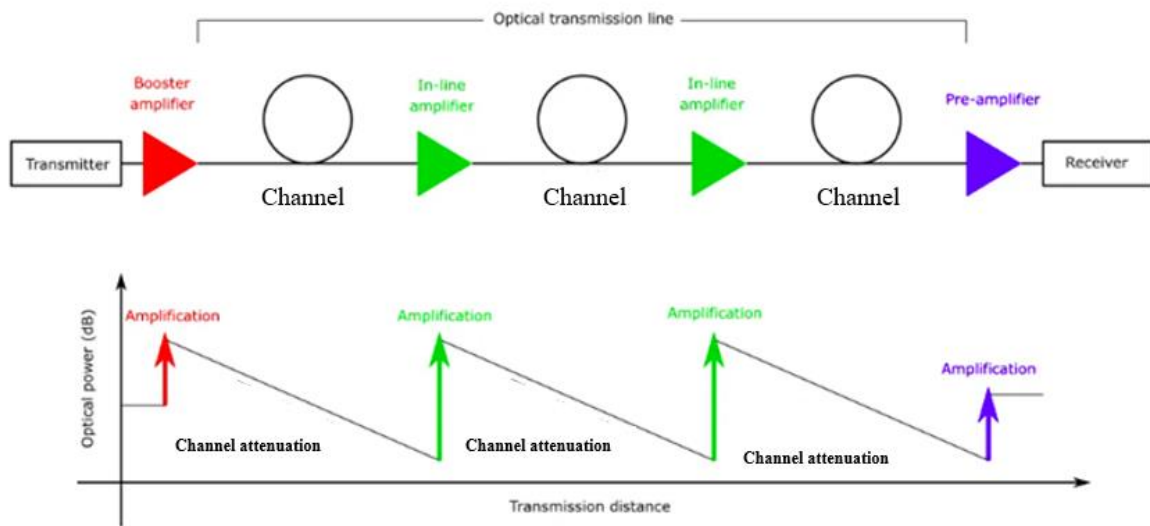
- The gain can reach up to 30 dB, varying based on the type of semiconductor used.
- The saturation output power ranges from 5 to 10 milliwatts.
- The optical bandwidth is approximately 5 THz, which corresponds to a range of 40 nm centered around 1550 nm.
- The saturation level is high, and there are noticeable non-linearities.
- This amplifier is the most compact option currently on the market and boasts remarkable efficiency.
- Manufacturing approach that can be easily combined with the integration of other active or passive parts in a single structure.
- The incident-beam coupling losses are significant because the active-layer diameter is bigger than the required thickness [33].

### **2.7.2. Erbium-doped fiber amplifier**

An Erbium-Doped Fibre Amplifier (or EDFA) is a specific form of optical amplifier employed in optical communication networks to enhance the power of optical signals. It is used in optical transmission lines as a power amplifier (or booster), line amplifier (or inline), and pre-amplifier.

The booster amplifier is positioned immediately following the transmitter to enhance the optical power introduced into the line. Inline amplifiers counteract the decrease in signal strength caused by the attenuation of optical channels along the transmission line. The pre-

amplifier is placed before the receiver to ensure an adequate optical power level. EDFAs are often separated by distances of several tens of kilometers, see Figure 2.10.



**Figure 2.10.** Booster, inline, and pre-amplifier EDFAs used in optical transmission line [42].

An EDFA modulator is a device that modulates an optical signal amplified by an EDFA. Modulation encompasses manipulating a signal's strength, phase, frequency, or polarisation to encode information or modify its qualities for many uses.

By modulating an optical signal after amplification using an EDFA, precise control over the amplified signal becomes possible. This control enables various tasks, such as signal processing, wavelength tuning, and implementing complex modulation schemes for optical communication systems [42].

**a. How it works**

Fiber-optic telecommunications networks use the erbium-doped fiber amplifier (EDFA) to amplify optical signals at 1550 nm. The fiber introduces Erbium (Er) as a dopant, stimulating it at two specific wavelengths: 980 nm or 1480 nm. A pump wavelength of 1480 nm stimulates the Er ion, causing it to transition into an excited state known as excited state 1. Stimulated emission occurs from this excited state at a wavelength of 1550 nm, enabling signal amplification in the event of population inversion. When stimulated with a 980 nm wavelength, the erbium ion transitions to a more energetically excited state, known as excited state 2. However, it quickly undergoes a non-radiative relaxation process, returning to excited state 1 and releasing thermal energy. At a wavelength of 1550 nm, signal amplification happens by

stimulated emission from excited state 1 when sufficient pump power is provided (see Figure 2.11).

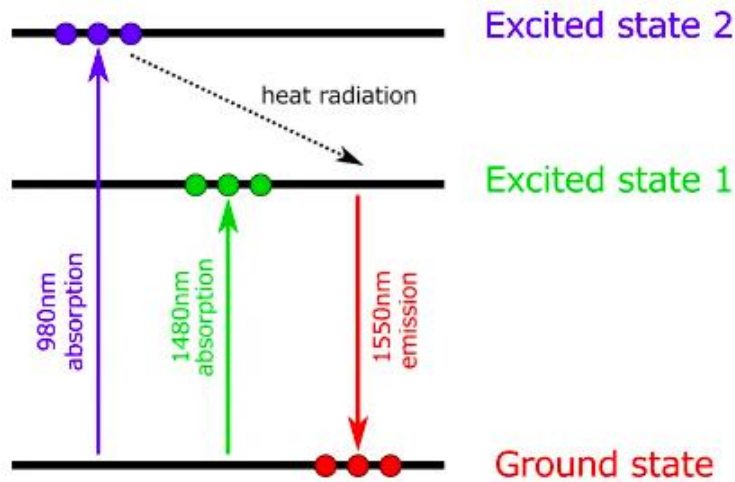


Figure 2.11. Energy diagram of Erbium [42].

**b. Internal configuration**

A WDM coupler merges the input signal with the pump light before transmitting it to the Erbium-Doped Fiber (or EDF). Stimulated emission enhances the input signal, and population inversion is created by the pump light aimed at the EDF. Filters strategically place themselves at both the input and output points to prevent the amplifier from functioning as a laser and to ensure stable signal amplification by removing undesired reflections from the output port. In this standard setup, an outside fiber Bragg grating precisely keeps the pump laser diode's wavelength close to the erbium absorption peak, usually between 974 and 980 nm. The diagram depicts a typical arrangement of an EDFA; see Figure 2.12 [42].

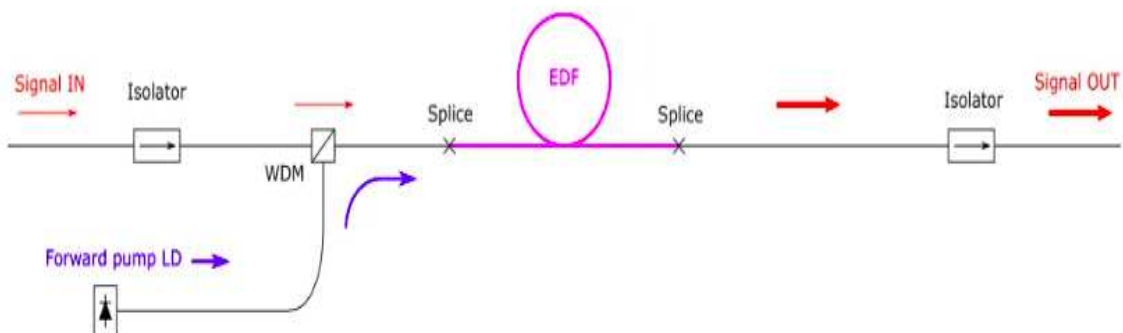


Figure 2.12. Current EDFA configuration [42].

**c. EDFA's main optical features**

The primary optical properties of EDFA are as outlined below:

- When an amplifier receives adequate input power, typically 0 dBm or higher, it can generate its highest level of control, known as saturated output power. This is an essential attribute for a power amplifier.
- When the input signal power is extremely low, often about -30 dBm, we achieve low signal gain. This attribute is crucial for a preamplifier that functions with feeble signals.
- The noise figure, specifically the enhanced spontaneous emission from the EDFA, reduces the signal-to-noise ratio. A low noise figure signifies a smaller amount of additional noise (theoretically, the minimum is 3 dB). This is crucial for a preamplifier with low input power.
- Flatness requirement: All WDM channels should exhibit uniform gain. Practically, there are modest variations in gains across different channels. We refer to this specific variation as increasing flatness. It is crucial to achieve optimal flatness, especially when linking multiple EDFAs in series [42].

