PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
IBN KHALDOUN UNIVERSITY – TIARET

MASTER'S THESIS

Submitted to the:

Faculty of Mathematics and Computer Science

Department of Computer Science

In partial fulfillment of the requirements for the degree of:

MASTER

Speciality : **Networks and telecomuniatios**

Presented by :

BRAHMI Naceur Abdelkader

Title of the Thesis

Free Space Optical systems (FSO) for 5G and beyond.

Publicly defended on June 18th , 2025, at Ibn Khaldoun University, Tiaret
Before the examination board composed of:
:

Mr BEKKI Khadhir	MAA	Ibn Khaldoun University Tiaret	President of the Jury
Mr KHERICI Cheikh	MCB	Ibn Khaldoun University Tiaret	Thesis Supervisor
Mr BAGHDADI Mohamed	MCA	Ibn Khaldoun University Tiaret	Examiner

Academic Year : **2024-2025.**

Acknowledgments

First and foremost, I thank **Allah** for granting me the strength, will, and perseverance to complete this final year project.

I would like to express my sincere gratitude to my supervisor, **Mr. Kherici Cheikh**, for his continuous support, patience, valuable guidance, and encouragement throughout the course of this work. His insightful comments and direction were crucial to the successful completion of this study.

I also extend my heartfelt thanks to the **members of the jury**, who have kindly accepted to evaluate this modest work and contribute their time and expertise.

My deepest appreciation goes to **my family** for their unwavering support, love, and sacrifices throughout my academic journey. I am equally grateful to all **my friends and colleagues** for their presence, motivation, and all the wonderful moments we've shared.

Dedication

No words in the world can fully express my appreciation, love respect, and gratitude. All I can say is

I dedicate this humble work to:

My beloved mother

You are my greatest source of inspiration, my guiding light, and the pillar of my life. Your unconditional love, prayers, and patience have carried me through every challenge. Even though words can never fully reflect my gratitude, I hope this dedication shows just how much I love and respect you.

My dear father

Your strength, sacrifices, and constant support have shaped me and brought me to where I am today. This work is the fruit of all you’ve invested in my education. I dedicate it to you with deep love and heartfelt thanks.

My dear brother Sidahmed

You have always been there for me, someone I could count on through everything. Your presence and encouragement have meant the world to me. I dedicate this work to you with all my affection.

To my friends

To those who stood by me with support and kindness, who offered encouragement and shared moments of joy and difficulty—I thank you from the bottom of my heart. I wish you all success, health, and happiness in life.

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Abbreviations

AI: Artificial Intelligence
AM: Amplitude Modulation
APD: Avalanche Photodiode
ASK: Amplitude Shift Keying
AWGN: Additive White Gaussian Noise
BER: Bit Error Rate
BTS: Base Transceiver Station
CC: Channel Capacity
DF: Distributed Feedback (Laser)
EMI: Electromagnetic Interference
FEC: Forward Error Correction
FM: Frequency Modulation
FP: Fabry-Perot (Laser)
FSO: Free Space Optics
IM: Intensity Modulation
ISI: Inter-Symbol Interference
LED: Light Emitting Diode
LOS: Line of Sight
MANET: Mobile Ad Hoc Network
MIMO: Multiple Input Multiple Output
MZI: Mach-Zehnder Interferometer
OFDM: Orthogonal Frequency Division Multiplexing
PAS: Probabilistic Amplitude Shaping
PCM: Pulse Code Modulation
PDF: Probability Density Function
PSK: Phase Shift Keying
QAM: Quadrature Amplitude Modulation
RX: Receiver
SIMO: Single Input Multiple Output
SNR: Signal-to-Noise Ratio
TX: Transmitter

VANET:	Vehicular Ad Hoc Network
VCSEL:	Vertical-Cavity Surface-Emitting Laser
WFO:	Wireless Free-space Optics

Introduction

Introduction:

The rapid evolution of telecommunication technologies, driven by an ever-increasing demand for higher data rates, lower latency, and reliable connectivity, has created a pressing need for alternative communication systems that go beyond the capabilities of conventional wireless and wired infrastructures. As the world transitions into the era of 5G—and actively prepares for the future with 6G and beyond—there is a growing focus on developing systems that can meet the ambitious requirements of ultra-fast, high-capacity, and energy-efficient communication. Among the various emerging technologies, Free Space Optical (FSO) communication has drawn considerable attention for its unique ability to deliver optical-fiber-like performance without the need for physical cabling.

FSO systems transmit information using light beams—typically lasers or LEDs—through the atmosphere, enabling high-speed, line-of-sight wireless communication. These systems offer several advantages, including immunity to electromagnetic interference, inherent security due to narrow beam divergence, license-free spectrum usage, and cost-effective deployment compared to optical fiber in hard-to-reach areas. However, they also face notable challenges, particularly their sensitivity to atmospheric conditions such as fog, rain, and turbulence, which can degrade the quality of the optical signal.

With growing interest in smart cities, the Internet of Things (IoT), and space-based communication systems, FSO technology presents a valuable solution for high-speed and flexible connectivity. Moreover, it serves as a critical component in bridging digital divides in rural or infrastructure-deficient areas, offering fast and secure data links where traditional fiber optics or radio frequencies are impractical.

This research aims to analyze and evaluate the technical aspects, modeling strategies, and performance characteristics of FSO systems. It investigates how such systems can be optimized and adapted to operate effectively despite environmental limitations. Through a blend of theoretical insights and simulation-driven evaluations, this work contributes to a broader understanding of the role of FSO communication in the development of future high-capacity and resilient wireless networks.

Chapter I

Presentation of Free Space Optical Communication Systems

I. Introduction

Free- space optical communication (FSO) systems use light beams to transmit data through the atmosphere or the vacuum of space, without the use of physical media such as cables or optical fibers. This technology combines the advantages of optical communications (high speed, security) with the flexibility of wireless networks.

Here is a detailed explanation of the operating principle of a FSO (Free Space Optics), accompanied by illustrations and references to clarify the concepts.

I.1. Operating principle:

A Free Space system Optics (FSO) is based on three main components: the transmitter (TX), the propagation channel, and the receiver (RX). Here's how each component works: [01]

1. 2. Transmitter (TX):

- **The transmitter** is responsible for converting an electrical signal into an optical signal. This transformation is carried out using a light source such as a laser or a light-emitting diode (LED).
- **Light Source** : A laser is typically used in FSO systems for its ability to generate a coherent and powerful beam, well suited for long-distance transmissions.
- **Modulation** : The electrical signal is modulated to encode data onto the light beam. Common modulation techniques include amplitude-shift keying (ASK) or intensity modulation (IM). [02]

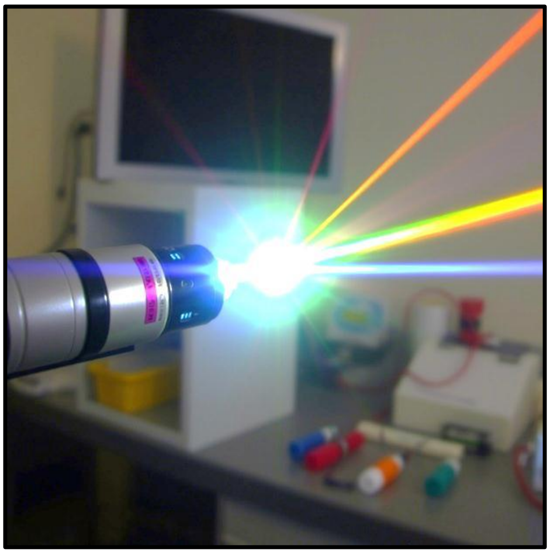


Figure I.1: Example of a light source used in an FSO (Laser) system.

I.3. Propagation channel

The optical beam emitted by the transmitter passes through the atmosphere to the receiver. However, this channel is not free from disturbances that can affect the quality of the transmission:

- **Fog:** Decreases signal intensity by absorbing some of the light.
- **Atmospheric turbulence** : Causes fluctuations in signal phase and intensity, resulting in bandwidth variations.
- **Rain or snow** : Can also attenuate the signal, although their impact is generally less significant than that of fog. [01]

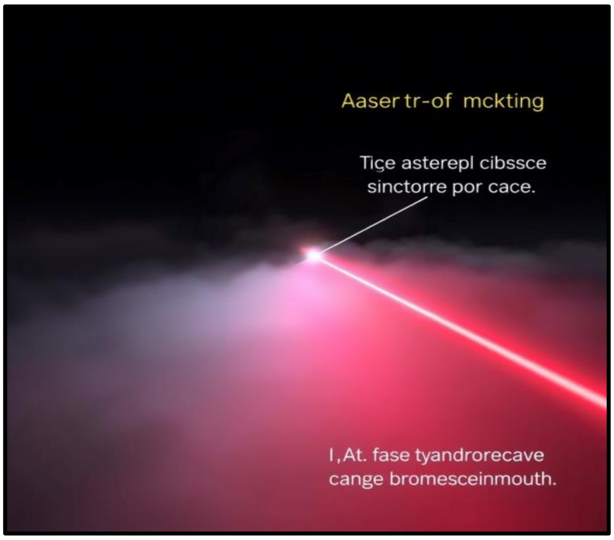


Figure I.2 : Effects of fog on optical signal propagation.

I.4. Receiver (RX)

The receiver captures the transmitted optical signal via a photodetector , which then converts the received light into an electrical signal. This process is called photo detection [01]

- **Photodetector** : Devices like photodiodes or phototransistors are commonly used to detect the light signal.
- **Demultiplexing** Once the electrical signal is recovered, it is processed to extract the transmitted data .[02]

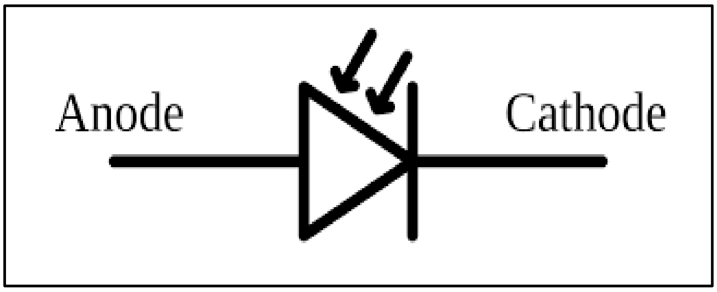


Figure I.3: Symbol of a photodiode used in an FSO receiver.

Key Requirement: Line of Sight (LOS)

To ensure reliable transmission, an FSO system requires direct visibility between the transmitter and receiver. This means that there must be no physical (trees, buildings, etc.) or atmospheric (dense fog) obstacles blocking the path of the light beam. [01]

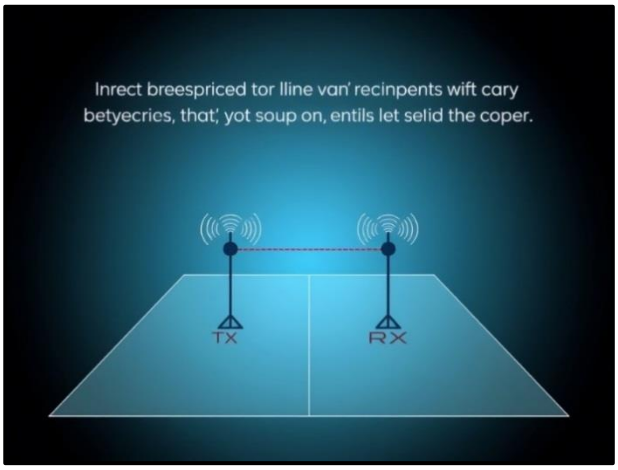


Figure I.4: Example of line-of-sight (LOS) required for an FSO system.

An FSO system enables fast, wireless data transmission using light as a signal carrier. However, its performance is highly dependent on atmospheric conditions and the presence of direct visibility between devices[02]

I.5.Key components of the FSO M system

I.5.1. Transmitter

Optical sources

Lasers: Lasers are widely used in FSO systems for long distance transmissions due to their ability to provide high data rates and a coherent beam with a wide bandwidth. [03]To illustrate the nature of the laser beam used [04].

Figure I.5: Example of laser beam used in FSO systems

Common types of diode lasers include : Fabry- Perot (FP) lasers, Distributed - Feedback Lasers (DF), and Vertical Cavity Surface Emitting Lasers (VCSELs). These lasers offer significant advantages over LEDs , such as better spectral stability and higher output power. [01]

LEDs :

LEDs (Light Emitting Diodes) are indeed an interesting option for free space optical communication systems (FSO, Free Space Optics), although they have some performance limitations. Here is a summary of the key aspects related to their use: [02]

Advantages of LEDs in FSO systems:

- Low cost: LEDs are cost-effective compared to lasers or other advanced light sources, making them an attractive solution for limited budgets.
- Ease of integration: They are easy to integrate and require fewer complex components for their operation, thus simplifying installation and maintenance. [03]
- Reduced energy consumption: LEDs consume relatively little energy, which is beneficial for applications where power supply is limited. [04]

Limitations of LEDs in FSO systems:

1. Limited Power: Compared to lasers, LEDs have lower transmit power, which limits their effective range for long-distance transmissions.

- Reduced directionality: LEDs diffuse light at a wide angle, which reduces the signal intensity received by the remote detector. This can lead to a degradation of the Bit Error Rate (BER) . [05]

- Moderate modulation speed: Although modern high-speed LEDs are available, they generally remain less efficient than lasers in terms of high modulation frequencies, which limits data throughput. [1]

Context of use:

LEDs can be successfully used in the following scenarios:

- Short distances: For example, in indoor environments or for connections between nearby buildings. [2]
- Non-critical applications: Where average signal quality is acceptable and cost is a major factor. [3]
- Experimental or educational systems: In research or learning projects where extreme performance is not required. [4]

Although LEDs are not ideal for all FSO applications, they remain a viable solution for specific cases where the trade-off between cost, simplicity and performance is essential.

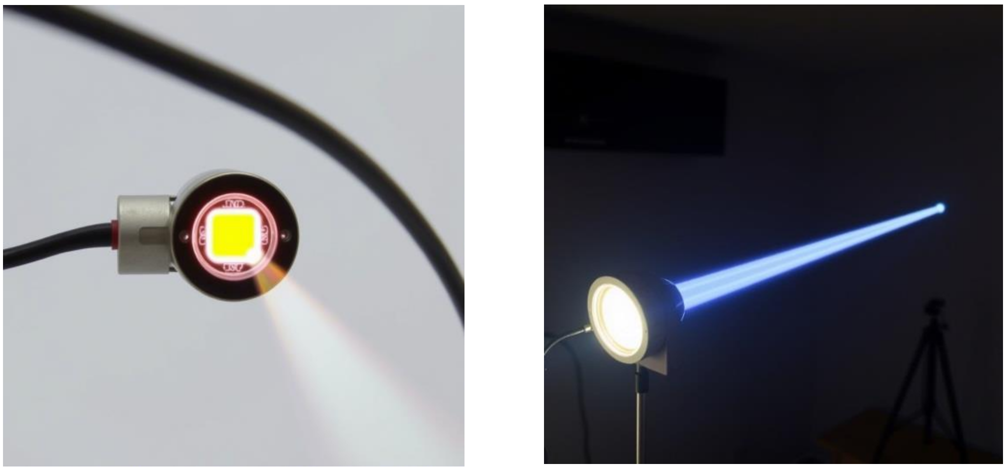


Figure I.6: Example of using an LED in an FSO system

Modulation

Intensity Modulation (IM): This method involves directly varying the current applied to the light source in order to digitally encode the data. It is simple to implement and commonly used in FSO applications. The relationship between injected current and light intensity is shown in Figure 1.4.