### **2.7.3. Raman and Brillouin amplifiers**

Non-linear fiber-optic amplifiers employ Raman or Brillouin phenomena rather than stimulated emission. A high-power laser pump produces energy transfers through non-linear processes to achieve amplification. Nevertheless, achieving poor efficiency necessitates using propagation distances greater than 1 kilometer. The 11 GHz disparity between the pump and the signal has limited the range of applications for Brillouin amplifiers, preventing their widespread use. Raman amplifiers provide a compelling alternative to doped-fiber amplifiers for amplification at 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  wavelengths. In particular, they can be used to balance the spectral gain of broadband signals or lessen the effect of Raman effects in 1.55  $\mu\text{m}$  WDM networks. Pumping entails the integration of numerous semiconductor lasers to achieve the required spectral gain profile, whether uniform or not [43].

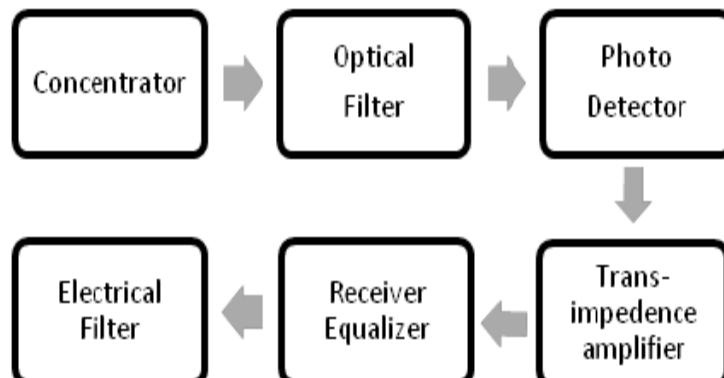
## **2.8. Optoelectronic receivers**

Optical communication systems use optoelectronic receivers to convert optical impulses into electrical signals. They comprise a photodetector that absorbs the incoming optical signal and converts it into an electrical current or voltage, together with accompanying electronic circuits for amplifying, filtering, and conditioning the signal.

Photodetectors are semiconductors with PN junctions that are reverse-polarized. They use the photoelectric effect to turn photons, which are light signals, into electrical signals. There

are two distinct varieties of photodiodes: PN and PIN, which lack internal gain, and avalanche photodiodes (or APD), which possess internal gain.

Optoelectronic receivers are essential components in optical communication systems since they allow for transmitting optical data by optical fiber or free-space optical networks. They are crucial in various applications, including telecommunications, data networks, sensing, and imaging (see Figure 2.13) [41].



**Figure 2.13.** A diagram of the optical receiver unit [41].

### 2.8.1. PIN photodiode

A PIN (or Positive-Intrinsic-Negative) photodiode is a specific kind that finds application in optical communication systems and detection and imaging purposes. The semiconductor device employs the photoelectric effect to convert optical signals into electrical impulses. The structure comprises three layers: a semiconductor layer with positive doping (P), an undoped intrinsic layer, and a semiconductor layer with harmful doping (N). When light reaches the inherent region, it creates electron-hole pairs, generating an electric current. The PIN structure possesses excellent photon absorption capabilities and low capacitance, rendering it ideal for applications requiring high-speed performance and minimal noise [44].

#### a. How it works

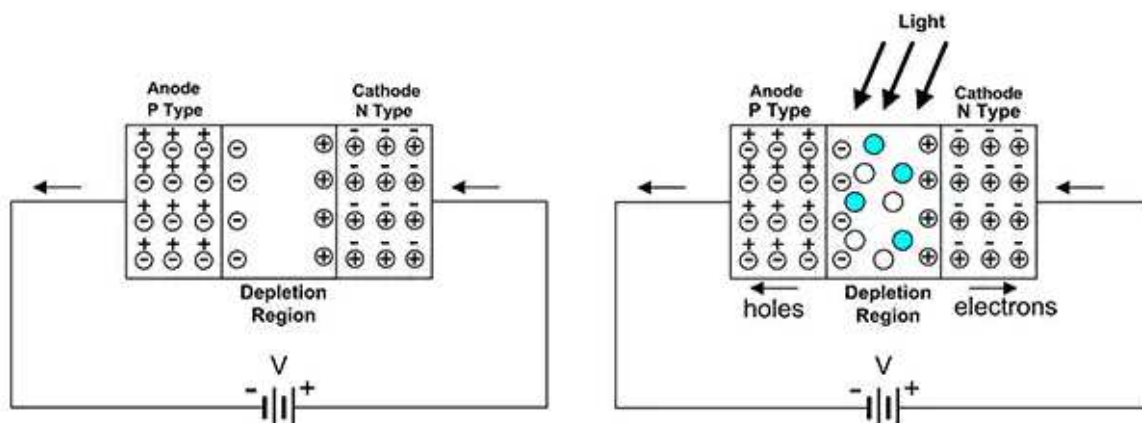
A transparent body or cover exposes a light-sensitive P-N or PIN junction in a photodiode, a semiconductor device. When light hits the intersection, it generates either a current or a voltage, depending on the mode of operation. The applied bias determines the three different modes in which the photodiode can operate (see Figure 2.14).

- The photovoltaic mode of operation refers to a device's ability to generate a tiny output voltage when exposed to light, similar to a solar cell, without external bias. It

proves advantageous for frequencies under 350 kHz and low light intensities. The voltage output needs to be increased.

- Applying a reverse bias to the P-N junction creates a depletion area in the photoconductive mode, allowing quicker response times. This mode exhibits elevated amounts of noise.
- Avalanche mode refers to a state in which there is a significant reverse polarization. In this state, an avalanche process amplifies each electron-hole pair a photo creates, increasing sensitivity.

In most applications, the photodiode typically operates in a state of reverse bias in the photoconductive mode [44].



**Figure 2.14.** How PIN works: the PIN photodiode, when subjected to reverse bias, generates a current that is directly proportional to the intensity of light. This is because the photodiode's depletion zone generates electron-hole pairs. The blue circles symbolize electrons, while the white circles indicate holes [44].

### b. Advantages of PIN photodiode

PIN photodiodes offer several significant benefits, including:

- Wide bandwidth: They possess the capacity to detect signals across a broad range of frequencies, which is advantageous for various applications.
- High quantum efficiency is a device's ability to convert incoming photons into electrical current efficiently. This maximizes the sensitivity of light detection.
- Rapid response speed: PIN photodiodes have quick response times to changes in the incoming light signal, making them essential for systems that demand swift detection.

To summarize, PIN photodiodes possess a broad frequency range, excellent efficiency in converting photons to electrons, and rapid response time, which makes them highly appealing for various optical and optoelectronic uses [45].

### **2.8.2. Avalanche photodiode**

An avalanche photodiode (or APD) is an extremely sensitive photodetector utilized in optical communication systems, LiDAR systems, and other applications that demand exceptional sensitivity and minimal noise. Avalanche breakdown is an internal multiplication process in a semiconductor device that turns incident light into electrical current using the photoelectric effect.

When photons collide with the absorption zone of the APD, they produce electron-hole pairs propelled by a powerful electric field. The electrons undergo collisions with the crystal lattice, generating further electron-hole pairs through impact ionization. The cascading, or avalanche, process leads to a fast increase in the number of charge carriers and a magnified output current, directly proportional to the intensity of the incoming light.

Avalanche photodiodes (APDs) provide superior sensitivity and reduced noise compared to regular photodiodes. However, they are more intricate and necessitate accurate bias voltage and temperature management to maximize their efficiency.

#### **a. How it works**

Avalanche photodiodes utilize a high reverse bias voltage to facilitate avalanche multiplication. The electron-hole pair first generated experiences the influence of both the electric field of the depletion area and the external electric field (see Figure 2.15) [46].

Due to the robust reverse polarization, each leading carrier produces secondary carriers through ionization impact when colliding with atoms in the crystal lattice. Fast-moving electrons collide with atoms, releasing more electrons. These newly released electrons are then accelerated and collide with other atoms, resulting in a constant generation of a significant number of minority carriers (see Figure 2.16).

In comparison to typical PIN photodiodes, Avalanche photodiodes emit a significantly higher number of charge carriers. They are commonly employed in situations where achieving a significant increase in output is a crucial consideration [46].



Figure 2.15. Real APD [47].

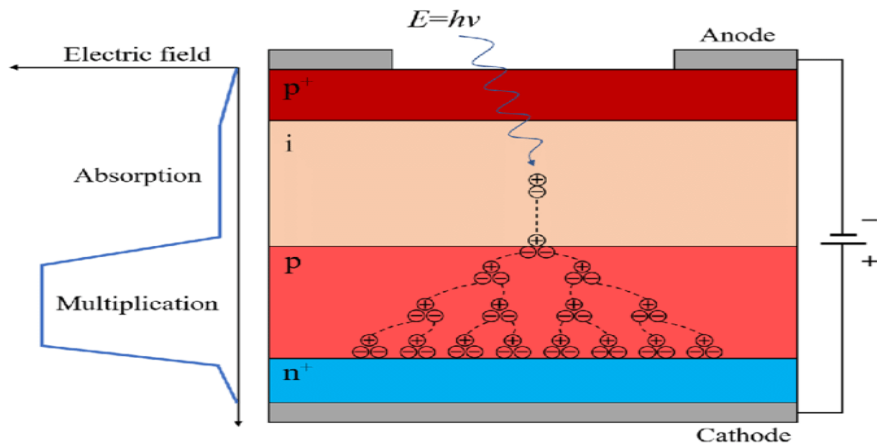


Figure 2.16. APD schematic diagram [48].

### 2.8.3. Comparison between PIN and APD

The stability and performance of PIN photodiodes and avalanche photodiodes (APD) are discussed in the following section:

- When exposed to temperature and applied voltage changes, the PIN photodiode is more stable than the APD.
- On the other hand, the APD photodiode has a higher quantum efficiency in the near-infrared, but it suffers from high noise and temporal instability.

In summary:

- Photodiode PIN: More stable in the face of temperature/voltage changes
- The APD photodiode exhibits superior infrared quantum efficiency, although it is noisier and less stable over time.

The PIN photodiode is preferred when stability is critical, while the APD is advantageous for detecting weak infrared signals despite its noise and lack of stability; see Table 2.3.

Features	Photodiodes	
	PIN	APD
Control voltage [V]	Low	High
Cut frequency [GHz]	> 60	Quelques
Quantum yield (%)	Low	High
Bandwidth [GHz]	Large	Low
Wavelength [nm]	1300 and 1550	1300 and 1550

**Table 2.3.** Comparison of PIN and APD characteristics [29].

## 2.9. Optical receiver parameters

The primary variables that define an optical receiver:

- Surface area is the complete measurement of the input window's outer surface, expressed in square meters. The choice of modulation format dictates the detection mechanism employed by the receiver.
- Sensitivity is the lowest optical level required to achieve a specific data transmission quality, measured in dBm.
- Saturation sensitivity refers to the highest degree of optical input a system can handle, regardless of whether automated attenuation adjustment is used. The dynamic range is determined by subtracting the sensitivity from the saturation.
- The angle of vision: The angle between the central axis and the direction at -3 dB is represented in milliradians (mrad). The angle can be defined as either a half-angle or a full-angle.
- Additional factors that were not specified include the modulation format, detection mechanism, and bit error rate.

Essentially, these criteria define an optical receiver's basic skills in terms of its ability to collect light, detect different power levels, receive light from different angles, and process different signal formats using various detection techniques [41].

## 2.10. Conclusion

The complex optical communications network relies on several crucial elements, including transmitters, receivers, modulators, and amplifiers. Laser diodes and LEDs are reliable sources of optical transmission, whereas modulation techniques act as the means for signal transmission. Optical amplifiers play a crucial role in extending the transmission range. By thoroughly comprehending these elements and their functions, we may proficiently coordinate

## **Chapter 2: Optoelectronic Components for a OWC System**

and enhance optical communication systems, guaranteeing smooth data and communication transmission. The next chapter analyzes the simulation outcomes and the suggested system's explanations.

## **CHAPTER 3**

# **Simulation results and interpretations**

### 3.1. Introduction

In this chapter, we present our study and design of an outdoor optical communication system using an OWC channel for a network of UAVs. The preceding theory has enabled us to develop a simulation using the industrial software Optisystem. We will present here the performance of this optical link in different configurations. These performances will be evaluated based on Bit Error Rate (or BER), with different optical amplifier configurations and certain attenuation conditions. Finally, we will summarize the various simulation results.

### 3.2. Optisystem software

Optisystem is a software application designed by a Canadian business to design optical communication systems. It simplifies the process of designing, testing, and optimizing optical connections, even those including non-linear devices and non-Gaussian noise sources, which are typically challenging and time-consuming.

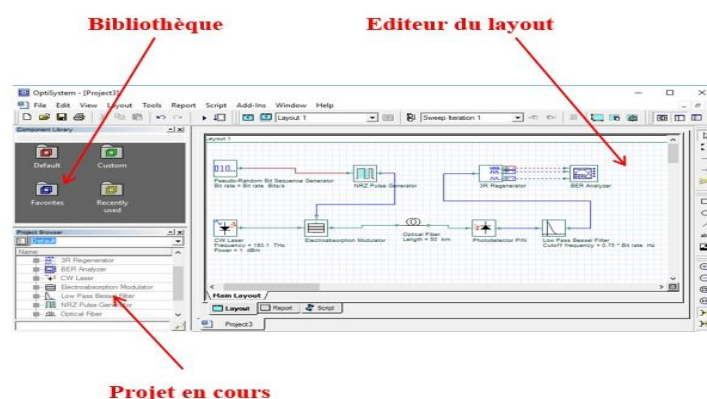
Optisystem is an essential component of the modeling, simulation, analysis, and design tools for signal processing modules, ranging from critical components to entire communication systems. The interactive environment merges robust math capabilities, sophisticated graphical functions, and a user-friendly interface.

The utilization of Optisystem can be divided into two primary stages:

- Constructing the operational prototype
- Conduct a thorough analysis of the model [49, 50].

#### 3.2.1. Optisystem interface

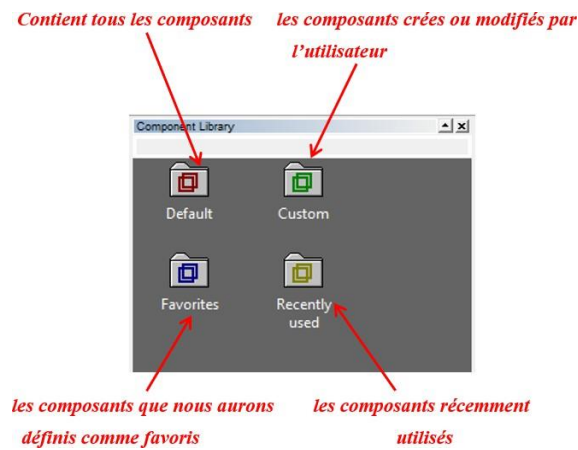
A graphical interface completes and controls the layout of the optical components, and has a central window divided into several sections, as illustrated in Figure 3.1.



**Figure 3.1.** Optisystem software interface.

### 3.2.2. Library

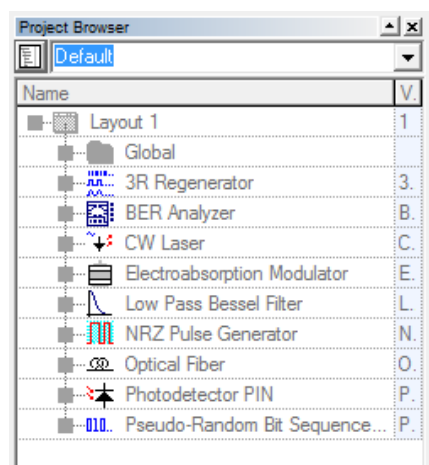
It incorporates every kind of model—sources, regenerators, encoders, modulators, filters, etc.—that can be utilized to determine the various functional patterns (see Figure 3.2) [51].



**Figure 3.2.** Optisystem software library.

### 3.2.3. Project browser

This window lists all project components (see Figure 3.3), making it easier for you to access them quickly—especially if your project is complicated and involves many different components [51].



**Figure 3.3.** Project browser.

### 3.2.4. Layout editor

The panel (refer to Figure 3.4), the layout editor, is where you create block diagrams using various library components. You can modify these settings to customize the components [51].