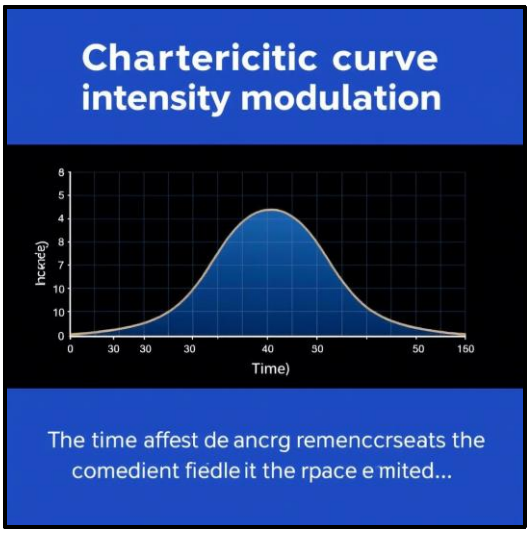


Figure I.7: Characteristic curve showing intensity modulation

External modulation

External modulation, as described in your context, is a technique used to manipulate the properties of a light signal (such as amplitude, phase, or frequency) after it has been generated by an optical source, usually a laser. Unlike direct modulation, where the signal is modified directly within the light source (e.g., by adjusting the current injected into a laser diode), external modulation involves the use of specific devices placed downstream of the light generator. [1]

Zehnder interferometer

A common example of an external modulator is the Mach- Zehnder interferometer (MZI). This device relies on interference principles to precisely control the phase or amplitude of the light signal. [3]Here's how it works:

- **Signal splitting** : The light beam from the laser is split into two separate paths called interferometer arms.
- **Modulation** : Each of these paths can be subjected to independent modulation (generally via a phase change induced by an electric field applied to certain materials such as lithium niobate).
- **Recombination** : The two signals are then combined at a common output. Due to the phase differences introduced in each arm, constructive or destructive interference occurs, thus controlling either the amplitude (intensity) of the outgoing signal or its phase. [4]

Advantages of external modulation:

- **Increased accuracy** : External modulation provides superior granularity and fidelity, which is essential in applications requiring optimal performance such as high-speed optical communications or advanced telecommunications systems. [1]
- **High bandwidth** : It supports much higher modulation frequencies than direct modulation, which is crucial for modern systems requiring very high data rates. [2]
- **Laser stability** : Because the laser is not directly modulated, it can remain stable in terms of power and wavelength, minimizing unwanted effects like noise or spectral fluctuations. [3]

Applications:

- Optical telecommunications: To transmit digital data over long distances with minimal distortion. [4]
- Measurement systems: In high-precision instruments requiring fine manipulation of light, such as in optical sensors or quantum measurements.
- Imaging and spectroscopy: Where highly controlled variations in phase or amplitude can improve the quality of the images or spectra obtained.

The use of an external modulator, such as a Mach- Zehnder interferometer , represents an elegant solution to achieve levels of control and precision that are difficult to achieve with direct modulation techniques. Although it may require more complex and expensive components, it remains essential in many technological fields where performance and reliability are paramount.

For better visual understanding, ***the mentioned Figure 1.5*** should clearly illustrate the schematic of this interferometer and its role in the modulation process.

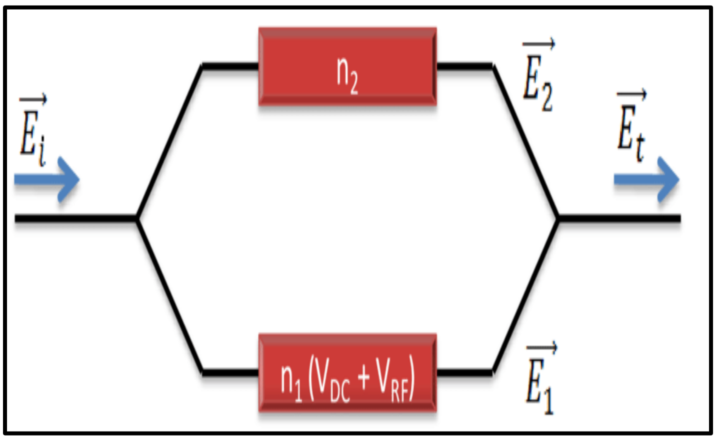


Figure I.8: Functional diagram of an external Mach- Zehnder modulator

Wavelengths:

Wavelength selection is a fundamental aspect in optical communication systems, especially for free space links . Optics - FSO) or fiber optic telecommunications. As mentioned, certain wavelength ranges are preferred because they minimize the harmful effects of the atmosphere, such as absorption and scattering, thus allowing for more efficient data transmission. [1]

Optimal Atmospheric Windows

1. Range 780–850 nm

This wavelength range is in the near-visible infrared region and is often used for applications where the size of optical components can be reduced while maintaining good performance.

The advantages:

- **Low atmospheric absorption** : This range avoids absorption peaks due to water (H_2O) , which is crucial for transmissions through air. [2]
- **Compatibility with silicon detectors** : Silicon (Si)-based detectors are very sensitive in this range, which facilitates their integration into receiving systems. [3]

Typical applications:

- Short-range optical communications.
- Remote control and measurement systems.

2. Range of 1520–1600 nm:

This range corresponds to the C and L band of the infrared spectrum, widely used in modern telecommunications.

The advantages

- **Very Low Atmospheric Absorption :** This range benefits from minimal absorption by water and other atmospheric gases, making it ideal for long-distance transmissions. [4]
- **Fiber Optic Compatibility:** Conventional fiber optics have minimal loss in this range, making them the standard for high-speed telecommunications networks.
- **Easy amplification** : Erbium-doped fiber amplifiers (EDFAs) operate efficiently in this range, compensating for losses over long distances without electronic conversion. [5]

Typical applications

- Land and submarine telecommunications networks.
- Free air links for high speed communications .

Factors Influencing Wavelength Selection

- **Atmospheric Absorption** : Some atmospheric molecules, such as water (H_2O) , carbon dioxide (CO_2) , and oxygen (O_2) , strongly absorb light in certain wavelength ranges. Therefore, it is crucial to choose ranges where these absorptions are minimal.
- **Atmospheric dispersion** : Atmospheric dispersion can cause distortion of the light signal, especially for wide bandwidth signals. The ranges around 1520–1600 nm have relatively low dispersion, which is advantageous for high-speed transmissions.
- **Available technology** : Optical components, such as lasers, detectors, and amplifiers, are designed to operate in certain specific ranges. For example, semiconductor lasers and detectors based on indium gallium arsenide (InGaAs) are commonly used in the 1520–1600 nm band.

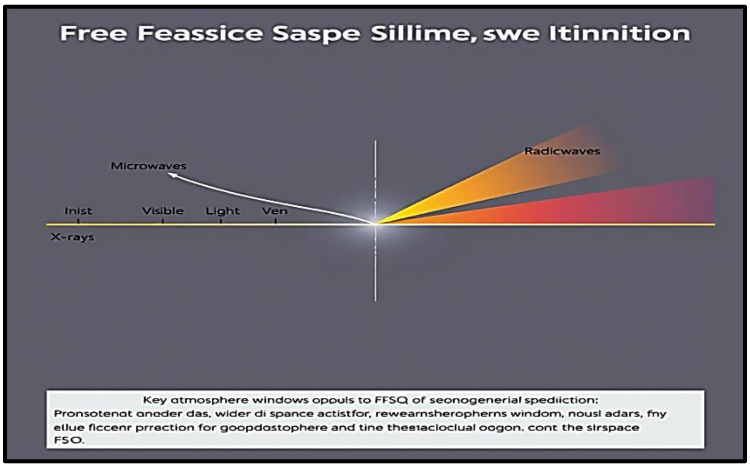


Figure I.9: Electromagnetic spectrum highlighting atmospheric windows for FSO

These elements form the technical basis of modern FSO systems, enabling fast and reliable communications without the use of traditional optical fibers.

I.6. Propagation channel

space optical communication systems. Optics - FSO). These challenges mainly include attenuation, atmospheric turbulence, and weather conditions. Here is a detailed analysis of these phenomena:

Mitigation

Attenuation is a key factor that decreases the intensity of the light signal as it passes through the atmosphere. It can have several causes:

Phenomenon	Description	Effect on FSO systems
Molecular absorption	Certain molecules in the atmosphere (eg , H_2O, CO_2, O_2) absorb light in certain wavelength ranges.	Significant loss of signal strength, particularly critical for optical communications.
Rayleigh scattering	Occurs when particles are much smaller than the wavelength of light. Mainly affects short wavelengths (visible/near IR).	Increased attenuation of signals in the visible and near infrared ranges.
Mie Diffusion	Occurs when particles are of a size comparable to the wavelength of light (e.g., mist droplets, pollution).	Dispersion of the light beam, reduction of signal intensity, impact on transmission quality.
Precipitation (Rain/Snow)	Raindrops or snowflakes that act as obstacles, absorbing and scattering light.	Moderate attenuation but variable depending on the intensity of precipitation and the size of drops or flakes
Atmospheric turbulence	Local fluctuations in air temperature and density, causing variations in the refractive index.	- Scintillation : Rapid variations in signal intensity. - Beam broadening : Beam dispersion. - Angular shift : Need for alignment correction.
Fog	Major source of attenuation, with losses of up to 100 dB/km according to the Kruse model .	Very high attenuation that makes FSO transmissions extremely difficult without advanced solutions.
Rain/Snow	Attenuation due to precipitation, although less severe than fog, remains significant.	Moderate but variable attenuation, influenced by rain/snow intensity and wavelength.

Strategies to mitigate these effects

To overcome the challenges posed by the atmosphere, several approaches can be adopted:

Choice of Wavelength

Use wavelengths within the optimal atmospheric windows (eg , 780–850 nm and 1520–1600 nm) to minimize absorption and scattering.

Advanced Modulation Techniques

Adopt robust modulation schemes (eg ., QAM, OFDM) capable of resisting the effects of turbulence and scintillations. [1]

Multi-Channel Systems

Multi-beam or multi-channel configurations to compensate for losses due to turbulence or weather conditions. [2]

Adaptive Correction

Implement adaptive optics systems to correct distortions caused by atmospheric turbulence.**Redundancy and Spatial Diversity:**

Add additional receiving antennas to exploit spatial diversity and improve system reliability. [3]

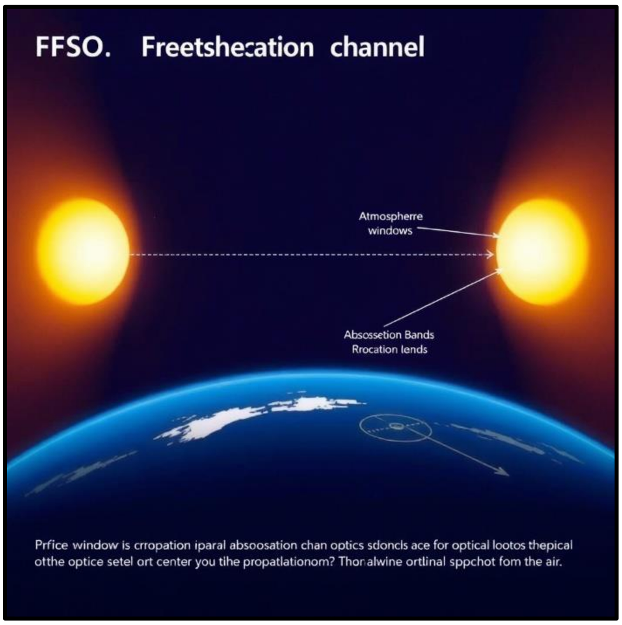


Figure I.10 : Illustration of signal processing stages

The atmospheric propagation channel presents several major challenges for free-air optical communication systems, including attenuation, atmospheric turbulence, and varying weather conditions. Each of these phenomena requires careful consideration when designing FSO systems. By combining judicious wavelength choices, advanced modulation techniques, and adaptive correction mechanisms, optimal performance can be ensured even in adverse environments.

- **Receiver**

The receiver plays a fundamental role in optical communication systems, converting the received light signal into a usable electrical signal. Among the key components of the receiver, the photodetector is essential for capturing and converting light into electrical current. Two main types of photodetectors are commonly used: PIN photodiodes and avalanche photodiodes (APDs). [1]

1. PIN photodiode

a) Operating principle

- A PIN photodiode consists of an intrinsic layer ("I") located between two doped layers respectively as anode ("P") and cathode ("N").
- When a photon hits the intrinsic region, it creates an electron-hole pair, which is then collected under the effect of the applied electric field.

b) Advantages

- **Linear Response** : The PIN photodiode offers a linear response over a wide light power range, which ensures accurate conversion of the light signal into an electrical signal. [2]
- **Low noise** : It generates less noise than avalanche photodiodes (APDs), making it ideal for applications where the signal-to-noise ratio (SNR) must be high. [3]
- **Reduced cost :** PIN photodiodes are generally less expensive than APDs, making them a cost-effective solution for systems requiring a good balance between performance and budget. [4]
- **(c) Limitations**

Limited sensitivity: Compared to APDs , the PIN photodiode has lower sensitivity, which may limit its use in applications requiring very weak signals.

d) Typical applications

- Medium-range optical communications.
- Systems where the received signal strength is relatively high.

2. Avalanche Photodiode (APD)

a) Operating principle

- An avalanche photodiode works on the principle of avalanche multiplication.
- When a photon strikes the photodiode, it creates an electron-hole pair. Under the effect of a strong internal electric field, this initial pair can cause the creation of new pairs by ionizing impact, thus amplifying the current produced.

b) Advantages

- **High sensitivity** : Thanks to the avalanche effect, the APD can detect extremely weak signals, making it ideal for long-distance or low-power systems.
- **High Gain** : The APD's internal gain allows the signal to be amplified before it is processed by subsequent circuits.

(c) Limitations

- **Increased noise:** Due to the avalanche effect, the APD generates more noise than the PIN photodiode, which can affect the signal-to-noise ratio.
- **Complexity and cost:** APDs require high bias voltages and are generally more complex and expensive to manufacture. [1]

d) Typical applications

- Long-range optical communications.

- Systems requiring ultra-sensitive detection, such as FSO (Free Space Optics).