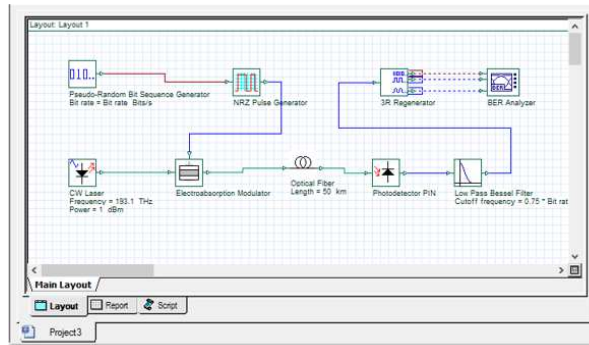


Figure 3.4. Layout editor.

### 3.2.5. Launch a simulation

The process to run the simulation is as follows (refer to Figure 3.5).

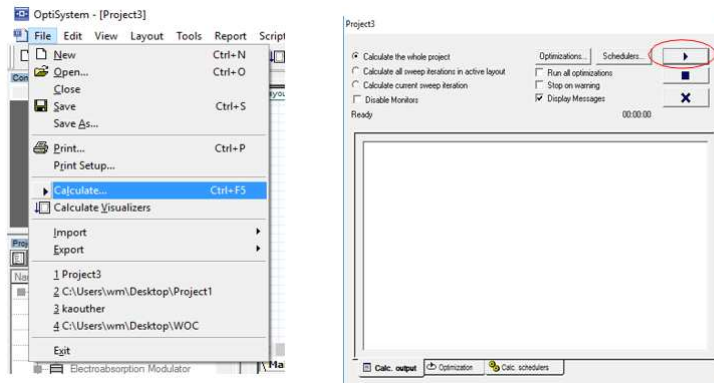


Figure 3.5. Window shows the launch of the simulation.

### 3.2.6. Optisystem features

The main characteristics of this software are as follows:

- Concerning the chosen precision, the virtual component library may replicate the identical operation and the designated effect, and actual components can replicate their efficacy.
- Thanks to the component library, it is possible to define parameters that actual devices may measure.
- Expert visualization tools produce various images and graphs, including constellation diagrams, eye diagrams, sound signals, polarization states, and spectral SAOSs.
- The monitor can have infinite observers linked to it on the same port.

- The data flow computation complies with state-of-the-art methodology. Based on the chosen data, the programmer determines which component modules execute in what order to manage the simulation [49].

### **3.2.7. Optisystem applications**

Optisystem has many uses, of which the following are the most popular ones:

- The physical layer component's optical communication system design.
- Passive optical networks (or PON) and TDM/WDM network design.
- Design of SONET/SDH ring networks.
- Rail amplifier and transmitter design [52].

### **3.2.8. Advantages of the Optisystem software**

The Optisystem software's benefits:

- Offers a summary of fiber-optic technology systems' overall performance.
- Assess the parameters' sensitivity in light of the design tolerance requirements.
- Show potential clients a graphic representation of the design alternatives.
- Make extensive system characterization datasets directly accessible.
- Permit parameter optimization and analysis to occur automatically [53].

## **3.3. Optical transmission quality criteria**

The bit error rate, or BER, is an important factor in assessing the quality of transmission in an optical wireless communication (OWC) channel. It quantifies the overall optical system reliability by expressing the number of incorrect bits relative to the total number of bits sent throughout a measurement period.

For optical systems, BER is typically in the range of  $1e-3$ ,  $1e-9$ ,  $1e-12$ , and  $1e-3$ ; in this case, BER is set at the following value:  $1e-3$ . The signal-to-noise ratio, based on the quality factor reflecting the received signal's power loss at the receiver, determines it. A low BER denotes a high-quality, error-free transmission [53, 54].

## **3.4. OWC/FSO Channel**

In OWC/FSO communications, point-to-point direct linkages are formed between optical transmitters and receivers via air. The transmitter transforms the electrical signal into an optical signal before sending it through the atmosphere. Conversely, the receiver converts the optical signal into an electric signal. The achieved BER is used to estimate the quality of the transmission line.

Free-space optical connection modeling is made possible through the OWC/FSO channel, a component of the receiver telescope, free space, and transmitter telescope subsystem. One of the key parameters in this modeling is Range, which defines the propagation distance between the transmitter and receiver telescope. The attenuation of the laser power, determined by two primary factors-attenuation and geometrical loss, is a crucial aspect. The first parameter, attenuation, describes the loss of laser power in the atmosphere. The second parameter, geometrical loss, is caused by the dispersion of the transmitted beam between the transmitter and the receiver [55, 56]. The link equation of OWC/FSO channel is:

$$P_R = P_T \cdot \frac{d_R^2}{(d_T + \theta \cdot R)^2} 10^{-\frac{\alpha \cdot R}{10}} \quad (3.1)$$

Where:

- $d_R$ : Diameter of receiver aperture [m];
- $d_T$ : Diameter of transmitter aperture [m];
- $\theta$ : Divergence of beams [mrad];
- $R$ : Range in [km];
- $\alpha$ : Attenuation of the atmosphere [dB/km].

Additionally, the user can define the transmitter and receiver losses resulting from the coupling efficiencies and fiber-telescope interface (parameters Transmitter loss and Receiver loss). Additional losses allow you to specify additional losses from scintillation, pointing error, and other sources. Measurement Using propagation delay, it is possible to calculate the delay between a transmitter and a receiver.

If the parameter intensity scintillation is enabled, a gamma-gamma distribution [57] can be used to simulate atmospheric fading.

However, the probability of a specific intensity  $I$  in the model of gamma-gamma distribution can be calculated as follows:

$$P(I) = \frac{2(\alpha\beta)^{\left(\frac{\alpha+\beta}{2}\right)}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\left(\frac{\alpha+\beta}{2}\right)-1\right)} \cdot K_{\alpha-\beta}\left(2 \cdot \sqrt{\alpha \cdot \beta \cdot I}\right), \quad I > 0 \quad (3.2)$$

The variances of the small and large-scale eddies are represented by  $1/\alpha$  and  $1/\beta$ , respectively [57]. The Gamma functions are denoted by  $\Gamma(\alpha)$  and  $\Gamma(\beta)$ , while the modified Bessel function of the second order is represented by  $K_{\alpha-\beta}\left(2 \cdot \sqrt{\alpha \cdot \beta \cdot I}\right)$ . The values of  $\alpha$  and  $\beta$  are appropriate for the plane wave beam at the optical receiver:

$$\alpha = \left( \exp \left[ \frac{0.49 \cdot \sigma_R^2}{(1 + 1.11 \cdot \sigma_R^{2.4})^{1.17}} \right] - 1 \right)^{-1} \quad (3.3)$$

$$\beta = \left( \exp \left[ \frac{0.51 \cdot \sigma_R^2}{(1 + 0.69 \cdot \sigma_R^{2.4})^{0.8333}} \right] - 1 \right)^{-1} \quad (3.4)$$

The Rytov variance  $\sigma_R^2$  is calculated from:

$$\sigma_R^2 = 1.23 \cdot C_n^2 \cdot k^{1.17} \cdot R^{1.83} \quad (3.5)$$

In this context,  $k$  represents the optical wave number,  $R$  represents the parameter range in  $[m]$  and  $C_n^2$ , represents the parameter for the index refraction structure in  $[m^{-2/3}]$ . This parameter indicates the intensity of air turbulence or, more simply, the magnitude of variations in the refractive index of the environment. The numerical values of  $C_n^2$ ,  $10^{-17} m^{-2/3}$ ,  $10^{-15} m^{-2/3}$  and  $10^{-13} m^{-2/3}$  are used to represent weak, moderate, and strong turbulence, respectively. The symbol  $C_n^2$  denotes the essential parameter that describes the atmospheric turbulence impacts on the optical signal transmitted through the Free Space Optics (FSO) channel. In this case, we have set the value of  $C_n^2$  to  $10^{-13} m^{-2/3}$  [57].

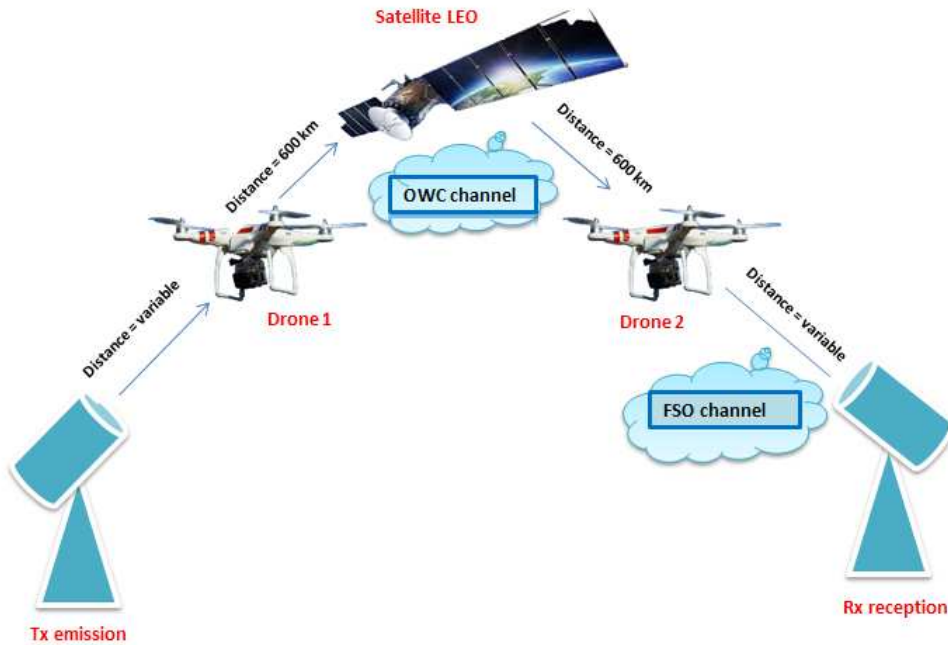
### 3.5. Simulation results and interpretations

#### 3.5.1. Proposed system

This sub-section will showcase the suggested system through the diagram of an outdoor optical communication system utilizing an OWC channel for a network of UAVs (refer to Figure 3.6) and its conceptual schema in Optisystem software (refer to Figure 3.7).

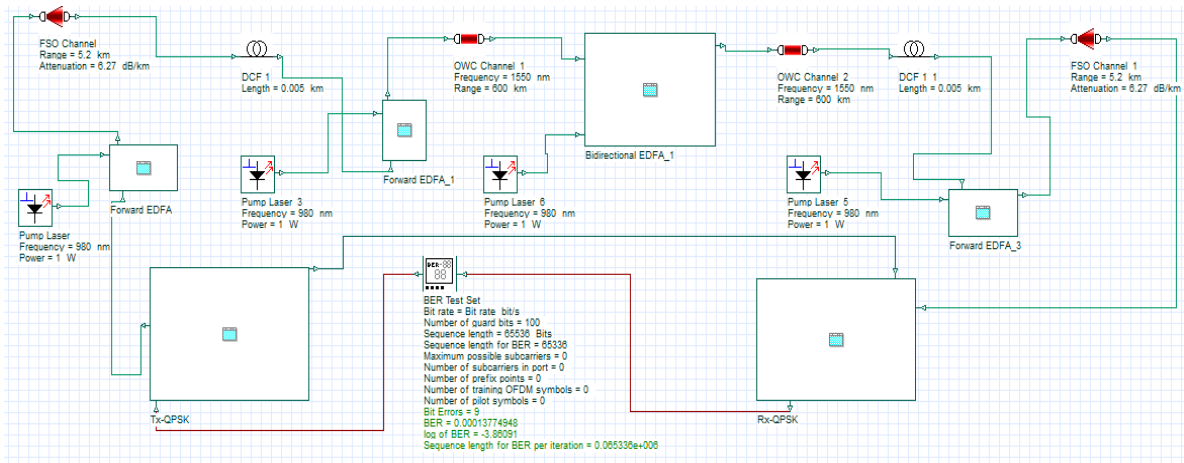
UAVs 1 and 2 are positioned between the transmitting and receiving stations to ensure the security of the information being transmitted to the satellite. The distance between the base station and the UAV might change depending on the location of the receiving side. Currently, the distance between UAVs 1 and 2 and the satellite is 600 km. We operate in Low-Earth Orbit (or LEO), meaning the drones and satellites are at 200 to 2000 km altitudes.

The UAV's primary purpose is to receive information from the base station, enhance its signal strength, and transmit it back to the satellite. This chapter will be revealed.



**Figure 3.6.** Simplified illustration of an outdoor optical communication system employing an OWC channel for a network of UAVs.

We have utilized Optisystem software to simulate and subsequently translate the image (see Figure 3.6), as depicted in Figure 3.7. Figures 3.8 and 3.9 provide a detailed explanation of the transmitter and reception components of the proposed system. We establish the simulation settings outlined in Table 3.1 to execute the simulation.



**Figure 3.7.** Proposed system using Optisystem.

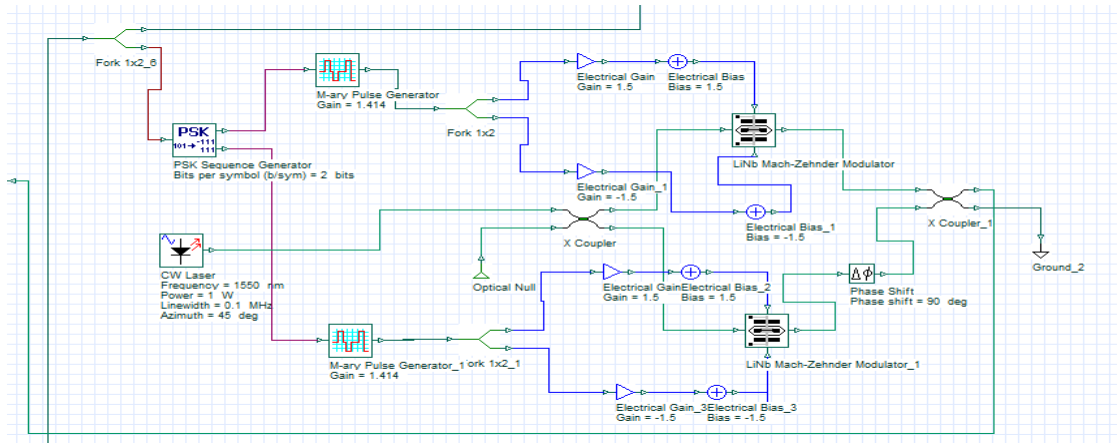


Figure 3.8. Transmitter section of proposed system using Optisystem.