Choice of Photodetector

The choice between a PIN photodiode and an APD depends on several factors:

1. Received signal strength

- If the received signal is relatively strong, a PIN photodiode may be sufficient.
- For very weak signals, an APD is preferable due to its high gain. [2]

2. Transmission distance:

- For short distances, a PIN photodiode is often sufficient.
- Over long distances, where attenuation is significant, an APD is usually required to compensate for low signal strength.

3. Required signal-to-noise ratio :

- If high SNR is critical, a PIN photodiode may be preferred for its low noise levels.
- In conditions where sensitivity takes precedence over noise, an APD is chosen. [3]

4. Cost and complexity:

- Systems with limited budget or simplicity constraints may opt for a PIN photodiode.
- High-end applications, requiring optimal performance, justify the use of an APD despite its higher cost. [4]

Optimization for Wavelengths:

Photodetectors must be optimized for the wavelengths used in the system. For example:

- For the 780–850 nm range, silicon (Si) detectors are commonly used because they provide excellent sensitivity in this range.
- Arsenide (InGaAs) detectors are preferred because they are sensitive to the infrared wavelengths used in modern telecommunications.

The choice of photodetector (PIN or APD) in an optical communication system is based on a compromise between sensitivity, noise, cost and performance. PIN photodiodes are ideal for applications where the received signal power is sufficient and where cost and simplicity are priorities. APDs , although more expensive and complex, are essential for detecting very weak signals, especially in long-distance or low-power systems. By combining these technologies with components adapted to the wavelengths used, the performance of optical reception systems can be maximized.

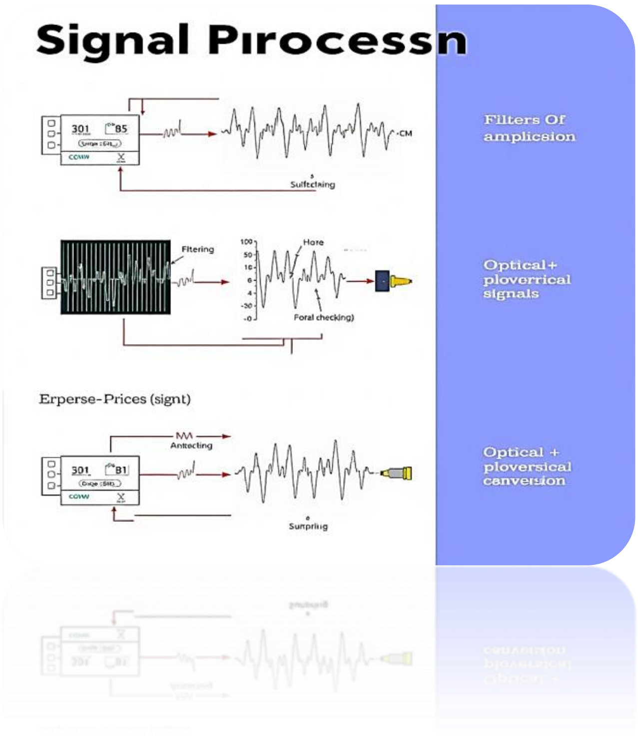


Figure 1.10: Signal processing: Filtering, amplification and optical/electrical conversion

I.7. Technical characteristics

Here is a detailed presentation of the technical characteristics and modeling of FSO channels in text and tables, based on the information provided:

I.7.1 Technical Characteristics

Free-air optical (FSO) communication systems offer varied performances depending on the technologies used, atmospheric conditions and specific requirements. [1] The main technical characteristics are summarized below:

Characteristic	Typical values	Description
Speed	1.5 Mbps to 10 Gbps	Maximum flow rate achievable depending on technology and environmental conditions.
Scope	10 m to 7.7 km	Maximum effective distance, influenced by atmospheric attenuation, turbulence and weather conditions.
Security	Class 1M (1550 nm)	Lasers emitting at 1550 nm are safe for the eyes (Class 1M), because this wavelength is absorbed before

Table 1.1: Performance of Commercial FSO Systems

Technical Details

1. Flow:

- Data rates vary from a few Mbps to several Gbps , depending on channel quality, modulation technology, and atmospheric conditions.
- Modern systems use advanced techniques such as quadrature amplitude modulation (QAM) or orthogonal frequency -division multiplexing (OFDM) to maximize throughput.

2. Scope:

- The effective range is limited by atmospheric attenuation (absorption, scattering, rain, fog) and atmospheric turbulence.
- Under ideal conditions (clear skies, low turbulence), systems can reach several kilometers.

3. Security :

Lasers emitting in the 1550 nm band are considered safe for the eyes because this wavelength is absorbed by ocular fluids before reaching the retina.

Classification: Class 1M These lasers are safe for eyes as long as they are not viewed through magnifying glasses

1.7.2. Modeling of FSO Channels:

FSO channel modeling allows predicting system performance based on physical parameters and atmospheric disturbances. The main aspects are described below:

I. 8. Geometric Attenuation:

Geometric attenuation is due to the natural divergence of the light beam as it propagates through the atmosphere. It can be modeled by the following equation:

$$Ageom = \frac{4\pi(D + z \cdot \theta)2}{4}$$

A_{geom}: Effective area of the received beam.

D : Initial beam diameter.

θ: Beam divergence angle.

z : Propagation distance.

This equation shows that the beam area increases with distance, which reduces the light power density received by the detector. Geometric attenuation is a critical factor in FSO systems because it limits the effective range of wireless optical communications. [1]

- **Scintillations**

Scintillations are rapid fluctuations in signal intensity caused by atmospheric turbulence. They can be modeled by the variance of the logarithmic amplitude (σ_I^2) :

$$\sigma L2 = 0.5 \cdot G2 \cdot Cn2 \cdot \frac{k7}{6} \cdot \frac{L11}{6}$$

C_n^2: Atmospheric turbulence parameter.

k : Wave number ($ k = \frac{2\pi}{\lambda} $).

L : Propagation distance.

This equation shows that scintillations increase with atmospheric turbulence (Cn2), wavelength (k) and propagation distance (L). Scintillations can significantly degrade signal quality in FSO systems, leading to transmission errors or data loss. [2]

- **. Channel Capacity:**

The maximum capacity of the FSO channel can be estimated by applying the Shannon-Hartley theorem:

$$C = B \cdot log2(1 + NP)$$

- *C:* Channel capacity (in bits/second).
- *B* : Channel bandwidth (in Hz).

- P : Power of the received signal (in watts).
- N : Noise power (in watts).

This equation shows that channel capacity depends directly on bandwidth and signal-to-noise ratio (NP). In FSO systems, factors such as atmospheric attenuation, scintillation, and thermal noise can reduce the NP ratio, thus limiting the maximum channel capacity. [1]

Geometric Attenuation	$A_{\text{geom}} = \frac{\pi D^2}{4} \cdot \frac{1}{(1+(\theta z)^2)}$	Reduction in received power due to beam divergence.
Scintillations	$\sigma_I^2 = 0.5 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6}$	Fluctuations in intensity due to atmospheric turbulence.
Canal Capacity	$C = B \cdot \log_2(1 + \frac{P}{N})$	Theoretical limit of the transmittable rate as a function of SNR and bandwidth.

Table 1.2: Factors Impacting FSO Channel Modeling

Conclusion:

FSO channel modeling relies on a thorough understanding of physical phenomena such as geometric attenuation, scintillation, and channel capacity. The equations provide mathematical tools to evaluate and optimize system performance based on operational conditions. By combining these models with advanced modulation and adaptive correction technologies, it is possible to design robust and high-performance FSO systems, even in adverse environments.

1.9. Advantages and limitations:

Benefits	limitations
High speed (equivalent to optical fiber)	Sensitivity to weather conditions
Fast and flexible installation	Range limited by atmospheric attenuation
No license required	Line of sight (LOS) requirement
Enhanced security (directional beam)	High cost for broadband systems

The table below summarizes the advantages and limitations of a technology probably related to very high-speed radio links, such as Free Space systems Optics (FSO) or some advanced wireless transmission solutions. Here is a more detailed analysis:

Benefits

1. High speed (equivalent to optical fiber)

Technologies using laser beams or signals in high frequency bands can offer speeds similar to those of optical fibers, reaching several Gbps or even Tbps . This performance is ideal for applications requiring rapid data transfer, such as high- definition streaming or metropolitan area networks. [1]

2. Quick and flexible installation

Unlike wired infrastructure, which requires significant work (digging and cabling), these systems can be installed quickly and with a simplified configuration. This flexibility makes them particularly suitable for varied environments, particularly in urban or hard-to-reach areas. [2]

3. No license required

In some cases, the frequency bands used by FSO systems do not require specific licenses, which can reduce administrative costs and speed up deployment. This is a significant advantage over traditional radio frequency technologies. . [3]

4. Enhanced security (directional beam):

Directional laser or radio frequency beams are difficult to intercept, thus providing better protection against unauthorized intrusions compared to conventional transmissions.

Limitations:

1. Sensitivity to weather conditions:

Atmospheric obstructions such as rain, fog, or dust can disrupt or weaken the signal, leading to potential service interruptions.

2. Range limited by atmospheric attenuation :

The maximum transmission distance is often restricted due to signal dispersion and absorption in the air, making this solution less suitable for long-distance links.

3. Need for direct visibility (LOS - Line of Sight):

A direct, unobstructed connection between the two points is required. This can be problematic in complex urban or mountainous environments where buildings or topography block the signal.

4. High cost for broadband systems:

Although initial installation is quick, the equipment needed to achieve high flow rates can be expensive, making this solution less accessible for some budgets.

This technology offers significant advantages in terms of performance and speed of installation, but its technical and environmental limitations must be taken into account during its deployment. It is particularly well suited to scenarios where fast and secure connectivity is required over short distances, in areas free from major physical and climatic obstacles. 1]

1.10. Applications of Free Space Systems Optics (FSO)

Space) systems Optics), based on data transmission via laser beams in free space, find a wide range of applications in various fields. Here is a more detailed description of the main uses.[2]

1. Urban networks

- **Building interconnection** : Enables the creation of fast and secure communication links between neighboring buildings, for example to connect offices, shopping centers or university campuses.
- **Extension of existing networks** : Effectively complement fiber optic infrastructures when laying cables is difficult or expensive.
- **Mobile access points** : Used to provide Wi-Fi or 5G connections in specific areas, such as public events or tourist areas.

2. Emergency connections

- **Temporary replacement of damaged fibers** : In the event of cable cuts or failed infrastructure, FSO systems can quickly establish temporary connections to restore essential services.
- **Rapid restoration of communications** : Ideal for situations following natural disasters, helping to maintain the continuity of critical operations.
- **Emergency networks** : Support real-time health, public safety, and emergency management applications. .[3]

3. Military communications

- **Secure transmission in complex terrain** : Thanks to their low probability of interception and their resistance to intrusions, FSO systems are ideal for military missions requiring reliable and confidential links.
- **Tactical Communication** : Used to link bases, vehicles and forward positions in hostile terrain.
- **Embedded systems** : Integrated into drones, armored vehicles or command stations for instant and robust communications. .[4]

4. Spatial connections

- **Satellite-to-satellite communication** : Enables rapid data exchange between satellites, improving the performance of space networks and satellite constellations.
- **Space-based Internet access** : Used to provide telecommunications and high-speed Internet access services, particularly in inaccessible areas.
- **Space exploration** : Used to establish connections between spacecraft, orbital stations and ground bases.

Other potential applications:

- **Mobile telephone stations** : To connect base station antennas (BTS) and optimize network coverage in hard-to-reach areas.
- **Smart Cities : Integration into** IoT infrastructures for centralized management of public services, such as lighting, video surveillance and transportation.
- **Industrial Projects** : Use in industrial environments for remote monitoring and maintenance of machines and equipment. .[1]

FSO systems offer remarkable flexibility and reliability, suitable for a variety of contexts, ranging from urban networks to military communications and space connections. Their ability to offer high data rates, enhanced security, and rapid installation make them an attractive solution for many applications requiring demanding performance and availability.

2. Review of 5G Networks and Perspectives for Future Generations (6G and beyond)

5G networks represent a significant advancement in telecommunications, offering speeds up to 10 times higher than 4G, ultra-low latency and increased capacity to connect a massive number of devices simultaneously. These characteristics make them an essential lever for the digital transformation of businesses and smart cities , while meeting the growing needs of the general public in terms of mobile connectivity. .[2]

However, as 5G continues to roll out globally, research is already focused on the next generation of networks: 6G. Expected for commercial deployment around 2030, 6G promises speeds up to 100 times faster than 5G, as well as near-zero latency and deep integration of technologies such as artificial intelligence (AI) and the Internet of Things (IoT). These advances will pave the way for innovative applications, particularly in the fields of connected health, autonomous vehicles and immersive environments (augmented and virtual reality).

However, these developments also pose significant challenges, particularly in terms of energy consumption and environmental impact. The design of 6G networks will need to integrate sustainable solutions to minimize their ecological footprint while maximizing their performance. .[3]

3. Positioning of FSOs in the 5G Ecosystem

a. Integration with Existing Networks

Free-space optical (FSO) communication systems play a key role in the integration of 5G and future (6G) networks. FSOs offer a complementary solution to existing infrastructure, bridging the gaps in traditional wired and wireless networks. Here are some examples:

- Optic Network ExtensionFSOs can be used to connect sites where fiber deployment is expensive or impossible, such as dense urban areas or rugged terrain. .[1]
- **5G Base Station Interconnection** : FSOs enable high-speed and secure transmissions between 5G antennas and data centers, facilitating the management of growing traffic in mobile networks. .[2]
- **Resilience to electromagnetic interference (EMI)** : Unlike radio frequency technologies, FSOs are not affected by electromagnetic disturbances, making them valuable in sensitive environments such as hospitals or military installations. .[3]

b . Key Applications (IoT , Smart Cities , etc.):

FSOs find varied applications in the 5G ecosystem, supporting initiatives such as the Internet of Things (IoT) and smart cities . Here are some examples:

Large-scale IoT : FSOs can handle the massive data streams generated by IoT sensors , especially in scenarios requiring low latency and high security. Their ability to transmit data quickly and securely makes them an ideal choice for complex.[4] IoT networks

Smart Cities : In Smart Cities , FSOs can be used to connect critical infrastructure, such as surveillance cameras, traffic management systems, and street lighting networks, while ensuring fast and reliable data transmission. These systems also help meet the growing connectivity requirements in urban environments. .[5]

Emergency communications : FSOs can provide temporary links during natural disasters or technical incidents, ensuring continuity of communications when traditional infrastructure is damaged. This capability is essential for maintaining critical operations in emergency situations. .[6]

Industrial applications : In smart factories (Industry 4.0), FSOs can be integrated to connect remote equipment or autonomous robots, improving operational efficiency and flexibility of production processes. Their speed and reliability make them a major asset for demanding industrial environments. .[7]

Conclusion:

5G networks and FSO systems are complementary technological pillars to address current and future broadband communications challenges. While 5G is already transforming industries and cities with its exceptional performance, FSOs offer a flexible, secure, and fast-to-deploy solution, ideal for strengthening existing infrastructure and supporting critical applications. As research progresses towards 6G, the integration of FSOs into the network ecosystem could become even more crucial, particularly for demanding use cases such as IoT , Smart Cities , and space communications. These combined technologies thus pave the way for a connected, sustainable, and innovative future.