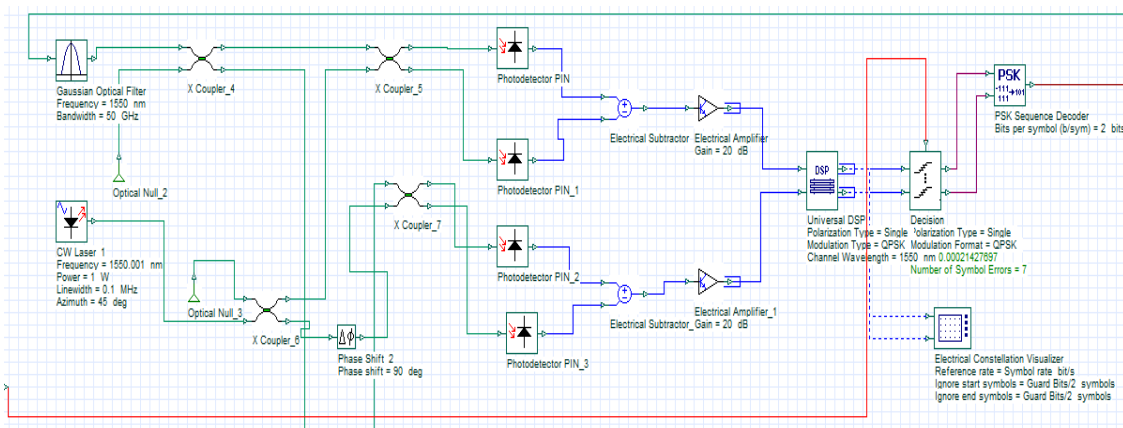


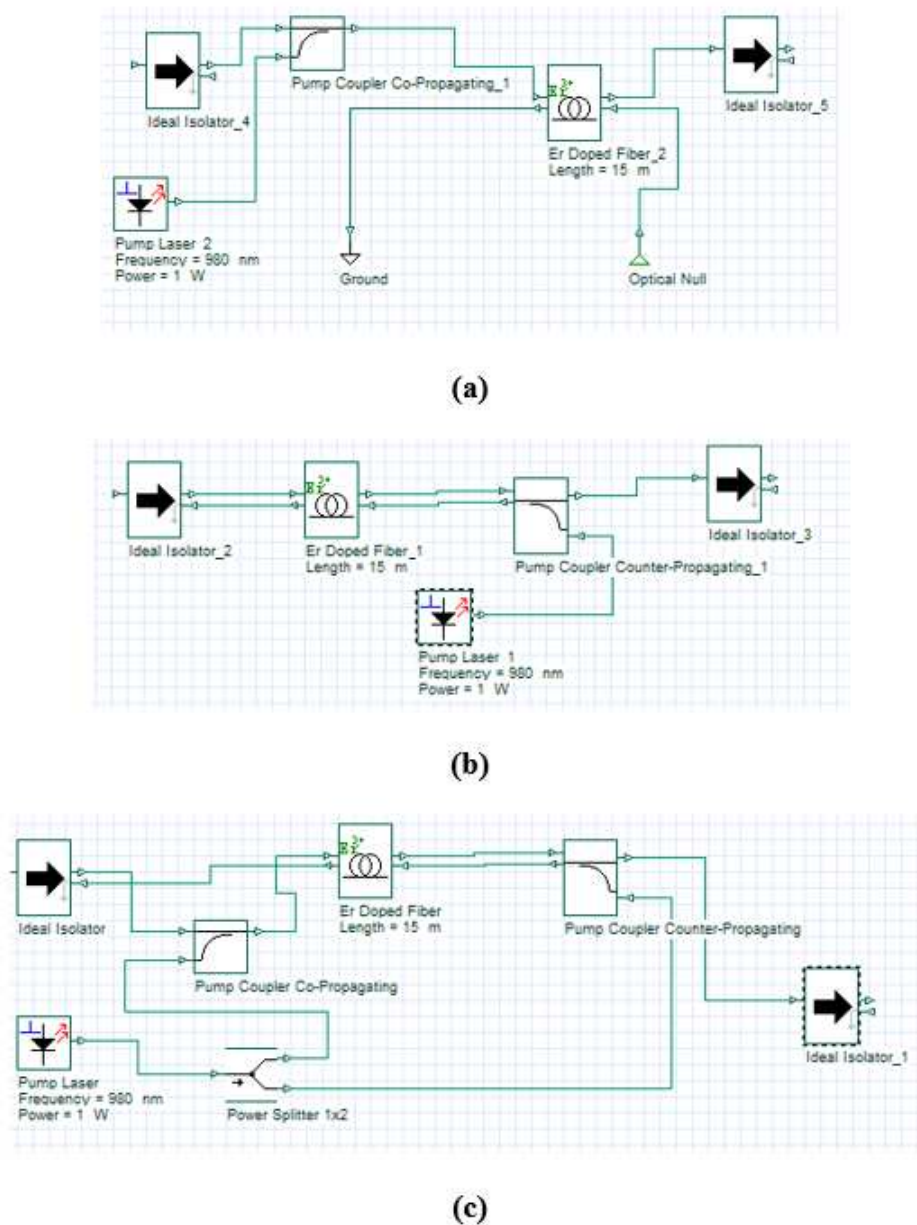
Figure 3.9. Reception section of proposed system using Optisystem.

Settings	Descriptions
Bit rate	500 Mbps
Distance from OWC link	600 km
OWC & FSO transmitter opening diameter	2 cm
OWC & FSO receiver opening diameter	15/30 cm
EDFA Optical Amplifier (Gain and Noise Factor)	20 dB and 4 dB
Pump laser (Frequency and Power)	980 nm / 1W
Er Dopped Fiber (Length)	15 m
CW laser (Frequency and Power)	1550 nm / 1W
Dispersion Compensation Fiber (DCF)	5 cm
M-ary pulse Generator (Gain)	1.114 dB
Electrical Amplifier (Gain)	20 dB
Gaussian Optical Filter (Frequency and Bandwidth)	1550 nm / 50 Ghz
PSK Sequence Generator	2 bits/symb
Phase shift	90 deg

Tableau 3.1. Simulation parameters.

### 3.5.2. Estimation of FSO channel distance under varying weather conditions

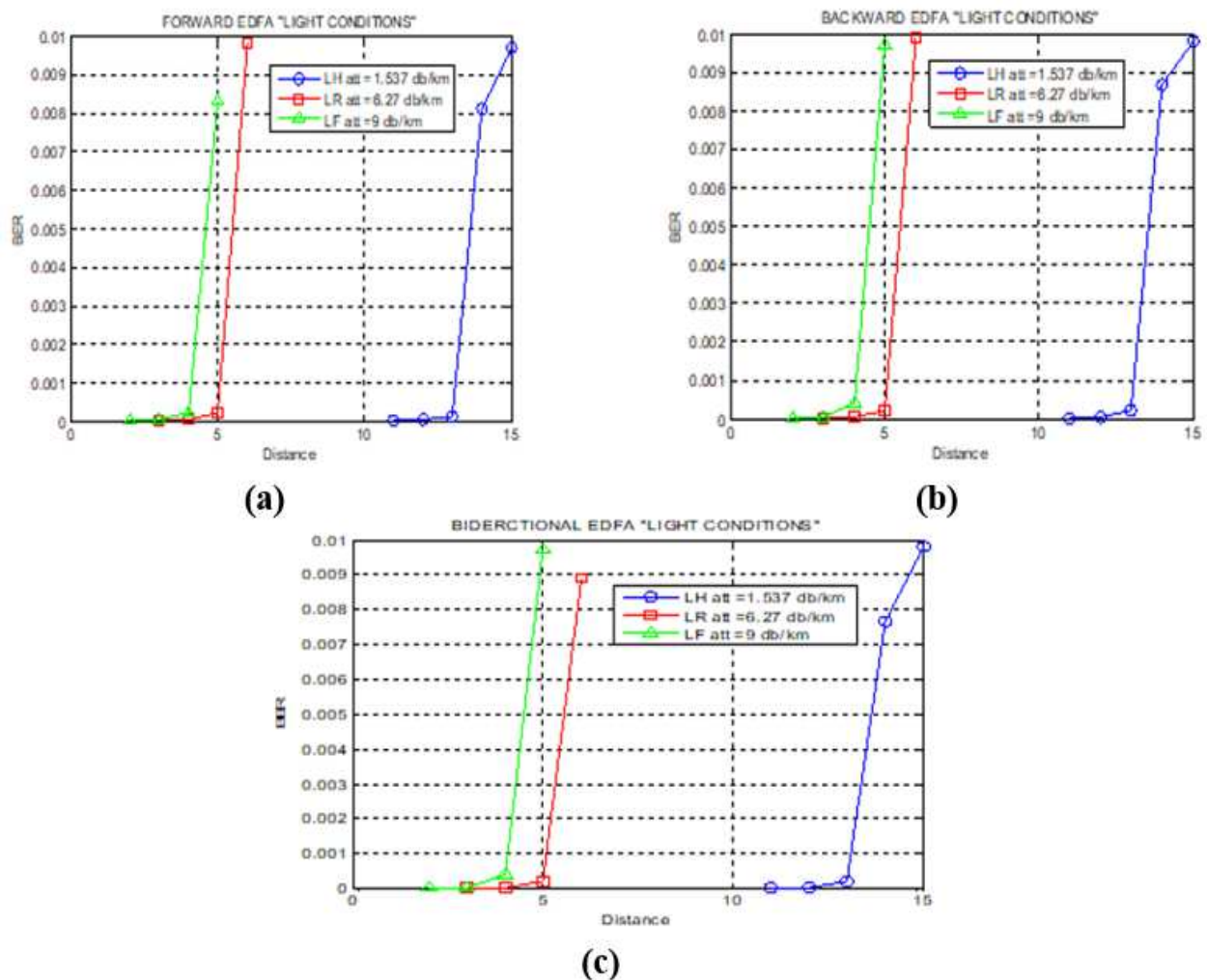
Estimating the distance of the FSO channel between the UAV and the base station is crucial for evaluating the proposed system's performance. Considering various weather conditions [58], we are specifically interested in assessing this distance in both the transmission and reception dimensions. The proposed system aims to achieve end-to-end data transmission at 500 Mbps. Furthermore, the FSO channel distance between the UAV and the base station will be estimated using various configurations of the EDFA optical amplifier. Figure 3.10 displays the three utilized configurations.