Outlook for 6G and beyond

6G is expected to introduce major innovations, combining record speeds, near-zero latency and tight integration of AI and IoT technologies . However, several challenges remain, including:

- **Energy Consumption** : 6G will have to be designed to minimize its energy consumption, in order to limit its environmental impact.
- **Security and Privacy** : With increased connectivity and integration of critical systems, data security and privacy become crucial.
- **Heterogeneous Networks** : 6G will need to integrate seamlessly with previous networks (4G, 5G) and new emerging technologies, such as satellite networks and FSOs.
- **Standards and Regulations** : Global adoption of 6G will require consistent international standards and appropriate regulations.

In conclusion, 5G networks and FSOs are key elements for the transition to a hyperconnected and sustainable society. 6G, with its advanced capabilities, will offer endless opportunities, but it will require close collaboration between the public and private sectors to address the associated technical and societal challenges.

I.**11. Conclusion**

Free-space optical (FSO) systems represent an innovative solution for high-speed communications , combining the flexibility of wireless technologies with the exceptional performance of optical systems. Thanks to their ability to transmit data at high speeds over short distances, these systems offer a valuable alternative or complement to traditional infrastructures, such as optical fiber and radio frequency networks.

Although FSO systems are sensitive to atmospheric conditions, such as fog, rain, or turbulence, recent technological advances have reduced these limitations. For example, the use of advanced modulation, adaptive correction, and spatial diversity techniques has significantly improved their robustness to environmental disturbances.

These advancements position FSOs as a key technology to meet the growing demands of modern networks, particularly in the 5G ecosystem and future generations of networks, such as 6G.

The ease of deployment of FSO systems is one of their main advantages. Unlike wired infrastructures, which require significant work and investment, FSO solutions can be implemented quickly, even in hard-to-reach or densely populated environments. This characteristic makes them particularly suitable for urgent applications, such as emergency communications or temporary links during natural disasters.

In addition, the inherent security of FSO systems, thanks to their difficult-to-intercept directional beams, makes them a preferred option for sensitive applications, such as military communications, critical infrastructure or hospital environments. Their immunity to electromagnetic interference is also a major advantage in sectors where reliability and resilience are essential.

As smart cities , the Internet of Things (IoT), and Industry 4.0 continue to develop, FSO systems will play an increasingly central role. They connect critical infrastructure, manage massive data flows, and ensure fast and secure transmission in diverse environments. By integrating innovations such as artificial intelligence (AI) and machine learning, FSOs could further strengthen their role in the networks of the future, optimizing their performance and minimizing their environmental footprint.

In short, while FSO systems are not without challenges, their potential to meet the needs of modern communications is undeniable. Their unique combination of speed, security, and flexibility makes them an essential technology for the networks of the future, helping to shape an increasingly connected and sustainable world.

Chapter II

Modeling of FSO systems for 5G

II.1. Architecture of a FSO (Free Space) system Optics)

a. Description of the optical transmitter and receiver

Space) communication system Optics) relies on the use of light beams to transmit data at high speed in free space. The typical architecture of an FSO system includes a transmitter, a transmission channel (free space), and a receiver.

Here is a detailed description of the main components.

- Optical transmitter

The transmitter is responsible for converting electrical data into modulated light signals. It consists of the following elements:

- Light source (Laser or LED):

FSO systems typically use modulated infrared lasers to emit precise light beams . These lasers are preferred over LEDs because they offer high directionality and the ability to transmit data over longer distances. Modulating the laser beam allows binary information to be encoded for bidirectional (full duplex) transmission. For example, lasers often operate in the 1550 nm wavelength range, which is less susceptible to atmospheric absorption. .[1]

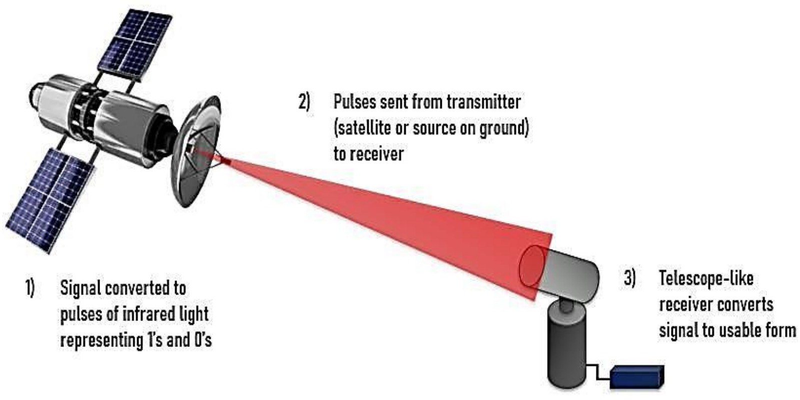


Figure II.1: Example of a laser used in an FSO Modulator system:

The modulator encodes electrical data onto the light beam. Common techniques include amplitude modulation (AM), frequency modulation (FM), or modulation (PCM). These techniques ensure that data is transmitted accurately and efficiently.

- Focusing optics:

Lenses or mirrors are used to focus the light beam towards the remote receiver. These components ensure that the beam remains collimated (parallel) over a long distance. This step is crucial to minimize signal losses due to atmospheric dispersion .[2]

- **Pointing and tracking system:**

To compensate for movement or vibration, a pointing mechanism automatically adjusts the beam direction to maintain alignment with the receiver. This system is essential to ensure stable communication, especially in environments where weather conditions can affect transmission .[1]

- **Optical receiver**

The receiver captures the transmitted light beam and converts it into electrical data. Its main components include:

- Photodetector :

The photodetector (usually a PIN photodiode or APD - Avalanche Photodiode) transforms the received light signal into an electrical signal. APD photodiodes are often used for their increased sensitivity, especially in low light conditions .

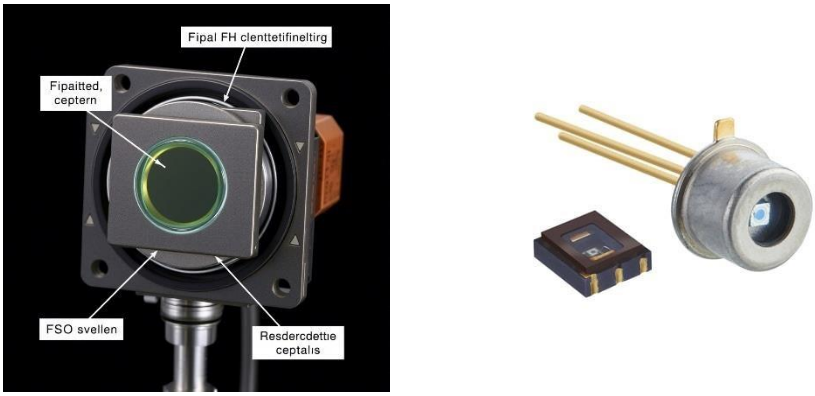


Figure II.2 : Example of a photo detector used in an FSO system

- **Amplifier :**

The electrical signal generated by the photodetector is often very weak. A low noise amplifier (LNA) is used to amplify this signal without introducing significant distortion. This ensures that the received data remains intact and accurate.[2]

- Demodulator**:**

The demodulator extracts the original data from the modulated signal. Demodulation techniques depend on the type of modulation used in the transmitter. For example, if amplitude modulation was used, the demodulator will apply a corresponding technique to recover the data. .[3]

- **Optical filtering:**

Optical filters are used to eliminate stray light interference (such as ambient or sunlight) to improve the quality of the received signal. These filters play a crucial role in urban environments where light pollution can be significant. .[1]

b . Use of lasers, detectors and optical components

- **Lasers**

Lasers play a central role in FSO systems due to their unique properties:

- High directivity: Lasers produce very narrow beams, which reduces transmission losses.
- High bandwidth: Lasers allow very high data rates (up to several Gbps).
- Common wavelength ranges:
- 780–900 nm: Near infrared band, often used for short distance applications.
- 1550 nm: Band used for longer transmissions, as it is less sensitive to atmospheric absorption.

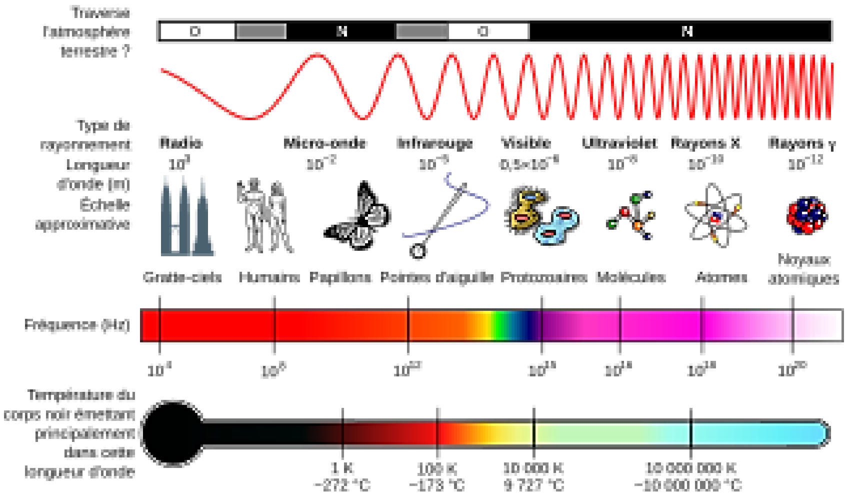


Figure II.3 : Spectrum of wavelengths used in FSO systems

- **Detectors**

Detectors play a crucial role in receiving optical signals:

- PIN photodiodes:

Used for short-range applications, they offer a good compromise between cost and performance.

- APD photodiodes:

Provide increased sensitivity due to the avalanche effect, making them ideal for long-distance transmissions or in adverse weather conditions .[2]

- **Optical components**

Optical components ensure the manipulation and focusing of light beams:

- **Lenses and mirrors:**

Focus and direct the light beam to minimize losses.

- **Optical filters:**

Eliminate unwanted light interference.

- **Optical isolators:**

Protect lasers from stray reflections that could damage the light source.

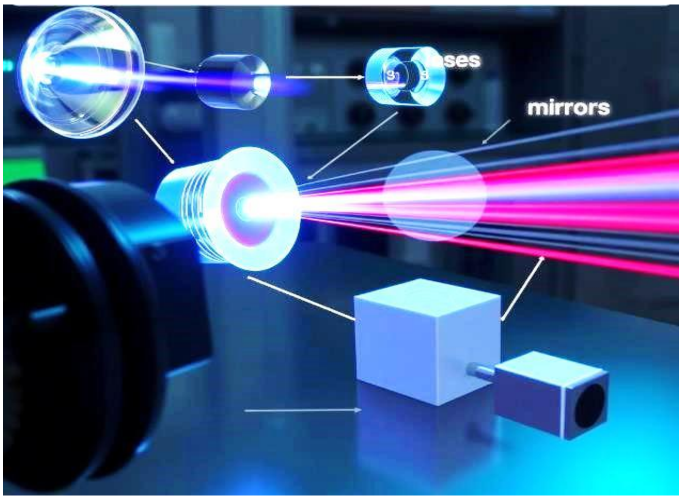


Figure II.4 : Optical components

II.2.Deepening FSO Channel Modeling with References and Illustrations

To deepen our understanding of atmospheric effects and disturbances in FSO systems, we will include detailed explanations, advanced mathematical models, additional references, and illustrations to better visualize these phenomena.

a. Atmospheric effects

1. Atmospheric turbulence

Atmospheric turbulence is one of the main challenges for FSO communications. It causes random fluctuations in the refractive index of the air, leading to distortions of the light beam. .[1]

Kolmogorov model

The Kolmogorov model describes refractive index fluctuations in the atmosphere using a power spectrum. The refractive index structure function Dn (r) is given by:

$$Dn(r) = \frac{Cn2r2^{n}}{3}$$

where Cn2 is the structure parameter of the refractive index (expressed in m−2/3), and r is the distance .

Gamma-Gamma Distribution for FSO Systems

Gamma-Gamma distribution is a key statistical model for describing light intensity fluctuations in free-space optical (**FSO**) communication systems caused by **atmospheric turbulence** . It allows capturing both **weak and strong turbulence effects simultaneously** , by combining two independent gamma processes:

- One models large-scale variations (scintillation effects).
- The other represents small-scale variations (diffraction and diffusion). .[1]

Probability density (PDF)

The PDF of the received optical intensity II is defined by:

$$p(I) = \Gamma(\alpha)\Gamma(\beta)2(\alpha\beta)(\alpha+\beta)/2I(\alpha+\beta)/2-1K\alpha-\beta(2\alpha\beta I$$

Or :

- α and β: Turbulence parameters dependent on atmospheric conditions.
- Γ(·): Euler Gamma function.
- Kν (·): Modified Bessel function of the second kind of order νν .

Parameters α and β

These parameters are linked to the physical characteristics of the FSO channel:

$$\alpha = \left[\exp\left(\frac{\left(1+\frac{1.11\sigma R12}{5}\right)7}{60.49\sigma R2}\right)-1\right]-1,$$

$$\beta = \left[\exp\left(\frac{\left(1+\frac{0.69\sigma R12}{5}\right)5}{60.51\sigma R2}\right)-1\right]-1^{n}$$

II.3. Turbulence

Applications in FSO

1. **Channel modeling** :

- Simulates signal losses due to turbulence.
- Predicts system performance in terms of **BER** or **channel capacity** .

2. **Performance analysis** :

- Calculation of the **probability of interruption** (*Outage Probability*):
- $Pout = \int 0Ithp(I)dI$
- Estimation of the **geometric mean** of the intensity:

$$\langle I \rangle = \frac{\alpha\beta}{\alpha + \beta}$$

Illustration: Scintillation due to turbulence

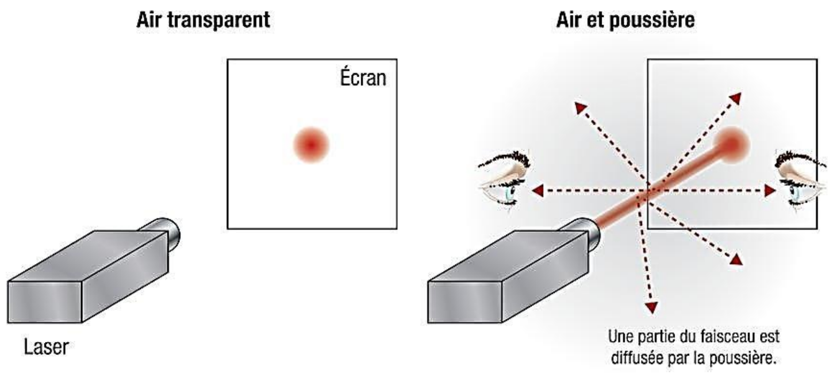


Figure II.5: Example of scintillation of a laser beam passing through a turbulent atmosphere.