**Figure 3.10.** Configurations of the EDFA optical amplifier: (a) Forward, (b) Backward and (c) Bidirectional.

a. Determining the distance of the FSO channel in different light weather circumstances

Figure 3.11 illustrates the BER change based on distance for various light weather conditions. The attenuation values for each condition are 1.537 dB/km for Light Haze (or LH), 6.27 dB/km for Light Rain (or LR), and 9 dB for Light Fog (or LF). The three optical amplifier configuration formats used are EDFA, forward, backward, and bidirectional. Based on the findings in this part, it has been noticed that when the attenuation in light weather circumstances grows, the distance of the FSO channel is negatively affected. This, in turn, leads to an increase in BER values and a decline in the proposed system's performance.



**Figure 3.11.** BER performance against the distance of the FSO channel [km] for different light weather conditions: (a) Forward, (b) Backward and (c) Bidirectional.

As an illustration, when aiming for a BER value of  $1e-03$ , the following pertinent findings are achieved: The estimated distance obtained for the forward and backward configurations for LH is 13.10 km, while for the bidirectional configuration, it is 13.11 km. For LR, the estimated

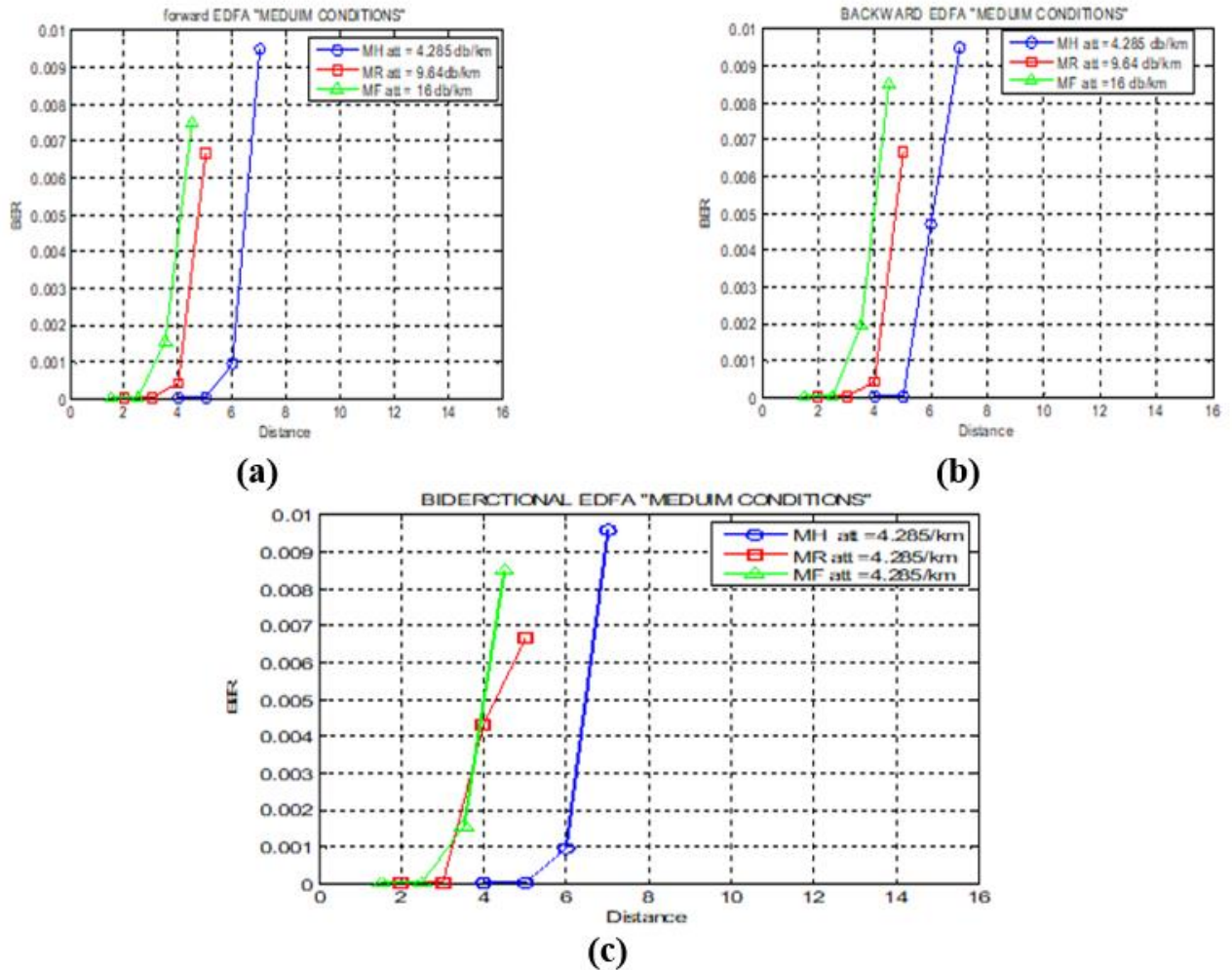
distance obtained for the forward and backward configurations is 5.2 km, and for the bidirectional configuration, it is 5.21 km. Lastly, for LF, the estimated distance obtained for the forward and backward configurations is 3.98 km, and for the bidirectional configuration, it is 3.99 km. Consequently, the bidirectional architecture is the most efficient for the proposed system.

#### **b. Determining the distance of the FSO channel in different medium weather circumstances**

Figure 3.12 illustrates the relationship between the BER performance and distance under various median weather conditions. The attenuation coefficients for each condition are 4.285 dB/km for Medium Haze (or MH), 9.64 dB/km for Medium Rain (or MR), and 16 dB/km for Medium Fog (or MF). The experiment tested three configurations of optical amplifiers: EDFA, forward propagation, backward propagation, and bidirectional propagation.

The findings indicate that the optical wireless link for the FSO channel experiences a significant drop in transmission distance when attenuation intensifies due to unfavorable weather conditions. As a result, the BER rises, and the suggested system's performance declines.

Poor weather conditions like fog or rain harm the maximum transmission distance. This is due to the increased attenuation of the optical signal, resulting in a higher error rate and a decrease in the quality of the optical wireless link. For instance, while targeting a BER of  $1e-03$ , the subsequent relevant results are obtained: The estimated distances for the forward, backward, and bidirectional configurations for MH are 6.02 km, 6.01 km, and 6.00 km, respectively. The estimated distance for MR is 3.70 km for the forward and bidirectional forms and 3.69 km for the backward scheme. Finally, the estimated distances for MF's forward, backward, and bidirectional configurations are 2.49 km, 2.51 km, and 2.50 km, respectively. Therefore, the proposed system achieves optimal performance under various weather conditions by employing different EDFA configurations. Specifically, the forward architecture is the most effective for MH, while both forward and bidirectional architectures yield the best results for MR. Lastly, the backward architecture is the most suitable for achieving optimal performance in MF.



**Figure 3.12.** BER performance against the distance of the FSO channel [km] for different medium weather conditions: (a) Forward, (b) Backward and (c) Bidirectional.