II.4. Atmospheric absorption

Atmospheric absorption is highly dependent on the wavelength used. Spectral windows around 850 nm, 1550 nm, and 10 µm are often chosen to minimize losses.

Beer -Lambert 's Law

Beer -Lambert law models the power loss due to absorption : Pr =Pt .e−αd

where Pt is the transmitted power, α is the absorption coefficient (in m−1), and d is the distance of propagation.

Atmospheric absorption spectrum

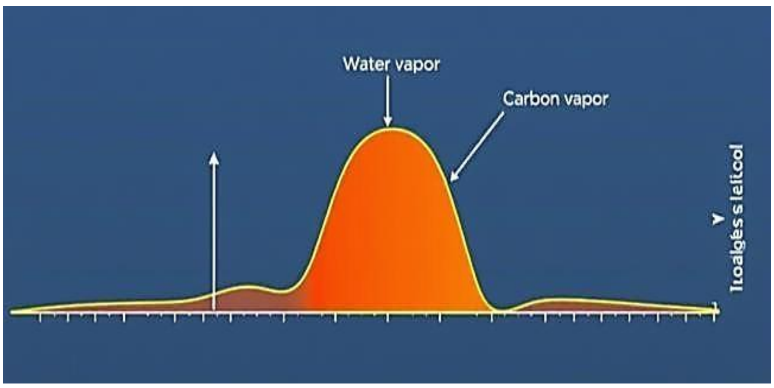


Figure II.6: Atmospheric absorption spectrum showing optimal transmission windows.

Atmospheric diffusion

Scattering can be classified into two main types: Rayleigh and Mie.

Rayleigh scattering

Rayleigh scattering is caused by particles smaller than the beam wavelength. The scattered intensity is proportional to λ−4: .[1]

$$I\ scat\ \propto \frac{1}{\lambda}4$$

Mie Diffusion

Mie scattering is caused by particles of size comparable to or larger than the wavelength. It is less dependent on wavelength.

Illustration: Atmospheric diffusion

Figure 3: Comparison between Rayleigh scattering and Mie scattering.

b. Noise and disturbance analysis

1. Thermal noise

Thermal noise is modeled as additive Gaussian noise (AWGN). The power spectral density of thermal noise is given by:

N0 = kBT

where kB is the Boltzmann constant (1.38×10−23J/K), and T is the absolute temperature in Kelvin. .[2]

SNR in an FSO system

The signal-to-noise ratio (SNR) is given by:

SNR=N0BPr

where Pr is the received power, N0 is the noise power spectral density, and B is the band passerby .

2. Solar background noise

Solar background noise can be modeled as an additive noise source. It depends on solar angle and weather conditions. [3]

Illustration: Solar background noise

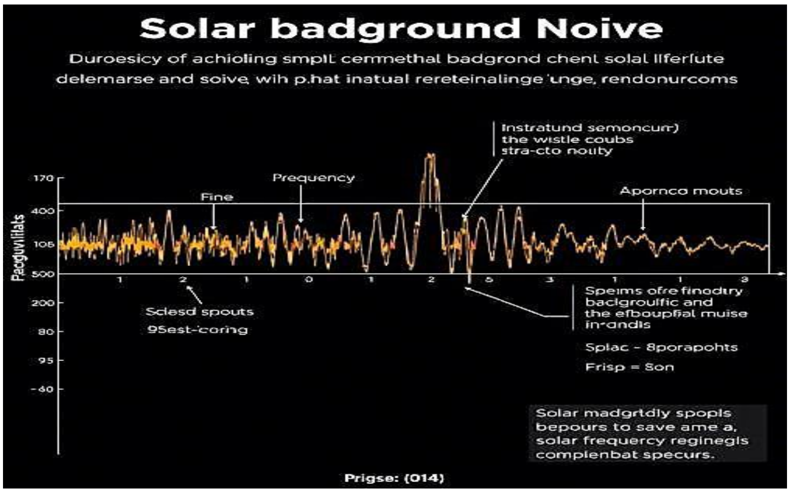


Figure II.7: Spectrum of solar background noise.

External disturbances

Artificial interference and intentional jamming can be modeled as additional noise sources. Their impact depends on the frequency and power of the interference .[1] .

Additional References

Study on the extinction of light in fog and mist.

- o Performance analysis of FSO links under Gamma-Gamma turbulence.

Atmospheric effects and disturbances play a crucial role in the performance of FSO systems. The mathematical models, illustrations, and references provided here provide a solid foundation for understanding and optimizing these systems.

II.5 Deepening Advanced Techniques to Improve FSO System Performance

In this section, we will delve deeper into the advanced techniques mentioned above (coding, modulation, OFDM, MIMO) by providing more detailed explanations, mathematical models, illustrations, and additional references.

a. Advanced Coding (QAM, QPSK, etc.) Mathematical Model of QAM

The QAM modulated signal can be expressed as follows:

$$s(t) = I(t)\cos(2\pi fct) - Q(t)\sin(2\pi fct)$$

- I(t): quadrature component "in phase" (In-Phase).
- Q(t): quadrature component "in quadrature" (Quadrature).
- fc : carrier frequency.
- cos(2π fct) and sin(2π fct): orthogonal carrier signals.

By combining these two orthogonal signals, each QAM symbol carries several bits of information.

Constellation of Points in QAM

In a QAM system, each symbol is represented by a point in the complex plane (called a constellation). The position of each point corresponds to a specific combination of amplitude and phase.

Example: 16-QAM

- In a **16- QAM system** , each symbol carries **4 bits** of information (24=16).
- The 16-QAM constellation is organized in a 4x4 grid, with 4 possible amplitude levels for I(t) and Q(t).

Here is an example constellation for 16-QAM:

Points ={ ±A,±3A}×{±A,±3A}

Each point represents a unique combination of I(t) and Q(t) values..[1]

II.6. QAM Features

1. **Spectral Efficiency** :

- QAM allows more bits to be carried per symbol than simple modulation techniques like BPSK or QPSK.
- For example, 64-QAM carries 6 bits per symbol, while 256-QAM carries 8 bits.

2. **Sensitivity to Noise** :

- As the number of QAM levels increases (e.g., from 16-QAM to 256QAM), the distance between constellation points decreases.
- This makes the system more sensitive to disturbances (noise, distortion), as it becomes more difficult to correctly distinguish the symbols.

3. **Applications** :

Wi-Fi (IEEE 802.11a/g/n/ ac / ax) uses up to 256-QAM to maximize throughput . DOCSIS (Data Over Cable Service Interface Specification) uses QAM for cable transmissions. FSO (Free Space Systems) Optics) can also use QAM to improve spectral efficiency.

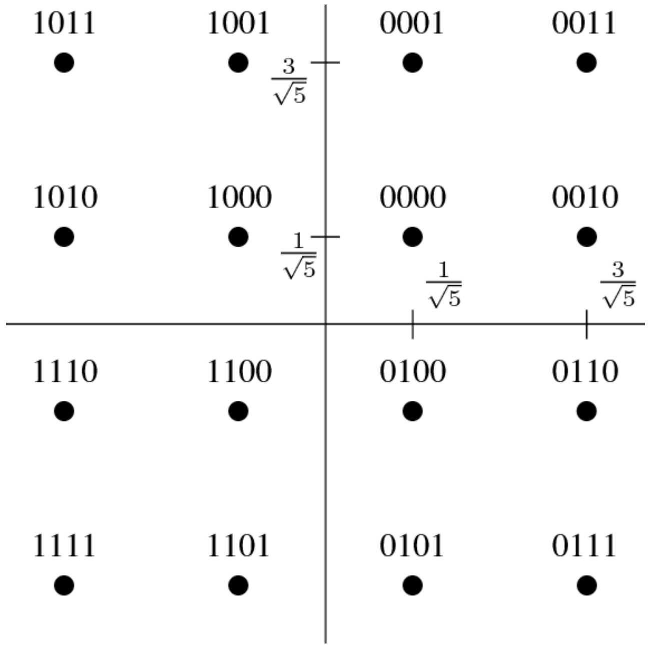


Figure II.8: 16-QAM constellation showing amplitude and phase levels.*

- **Advantages and Disadvantages**

- Advantages:
- High spectral efficiency.
- Suitable for channels with high signal-to-noise ratio (SNR).

Disadvantages:

- Sensitive to distortions due to atmospheric turbulence.
- Requires precise synchronization between transmitter and receiver. .[1]
- Detailed analysis of the performance of wireless communication systems, including the effects of QAM modulation.

- Quadrature Phase Shift Keying (QPSK)

QPSK modulation uses only two orthogonal phases to represent data. Each symbol carries 2 bits of information.

Mathematical Model

$$s(t) = \sqrt{\frac{2E}{T}[I(t)\cos(2\pi fct) - Q(t)\sin(2\pi fct)]}$$

Or :

- I(t): in-phase component.
- Q(t): quadrature component (Quadrature).
- fc : carrier frequency.
- Es: energy of the symbol.
- Ts : duration of the symbol.
- cos(2π fct) and sin(2π fct): orthogonal carrier signals

Each QPSK symbol carries **2 bits** of information, because there are 4 possible combinations of the values of I(t) and Q(t) (+1 or −1).

Illustration: Constellation QPSK

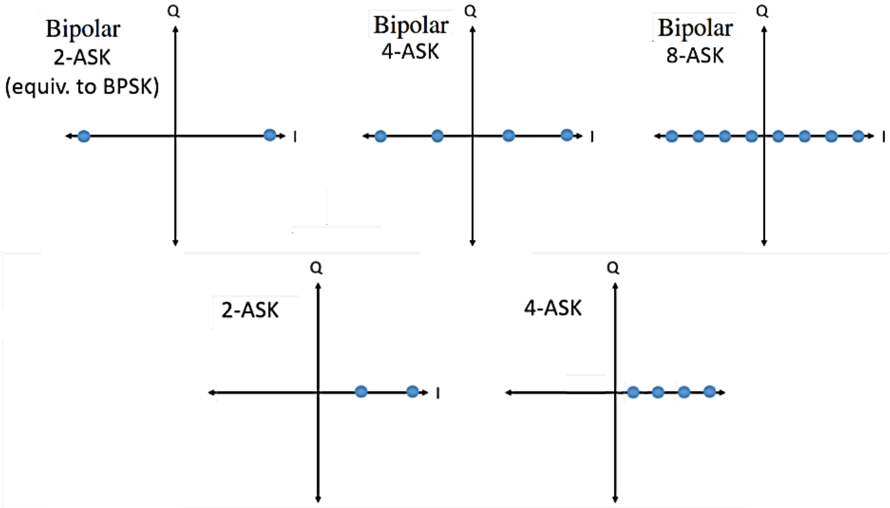


Figure II.9 : QPSK constellation showing the four possible symbols.

- **Advantages and Disadvantages**

- Benefits :

- Robust against intensity fluctuations due to turbulence.

- Less susceptible to interference than variable amplitude modulations.

- Disadvantages:

- Lower spectral efficiency than QAM.

b. Optical Modulation and Multiplexing

1. Optical modulation: OOK, PPM, DPSK

OOK (On-Off Keying)

OOK modulation is the simplest form of optical modulation, where data is represented by the presence or absence of light.

PPM (Pulse Position Modulation)

PPM modulation encodes data in the time position of light pulses.

It is particularly robust against intensity fluctuations due to turbulence. .[1]

DPSK (Differential Phase Shift Keying)

DPSK modulation encodes data in the phase difference between two consecutive symbols. It is less sensitive to intensity variations than variable amplitude modulations.

Illustration: PPM modulation

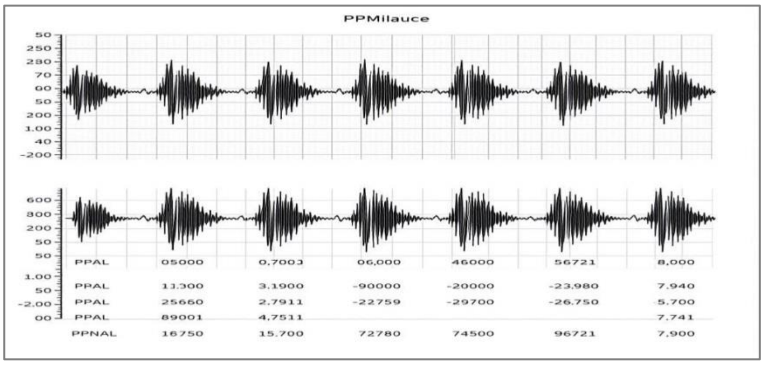


Figure II.10: Example of PPM modulation.*

- Detailed study of optical modulation techniques, including OOK and PPM.
- Performance analysis of wireless optical communication systems under different modulation conditions. .[2]

- **Multiplexing: TDM, WDM, OFDM**

TDM (Time Division Multiplexing)

Data is transmitted sequentially in distinct time slots.

WDM (Wavelength Division Multiplexing)

Multiple wavelengths are used to transmit independent data streams.

OFDM (Orthogonal Frequency Division Multiplexing)

OFDM divides the spectrum into several orthogonal subcarriers, each carrying a portion of the data.

Illustration: OFDM architecture

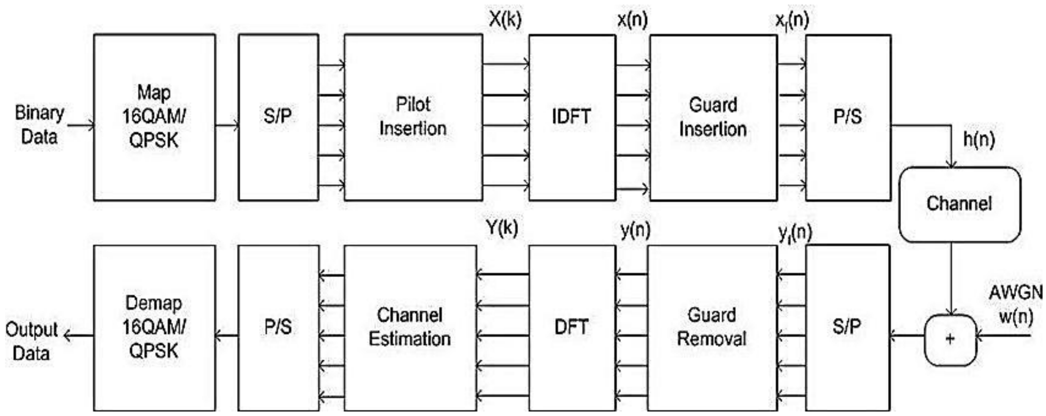


Figure II.11: Architecture of an OFDM system.*

c. OFDM and MIMO systems

1. OFDM (Orthogonal Frequency Division Multiplexing)

OFDM is particularly suitable for FSO channels affected by distortions

frequency.[1]

- **Advantages and Disadvantages**

- Advantages:
- Reduces inter-symbol interference (ISI).
- Allows simple equalization using FFT (Fast Fourier Transform) algorithms.
- Disadvantages:
- Sensitive to beam misalignment.
- Increased complexity due to Fourier transform.
- Study on the average capacity of FSO systems under turbulence.

2. **MIMO (Multiple Input Multiple Output)**

MIMO systems use multiple antennas to improve communications capacity and reliability.

Common MIMO Techniques

- STBC (Space -Time Block Coding): Encodes data across multiple antennas to improve robustness. .[1]
- Alamouti Coding : A simple spatio-temporal coding technique for two antennas.

Illustration: MIMO architecture

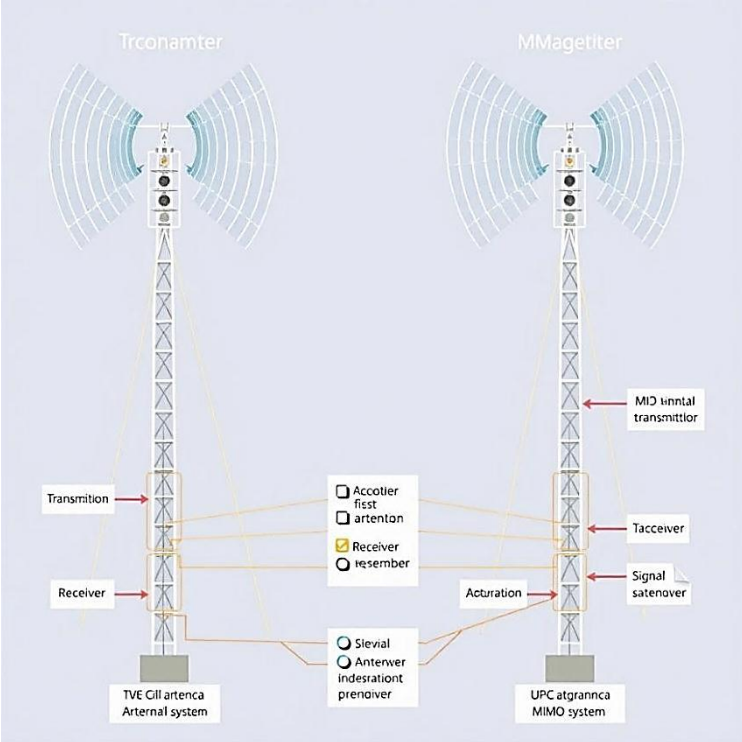


Figure II.12: Architecture of a MIMO system.*

- Introduction to spatial modulation in MIMO systems.

Advanced techniques such as QAM, QPSK, OFDM, and MIMO play a crucial role in improving the performance of FSO systems. These methods help maximize spectral efficiency, reduce errors, and enhance robustness against atmospheric disturbances.

Chapter III

Methodology and analysis tools

Introduction

In this chapter, we present the tools and methodologies used to model, analyze, and simulate wireless optical (WFO) communication systems. These tools enable validation of the performance of advanced techniques such as coding, modulation, OFDM, and MIMO under realistic conditions.

III.1. Presentation of the Tools Used

In this section, we present in detail the commonly used tools for modeling, analyzing, and simulating wireless optical (WFO) communication systems. These tools enable validation of the performance of advanced techniques such as coding, modulation, OFDM, and MIMO under realistic conditions.

OptiSystem, or BER Analyzer

OptiSystem

OptiSystem is a comprehensive simulation software for optical communication systems, developed by Optiwave . It is designed to allow users to plan, test and simulate virtually any type of optical link in the physical layer of a wide range of optical networks, from local area networks (LANs) to ultra-long distance systems. .[1]

Key aspects of OptiSystem include:

System-level simulation : It provides a realistic modeling environment for fiber optic communication systems.

Hierarchical design : It allows a structured definition of components and systems.

Extensive Component Library : It has a library of hundreds of active and passive components with customizable parameters. .[2]

Advanced Modulation Support : It supports various modulation formats such as mQAM , PAMx , DPSK, mPSK , OFDM and Probabilistic Pulse Shaping (PAS).

Performance Analysis : It enables analysis of key performance metrics such as Bit Error Rate (BER), Q-factor and Signal-to-Noise Ratio (SNR). .[3]

Visualization Tools : It offers advanced tools for visualizing optical and electrical signals, including eye diagrams, constellation diagrams, and optical spectrum analysis.

Integration Capabilities : It can integrate with other Optiwave tools (OptiSPICE , OptiInstrument , OptiGrating , OptiBPM) and even MATLAB for custom component development and co -simulation.

The uses of OptiSystem in free-space optical (FSO) communication systems are numerous and varied, making it a powerful tool for the design, simulation, and analysis of these systems. The main applications include: .[4]

Modeling and simulation of complete FSO links : OptiSystem allows to build detailed models of point-to-point FSO systems, including transmitters (lasers, LEDs , modulators), the free-space propagation channel (with models of atmospheric attenuation, turbulence, scintillation, absorption and scattering due to fog, rain, snow, etc.), and receivers (photodetectors , amplifiers, filters, demodulators). .[1]

System Performance Analysis: Engineers can use OptiSystem to evaluate crucial performance parameters such as bit error rate (BER), Q factor, and signal-to-noise ratio (SNR) based on various environmental and system design factors. .[2]

Simulation of different modulation techniques : OptiSystem supports a wide range of modulation formats used in FSO systems, including OOK (On-Off Keying), QPSK (Quadrature Phase Shift Keying), QAM (Quadrature Amplitude Modulation), and more advanced techniques like OFDM (Orthogonal Frequency Division Multiplexing). This allows comparing the effectiveness of different modulations under specific FSO conditions.

Study of the impact of atmospheric conditions : A key advantage of OptiSystem is its ability to model the influence of various weather conditions on the propagation of the FSO laser beam. Users can simulate different levels of fog, rain, atmospheric turbulence and analyze their impact on the quality of the received signal and the range of the link. .[3]

Design and Evaluation of Mitigation Techniques : OptiSystem can be used to simulate and evaluate the effectiveness of different techniques to mitigate the negative effects of atmospheric conditions, such as Multiple-Input Multiple-Output (MIMO) systems with spatial diversity, adaptive aperture techniques and forward error correction (FEC) systems.

System Parameter Optimization : Designers can perform parameter sweeps (parameter sweeps) in OptiSystem to identify optimal FSO system configurations. This includes optimizing transmit power, laser beam divergence, receiver sensitivity, and signal processing algorithms. [4]

Simulation of FSO systems for specific applications : OptiSystem is adaptable to various FSO applications, such as point-to-point communication links in urban areas, backup links for fiber optic networks, building-to-building communications, satellite-to-ground links and airborne communications.

Integration with other tools : OptiSystem can be integrated with other software such as MATLAB for further analysis or for the incorporation of custom algorithms into FSO simulations.[5]

Versatile Applications : It caters to a wide range of applications, including CATV/WDM network design, SONET/SDH ring design, FSO system simulation, and transmitter, channel, amplifier, and receiver design ..[1]

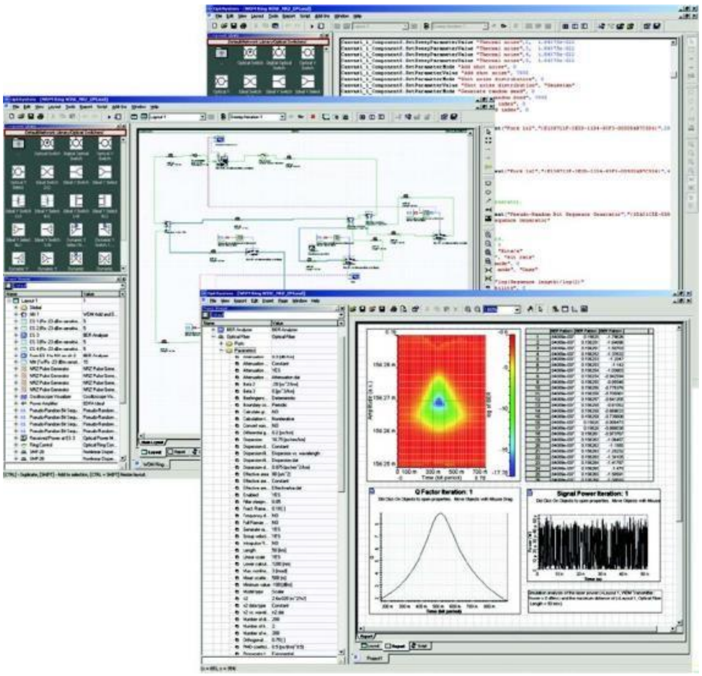


Figure III.1 OptiSystem Simulation Environment for FSO Design

- **Applications in FSO:**
- Design of FSO links with accurate atmospheric turbulence models (GammaGamma , Log-Normal).
- Performance evaluation in the presence of thermal noise, scintillation and interference.
- Optimization of system parameters such as transmitted power, wavelength and optical antenna configuration.
- **Benefits :**
- Intuitive graphical interface for designing optical systems.
- Predefined templates for atmospheric effects and optical components.
- Detailed performance reports (BER, received power, etc.).
- Example of use:

OptiSystem can be used to simulate an FSO link with PPM (Pulse Position Modulation) modulation and analyze the impact of atmospheric turbulence on BER.

- **Illustration: OptiSystem interface .**

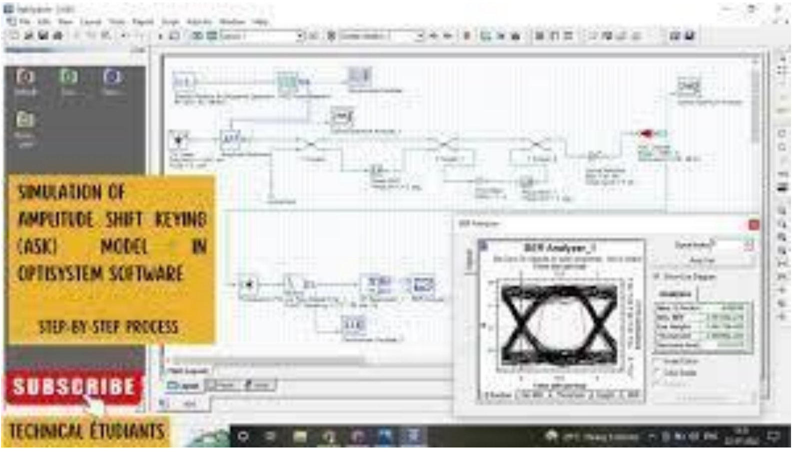


Figure III.2 OptiSystem graphical interface for FSO system simulation.*

BER Analyzer

A BER analyzer evaluates the performance of communication systems by measuring the bit error rate (BER). It can be integrated into MATLAB or used standalone.

Figure III.3 BER Analyzer Interface

- **Applications in FSO:**

- The BER analyzer accurately measures the bit error rate to evaluate the performance of communication systems with various modulations (OOK, QPSK, QAM), allowing comparison before and after error correction and validation of theoretical models by simulation. Its advantages include fast and accurate calculation, wide compatibility with different channel and modulation configurations, and easy integration with other simulation tools. .[1]

Example of use:

The BER Analyzer can be used to compare the performance of QPSK and 16-QAM modulations in an FSO channel affected by atmospheric turbulence modeled by a Gamma-Gamma distribution.

III.2. OptiSystem

OptiSystem is a software program specialized in the design and simulation of optical communication systems. It is particularly suitable for modeling optical channels and fiber optic transmission systems. [1]

Main features:

- Modeling of optical channels:
- Simulation of propagation in optical fibers.
- Taking into account the effects of dispersion, attenuation and non-linearity.
- Performance analysis:
- Calculation of bit error rate (BER) and signal-to-noise ratio (SNR).
- Evaluation of the performance of optical amplifiers (EDFA, Raman).
- Ap**plications** : WDM (Wavelength Division Multiplexing) networks, coherent optical systems. .[2]

3. NS-3 (Network Simulator 3)

NS-3 is a widely used open-source simulator for modeling communications networks, including wireless networks and cellular networks. .[3]

Main features:

- Wireless Channel Modeling:
- Wi-Fi, LTE, 5G channels.
- Taking into account propagation effects (path loss , shadowing , fading).
- Simulation of network protocols:
- MAC, TCP/IP, routing protocols.
- Analysis of network performance in terms of throughput, latency, packet loss.
- Applications: IoT networks , mobile ad hoc networks (MANET), vehicular networks (VANET). .[3]

III.3.. Methods for evaluating the performance of FSO systems:

a. Bit Error Rate (BER)

Bit error rate (BER) is a fundamental metric for evaluating the performance of communication systems, including free-space optical (FSO) communication systems. BER represents the probability that a transmitted bit is received incorrectly, and is often expressed as a ratio of the number of errored bits to the total number of transmitted bits [[2]].

In FSO systems, BER is influenced by several environmental and technical factors.

Factors influencing BER in FSO systems:

- **Atmospheric turbulence:**

Atmospheric turbulence causes fluctuations in optical signal intensity, which can lead to significant BER degradation. For example, studies have shown that FSO channels subject to strong turbulence exhibit higher error rates due to turbulence-induced fading effects .

- **Pointing errors:**

Pointing errors, or * boresight errors *, occur when the laser beam is not perfectly aligned with the receiver. These errors also contribute to increased BER, especially in FSO systems using Single Input Multiple Output (SIMO) configurations.

- **Weather conditions:**

Phenomena such as fog, rain, and clouds can attenuate the optical signal, reducing transmission quality and increasing BER. For example, one study showed that FSO systems are severely degraded in the presence of dense fog or atmospheric turbulence.

- **Modulation and coding technologies:**

The use of advanced modulation and coding techniques can improve BER. For example, polar codes have been proposed to optimize the performance of FSO systems under low to moderate turbulence conditions. Similarly, the use of avalanche detectors (APDs) in FSO systems with on-off keying (OOK) modulation has been shown to reduce BER by increasing receiver sensitivity.

Example of BER performance:

In a study of FSO systems using a wavelength of 1550 nm, a BER of \(10^{-12}\) was achieved, which is considered optimal compared to wavelengths of 850 nm and 785 nm. This performance highlights the importance of wavelength selection to minimize errors in FSO systems.

BER is a critical metric for assessing the reliability of FSO systems. A thorough analysis of environmental and technical factors helps identify strategies to minimize BER and improve the overall performance of FSO systems.

III.4.. Methods for evaluating the performance of FSO systems:

Space) systems Optics) are optical communication technologies that use visible or infrared light to transmit data wirelessly. To evaluate the performance of these systems, several methods are used. Here are the three you mention:

Bit Error Rate (BER) is a fundamental measure for assessing the quality of a data transmission in various communication systems, including Free Space Switching (FSO) systems. Optics). It quantifies the proportion of incorrectly received bits compared to the total bits sent over a communication channel. A low BER indicates good transmission quality.