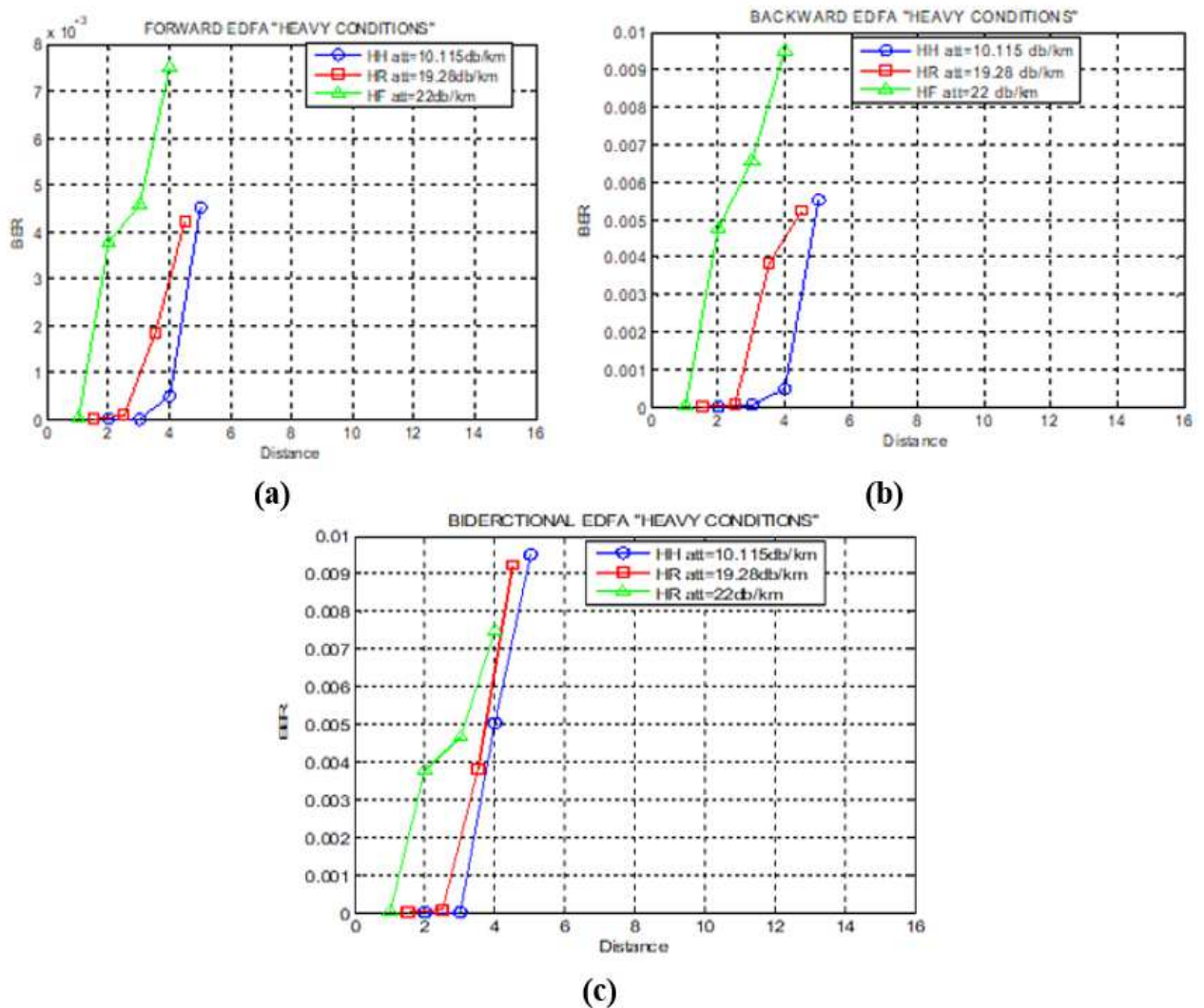
**c. Determining the distance of the FSO channel in different heavy weather circumstances**

Figure 3.13 depicts the correlation between the BER performance and distance over different heavy weather conditions. The attenuation coefficients for each condition are as follows: 10.115 dB/km for Heavy Haze (or HH), 19.28 dB/km for Heavy Rain (or HR), and 22 dB/km for Heavy Fog (or HF). The experiment evaluated the performance of three different optical amplifier configurations: EDFA, forward propagation, backward propagation, and bidirectional propagation.

Nevertheless, the findings from this stage show that the performance of the suggested system still needs improvement, particularly in severe weather conditions. To provide further clarification, to achieve a BER of  $1e-03$ , the following pertinent outcomes have been obtained: The estimated distances for HH's forward, backward, and bidirectional configurations are 3.54

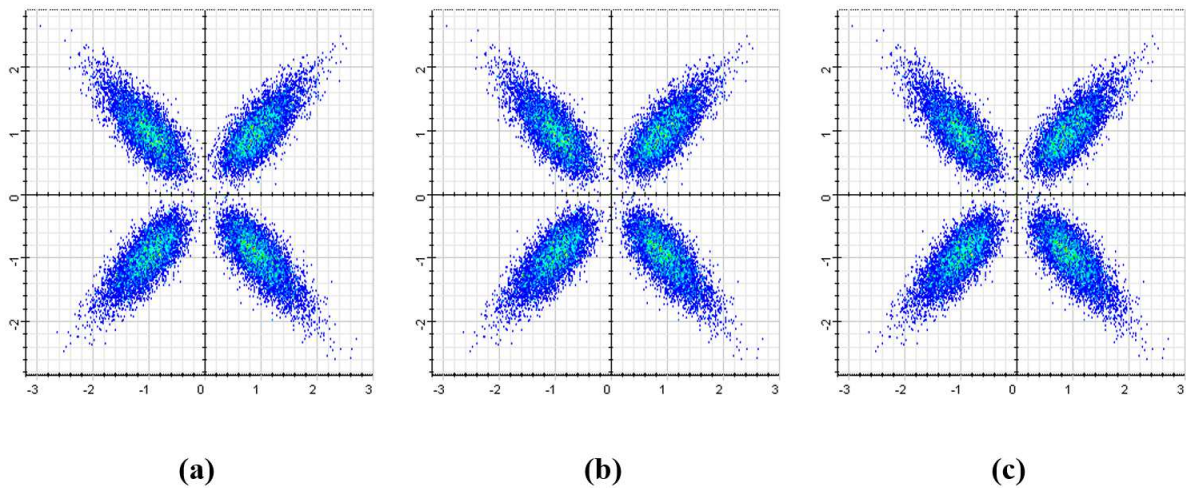
km, 3.52 km, and 3.51 km, respectively. The estimated distances for HR are 2.08 km for the forward configuration and 2.07 km for the backward and bidirectional layouts. The estimated distances for the front, backward, and bidirectional configurations of HF are 1.96 km, 1.98 km, and 2.00 km, respectively.

Our proposed system stands as a testament to the effectiveness of our research, as it successfully achieves optimal performance in diverse weather situations by employing multiple EDFA configurations. Specifically, the forward layout demonstrates superior efficiency for HH and HR, while the bidirectional architecture yields optimal outcomes for HF, further highlighting the success of our approach.



**Figure 3.13.** BER performance against the distance of the FSO channel [km] for different heavy weather conditions: (a) Forward, (b) Backward and (c) Bidirectional.

To summarize, the distance of the FSO link significantly affects the quality of the signal received by the receiver. As the distance increases, the effect of climate change on the quality of the received signal becomes more significant. The findings indicate that when attenuation increases in each weather condition, the distance reduces, leading to a corresponding increase in the BER. The provided constellation diagram demonstrates the visual representation of the proposed system's performance in acceptable conditions when the distance between the base station and the UAV is at its highest, regardless of whether it is on the transmitting or receiving end, see Figure 3.14.



**Figure 3.14.** Constellation diagram: (a) Forward, (b) Backward and (c) Bidirectional.

### 3.6. Conclusion

The examination of the final chapter unequivocally demonstrated that the EDFA configurations offer a highly promising resolution for long-distance networks. Utilizing this optical amplifier leads to a substantial enhancement in transmission capacity. This study also highlighted the significance of assessing the efficiency of an outdoor optical communication system using an OWC channel for a network of UAVs based on particular parameters, such as BER. Additionally, they can ascertain whether a decline in network quality may affect the service level with a constellation diagram.

# **General conclusion**

Optical Wireless Communication (or OWC) and Free Space Optics (or FSO) are emerging technologies with great potential for transmitting data at fast speeds and large bandwidths. OWC utilizes light to transmit data without physical connections. This technology provides numerous benefits, such as fast data transfer speeds, little delay, and improved data protection. FSO, a subset of OWC, utilizes light to send data between two sites without requiring physical fiber. This makes it well-suited for situations where standard fiber optic cables are not feasible.

While the OWC channel is a crucial component of satellite communications, it's important to acknowledge the challenges posed by atmospheric factors. These factors can significantly impact the strength and reliability of signals, necessitating the use of mitigation measures such as adaptive optics and error correction algorithms. The OWC channel's ability to effectively manage the enormous data rates required for modern applications is a testament to its importance. For instance, low Earth Orbit (LEO) satellites can optimize their performance by utilizing OWC to establish high-capacity connections with ground stations, UAV networks, and other satellites. This enhances the overall capacity and flexibility of the communication network and underscores the urgency and importance of conducting comprehensive performance studies of satellite communication systems, particularly when implementing OWC and considering different atmospheric conditions.

Ultimately, this project focuses on researching and creating an outdoor optical communication system that utilizes an OWC channel for a network of UAVs, employing OptiSystem software. This simulation employs three configurations of EDFA: forward, backward, and bidirectional. The configurations are tested with various parameters, including FSO channel mitigation, OWC and FSO transmitter diameter, OWC and FSO reception aperture, distance link, and binary flow.

After careful analysis, we have determined that the proposed system's performance may be adjusted to match the specific configuration of the EDFA in different weather circumstances as long as the conditions are within acceptable limits. If weather permits, we can extend the FSO channel range. Additionally, we estimated that as the data attenuation grows relative to the signal wavelength, the maximum distance of the FSO link drops, and the BER experiences a significant increase.

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