1. Definition and Calculation of BER

The **Bit Error Rate (BER)** is calculated by dividing the number of errored bits (or bits received incorrectly) by the total number of bits transmitted:

BER=Number of bits in error´sTotal number of bits transmitted\ text { BER} = \frac{\ text {Number transmitted}}BER=Total number of bits transmittedNumber of bits in error´s

BER can also be expressed in exponential form (e.g., 10−610 ^{6} 10−6), which indicates that 1 bit in a million bits is in error. **Mathematical Definition of BER**

BER is defined as:

BER=Total number of bits transmittedNumber of erroneous bits

Or, in probabilistic terms:

BER= P(erroneous bit ´)

This can also be expressed in decimal or logarithmic form (in dB). For example:

- BER=10−3 means that there is 1 error for every 1000 bits transmitted.
- In dB, this corresponds to −30dB.

Calculation of BER

1. Simulation or Experimental Measurement

In a simulation or practical experiment, the BER can be calculated directly by counting bit errors:

$$Points = \{\pm 1, \pm j\}$$

BER = NtNe

Or :

- Ne: Number of bad bits (bits received incorrectly).
- Nt: Total number of bits transmitted.

Example :

- If 1000 bits are transmitted and 5 bits are received incorrectly : BER = 10005 = 0.005 or 0.5%.

2. Theoretical Formulas for Certain Modulations

For some modulation techniques, the BER can be theoretically estimated as a function of the signal-to-noise ratio (Eb /N0), where:

- Eb : Energy per bit.
- N0: Noise spectral power.

Here are some common formulas for different modulations:

a. BPSK (Binary Phase Shift Keying)

The BER for BPSK in an AWGN (Additive White Gaussian Noise) channel is given by : BERBPSK =Q(N02Eb)

where Q(x) is the complementary function of the error, defined by:

Q(x)=2π1∫x∞e−t2/2dt

b. QPSK (Quadrature Phase Shift Keying)

The BER for QPSK is the same as that of BPSK, because each symbol carries two bits, but the bit errors are independent:

BERQPSK=Q(N02Eb)

c. 16-QAM

For 16-QAM, the BER is generally higher due to the increased density of points in the constellation. The approximate formula is:

BER16-QAM≈43 .Q(5N04Eb)

d. 64-QAM

For 64-QAM, the BER is even higher:

BER64-QAM≈86 .Q(10N06Eb)

Factors Affecting BER

Several factors influence BER in a communication system:

1. **Signal/Noise Ratio (Eb /N0)** :
   - The higher Eb /N0, the better the BER.
2. **Modulation Type** :
   - More complex modulation techniques (like QAM) generally have higher BER than simpler techniques (like BPSK).
3. **Interference and Distortion** :

- External interference, linear or nonlinear distortion, and dispersion effects can increase BER.

4. **Equalization and Error Correction** :

- Techniques such as adaptive equalization or error correcting codes (eg.: FEC - Forward Error Correction) can reduce BER.

Graphical Representation of BER

BER is often plotted as a function of Eb /N0 on a semi-logarithmic curve. Here is a typical example:

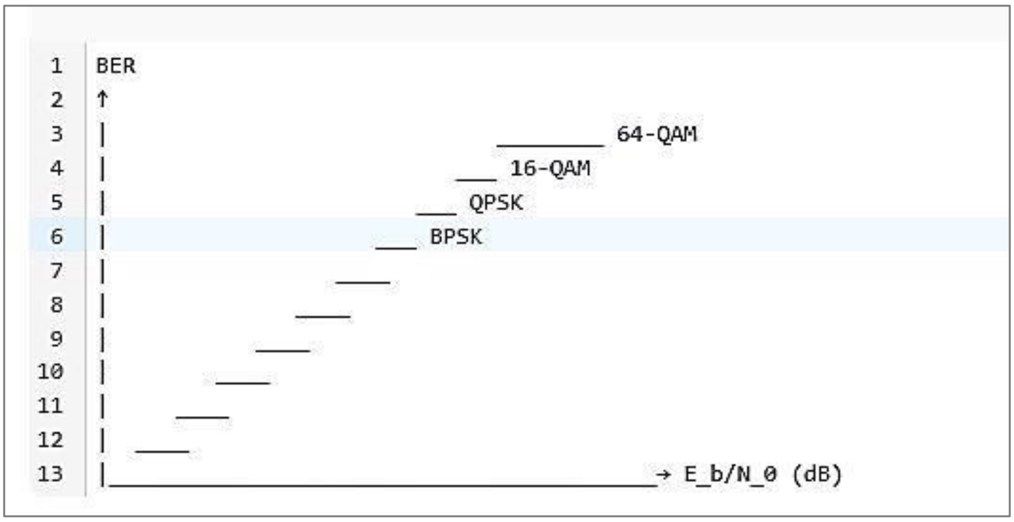


Figure III.4: BER vs Eb/N0 curve (modulation comparison)

On this curve:

- At low Eb /N0, all modulation schemes have high BER.
- At high Eb /N0, BPSK offers the best BER, followed by QPSK, then QAM modulations.

2. Factors Affecting BER in FSO Systems

In FSO systems, several factors influence BER:

- **Background noise** : Ambient light, atmospheric interference, and noise sources affect signal reception. .[1]
- **Signal Attenuation** : Absorption or scattering of light due to weather conditions such as rain, fog, or snow can decrease signal quality and increase BER.
- **Angular Misalignment** : Incorrect alignment of light beams between the transmitter and receiver can cause errors.
- **Signal distortion** : Optical signal propagation through the atmosphere can distort the light wave and create transmission errors.

- **Environmental factors** : Changes in temperature and humidity can influence optical signal propagation.

3. BER measurement

BER is often measured using simulation techniques or experimentation in a controlled environment. It can also be calculated by analyzing the signal-to-noise ratio (SNR), which has a direct relationship with BER in digital communication systems.

- **Shannon-Hartley Theorem** : It defines the maximum capacity of a communication channel as a function of the signal-to-noise ratio (SNR). This theorem is essential for understanding how BER behaves as a function of signal strength and noise. .[1]

- **FSO Communication Model** : FSO systems can use light modulation techniques to reduce errors. These techniques include phase-shift keying (PSK), amplitude-shift keying (QAM), and other forms of modulation tailored to specific optical channel conditions.

5. Practical Examples

FSO systems, such as those used for satellite-to-satellite communications or in urban environments, must maintain low BER to ensure efficient transmission. For example, in foggy conditions, an FSO system could experience a significant increase in BER due to signal attenuation.

BER is a key performance indicator for FSO communication systems. A thorough analysis of BER allows engineers to design robust and resilient systems **capable** of maintaining quality communication even in harsh environmental conditions. To ensure the reliability of an FSO system, it is necessary to keep BER as low as possible, which may involve the use of advanced modulation techniques and compensation for losses due to atmospheric conditions.

Channel capacity:

The **channel capacity** of a communication system refers to the maximum amount of information that can be transmitted over the communication channel without exceeding a certain error rate, as defined by **Shannon's theorem . In the context of Free** Space (FSO) systems Optics), this is particularly relevant because of the effects of the atmosphere on the optical signal.

Definition of Channel Capacity

Channel capacity (CC) is the maximum transmission capacity of a channel without errors, for a given bandwidth and signal-to-noise ratio. It is calculated using the following formula:$C = B \cdot log2/(1 + 2SNR)$

- CC: channel capacity in bits per second (bps),
- WW: bandwidth in hertz (Hz),
- SS: signal strength,
- NN: noise power,
- S/NS/N: signal-to-noise ratio (SNR).

Factors Affecting FSO Channel Capacity

FSO systems are particularly sensitive to various environmental factors that can affect channel capacity, including:

- **Light Attenuation** : The presence of fog, rain, or snow can significantly decrease the received signal strength, thus reducing channel capacity.
- **Atmospheric distortion** : Atmospheric turbulence can cause light signals to scatter and disperse, affecting transmission capacity.
- **Weather Conditions** : Weather conditions such as clouds, temperature changes or humidity levels can affect the transparency of the atmosphere and, therefore, the capacity of the channel.

Relationship with Signal to Noise Ratio (SNR)

Channel capacity is directly influenced by the signal-to-noise ratio (SNR). The higher the SNR, the greater the channel capacity. In FSO conditions, increasing signal strength or reducing ambient noise can increase channel capacity.

- **Increasing SNR** : Increasing signal power or using more sensitive receivers improves SNR, thereby increasing channel capacity.
- **Noise Reduction** : Reducing interference and disruption from things like light pollution, weather, or physical obstructions can improve channel quality.

Canal Capacity as a Function of Atmospheric Conditions

Channel capacity in an FSO environment depends significantly on atmospheric conditions. For example:

- **Under ideal conditions** (clear sky, no turbulence), the canal capacity can be high.
- **Under adverse conditions** (heavy fog, heavy rain), channel capacity will be significantly reduced due to signal loss.

References and Models

The calculation of the FSO channel capacity can be based on classical communication theories, but the specific conditions of optical communications must be taken into account:

- **Shannon's Theorem** : Shannon introduced the concept of channel capacity in 1948, showing that the capacity of a channel depends on the signal-to-noise ratio and the bandwidth. .[1]
- **Models for FSO** : FSO systems use models that account for optical attenuation, atmospheric turbulence, and other phenomena related to the propagation of light in air [2] .

Channel capacity in an FSO system depends on many factors, including bandwidth, signal-to-noise ratio, and environmental conditions. Due to the specifics of FSO systems, it is important to study and adapt transmission technologies to maximize channel capacity in real-world environments.

c. Reliability and latency

- **Space Systems Optics**

Reliability and **latency are two essential aspects for evaluating the performance of communication systems, including FSO systems. These two parameters have a direct influence on the quality of service, particularly** for real-time applications such as video communications, telemetry or critical data communication.

III.5.Reliability

Definition of Reliability

The reliability of a communication system represents the system's ability to maintain stable and correct transmission, despite changing environmental conditions. In the case of FSO systems, this reliability is affected by external factors such as weather, air pollution, and interference.

Factors Influencing FSO Reliability

- **Atmospheric conditions** : Rain, fog, snow, or dust can reduce optical signal quality, increasing the bit error rate (BER) and decreasing system reliability.
- **Light Interference** : Stray light sources, such as car headlights or ambient light, can also disrupt the optical signal, affecting reliability.
- **Transmitter and Receiver Alignment** : Improper alignment of light beams can cause signal loss, reducing system reliability.
- **Atmospheric turbulence** : Turbulence in the air, due to variations in temperature or pressure, can distort the light beam and affect transmission.

.Reliability Measurement

Reliability in an FSO system is often measured by the **bit error rate (BER)** , but also by the probability of failure or interruption of the connection. One can also use indices such as the **availability rate** , which indicates the percentage of time during which the system operates correctly without failure.

Reliability Measurement

III.6.Latency

1. Definition of Latency

Latency is the delay between sending a signal and receiving it. In FSO systems, this delay can vary depending on the distance between the transmitter and receiver, as well as any disturbances that affect the signal during its propagation.

2. Factors Influencing Latency

- **Distance** : The greater the distance between the transmitter and receiver, the higher the latency, because the signal has to travel a longer path.
- **Atmospheric conditions** : Atmospheric conditions, such as turbulence or humidity, can affect the propagation speed of the light signal, introducing additional delays.
- **Equipment and signal processing** : Latency can also depend on the equipment used to transmit and receive signals, as well as the modulation or coding technologies applied. Adding complex modulation or error correction processes can cause additional latency.
- **Feedback and Bi-Directional Transmission** : In FSO systems used for bi-directional or mesh communications, the feedback management process can also add to latency.

3. Impact of Latency

Latency has a crucial impact on real-time applications. For example, for video calls or video conferencing, high latency can cause audio-video synchronization delays, disrupting communication. Similarly, for online gaming or remote control applications, high latency can make interaction less responsive and less enjoyable.

- **Minimizing Latency**

Solutions to minimize latency in FSO systems include:

- **Alignment optimization** : Improved accuracy in aligning light beams can reduce losses and improve transmission speed.
- **Data compression** : Reducing the amount of data transmitted can also help reduce latency.

- **Improving communication protocols** : Using low-latency protocols and improving signal processing efficiency can also help.
- **References and Models for Reliability and Latency**
- **FSO Reliability** : The reliability of an FSO system is often modeled by equations that take into account signal attenuation, signal-to-noise ratio (SNR), and environmental effects. These models may include Markov or stochastic model approaches. .[1]
- **FSO Latency** : Latency calculations in an FSO system can be done by taking into account the speed of propagation through air and delays caused by processing equipment. Communication protocols can also add an additional latency factor. .[2]

Reliability and **latency** are two key factors that determine the quality and efficiency of an FSO system. Low latency and high reliability are crucial for real-time applications, while poor reliability or high latency can significantly degrade the user experience. Therefore, optimal management of **these** two parameters is essential for the design and operation of high-performance FSO systems that can operate efficiently in diverse environments.

III.7. Practical Study and Simulation Results

1. Introduction

In the era of 5G and the transition to future generations of wireless communication systems, the demand for ultra-high data rates, ultra-low latency, and highly secure links has led to increased attention to optical wireless technologies. Among these, Free Space Optical (FSO) communication systems offer a promising solution by leveraging the benefits of fiber-optic transmission—such as high bandwidth and immunity to electromagnetic interference—while maintaining the flexibility of wireless networks.

This practical study investigates the performance of two FSO system architectures using the simulation tool **OptiSystem**. The focus is on how system parameters such as **distance**, **atmospheric attenuation**, and **transmitter power** influence signal quality, under **ideal propagation conditions**, i.e., where **atmospheric turbulence, scattering, and absorption are neglected**.

The experiments are divided into two key simulation setups:

1. A **single-user point-to-point FSO link**, representing a basic system.
2. A **multi-user FSO system** capable of supporting up to **512 users**, representing a scalable and more realistic deployment scenario.

Each simulation scenario is analyzed using tools like **eye diagrams**, **constellation diagrams**, **Q-factor**, and **Bit Error Rate (BER)** to assess signal degradation and overall system performance.

✍ ***Note:*** *The results and observations presented in this section assume clear atmospheric conditions. Later, we will consider the impact of adverse weather conditions such as fog, rain, or dust and discuss appropriate modifications to the system architecture.*

2. Architecture 1: Single-User FSO System

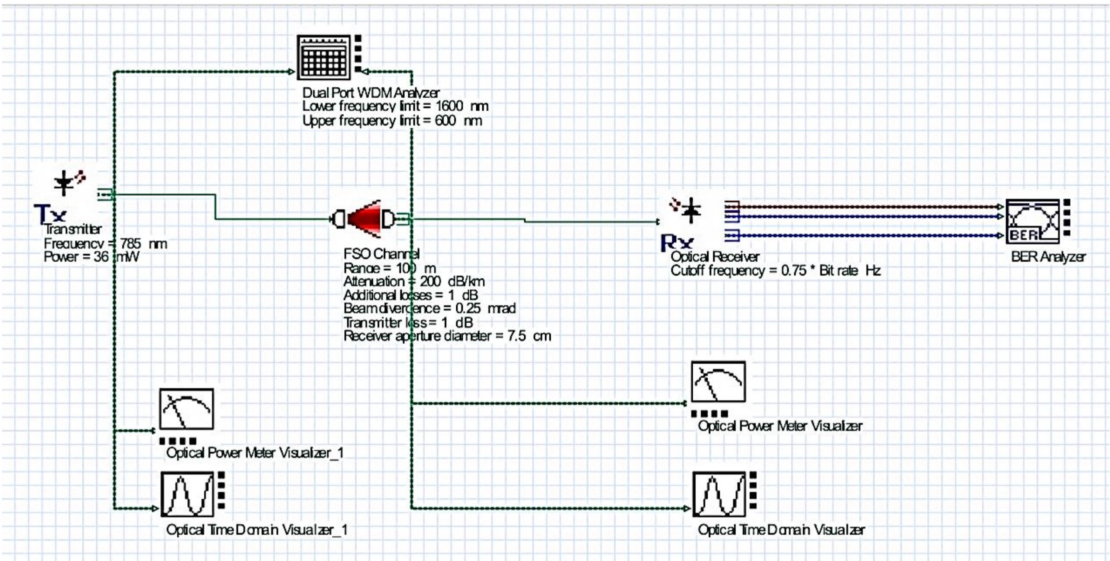


Figure III.5: Single-User FSO System Simulation Architecture

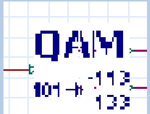
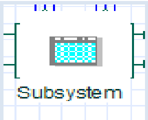
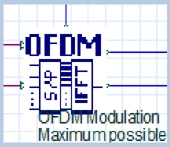
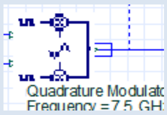
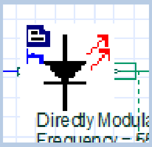
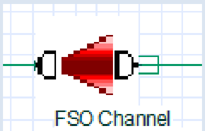
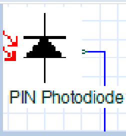
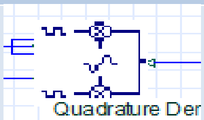
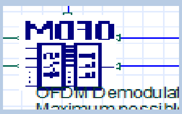
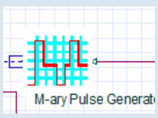
2.1 Objective and Scope

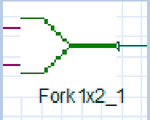
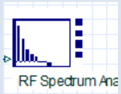
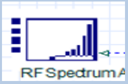
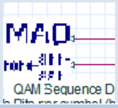
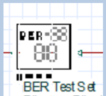
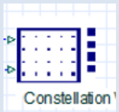
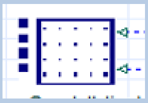
This first simulation aims to understand how a basic point-to-point FSO link reacts to changes in **transmission distance** and **atmospheric attenuation**, focusing on its effects on signal quality as observed through **eye diagrams**, **Q-factor**, and **BER**.

2.2 Simulation Setup

- **Number of users**: 1 (single transmitter and single receiver)
- **Modulation format**: QAM (default)
- **Laser Power**: Fixed
- **Attenuation values**: 50 dB/km, 100 dB/km, 150 dB/km, 200 dB/km
- **Distances**: Varied progressively for each attenuation level
- **Atmospheric effects**: **Neglected** (ideal clear-weather scenario)

- OptiSystem Architecture – Component Table

Component Name	Image	Description
QAM Sequence Generator		Generates a digital sequence modulated using Quadrature Amplitude Modulation (QAM) for encoding bits into symbols.
Subsystem		Encapsulates a sub-circuit that may contain additional components used in the processing chain.
OFDM Modulation		Applies Orthogonal Frequency Division Multiplexing (OFDM) technique by splitting the data across multiple subcarriers.
Quadrature Modulator		Modulates the input signal by combining I and Q components using a specific carrier frequency.
Directly Modulated Laser		Converts electrical signals to optical signals using direct modulation at a given wavelength and power.
FSO Channel		Simulates the Free Space Optics (FSO) channel with parameters like range and atmospheric attenuation (dB/km).
PIN Photodiode		An optical detector that converts received light into electrical current for further processing.
Quadrature Demodulator		Demodulates the received signal by extracting I and Q components using a local oscillator.
OFDM Demodulation		Performs inverse OFDM processing to retrieve the original data from multiple subcarriers.
M-ary Pulse Generator		Generates M-ary pulse sequences used for modulating data symbols in the transmission chain.

Fork		Splits the signal into two branches for parallel processing or diversity purposes.
RF Spectrum Analyzer Upper		Analyzes the RF spectrum of the modulated signal before optical conversion.
RF Spectrum Analyzer Lower		Analyzes the RF spectrum of the demodulated signal post-reception.
QAM Sequence Decoder		Decodes the received QAM signal to retrieve the transmitted bit sequence.
BER Test Set		Computes the Bit Error Rate (BER) by comparing transmitted and received bit sequences.
Constellation Visualizer 1		Displays constellation diagrams for visualizing symbol modulation quality (transmitter side).
Constellation Visualizer 2		Displays constellation diagrams on the receiver side to assess transmission distortion.

2.3 Eye Diagram Observations (Per Attenuation Level)

To visualize how signal quality degrades with distance, **eye diagrams** were analyzed for each attenuation level.

Attenuation: 50 dB/km

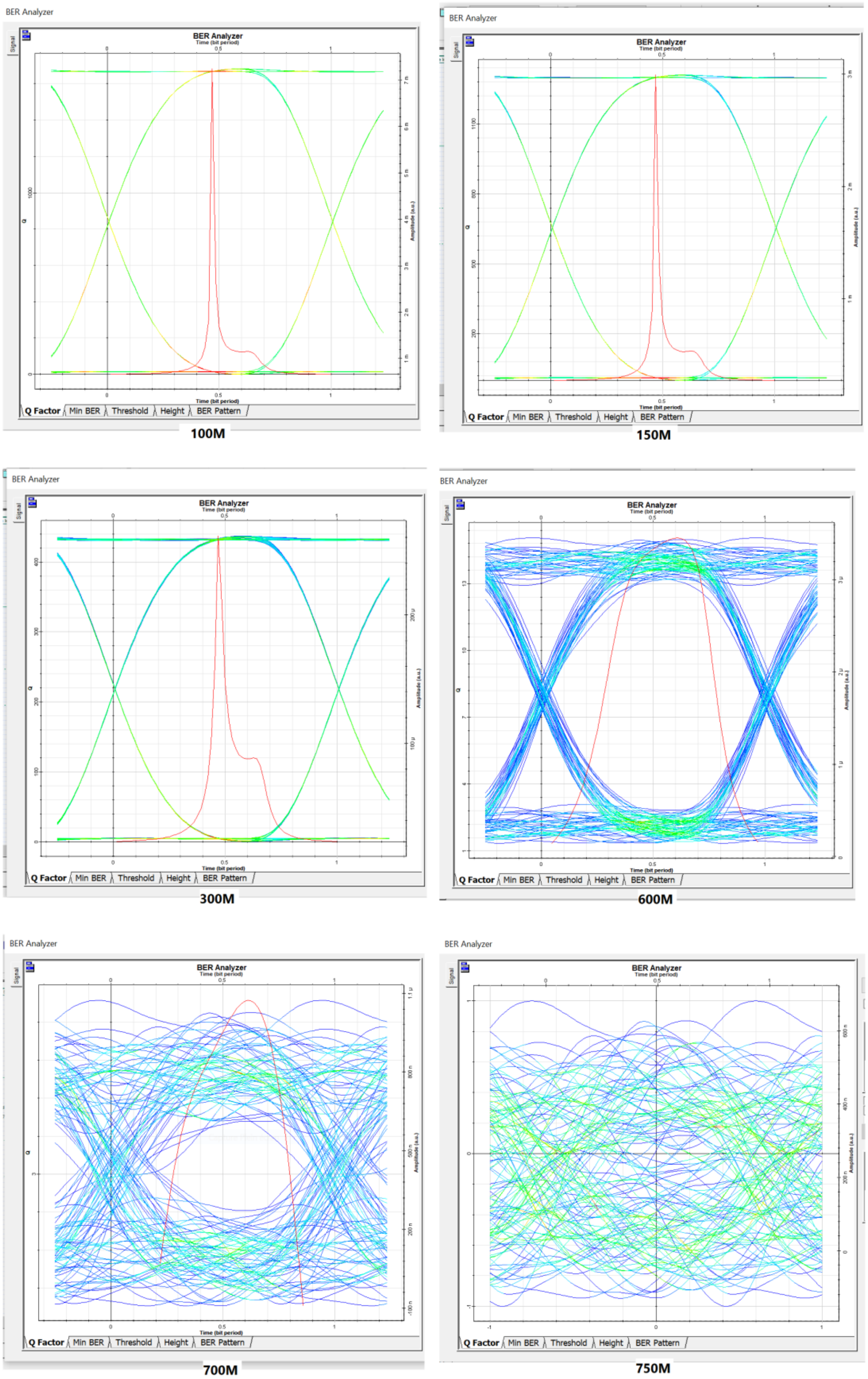
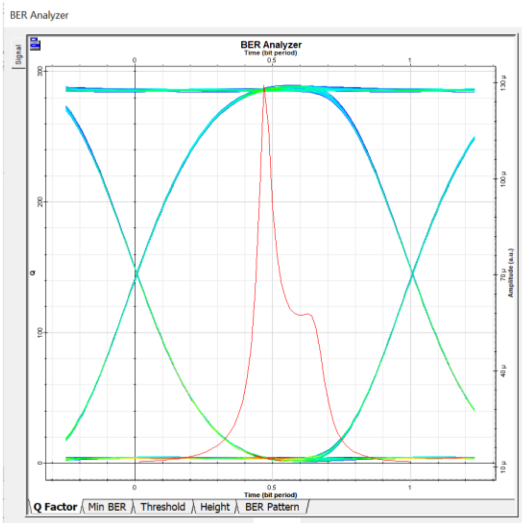


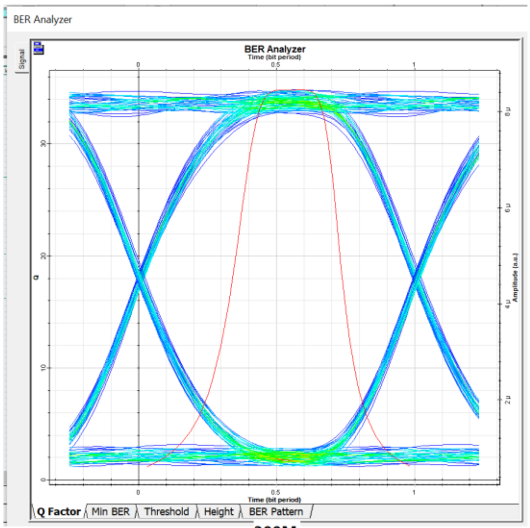
Figure III.6: Eye diagram under ideal conditions (titre proposé)

At this moderate level of attenuation, the eye diagrams remain relatively open at short to medium distances. However, as the transmission range increases, the signal begins to degrade subtly, visible in the narrowing of the eye opening and slight jitter on the crossing points. Performance is still acceptable for most practical uses.

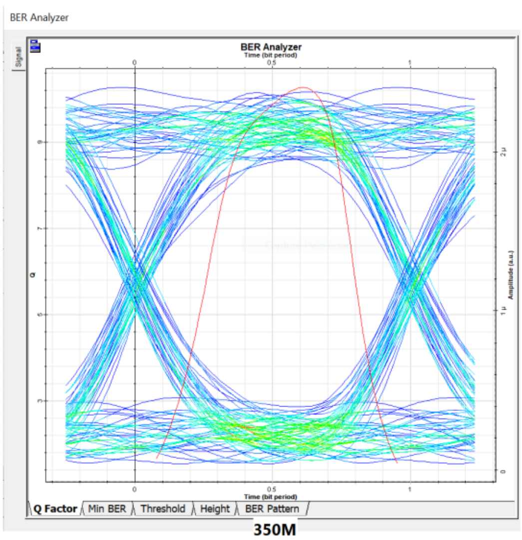
Attenuation: 100 dB/km



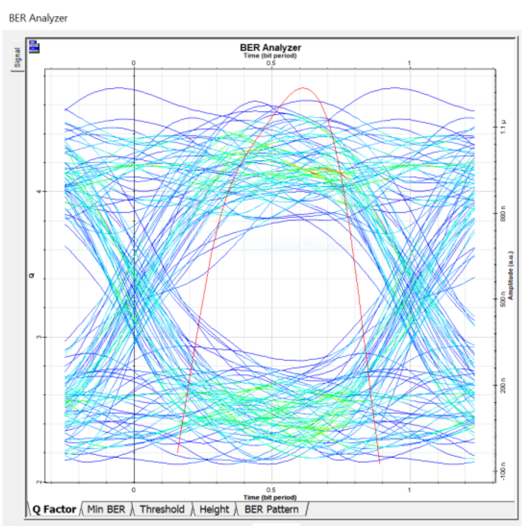
200M



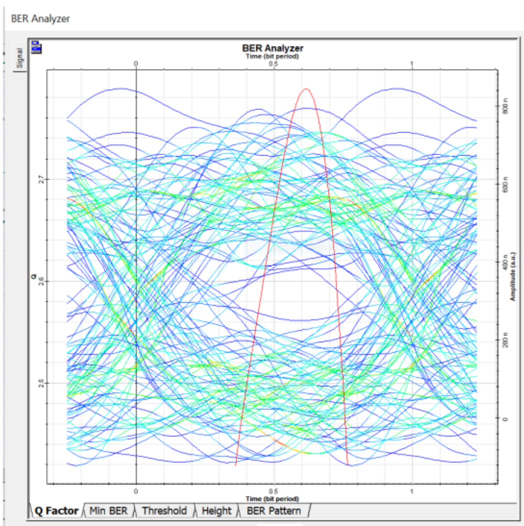
300M



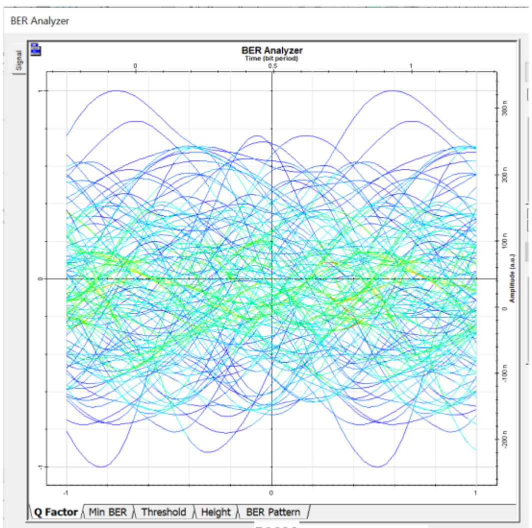
350M



380M



400M



500M

Figure III.7: Eye diagram under moderate attenuation (titre proposé)

With higher attenuation, the eye opening becomes significantly smaller even at mid-range distances. There is noticeable vertical noise, and the eye height decreases, indicating signal amplitude reduction and increased inter-symbol interference (ISI).

Attenuation: 150 dB/km

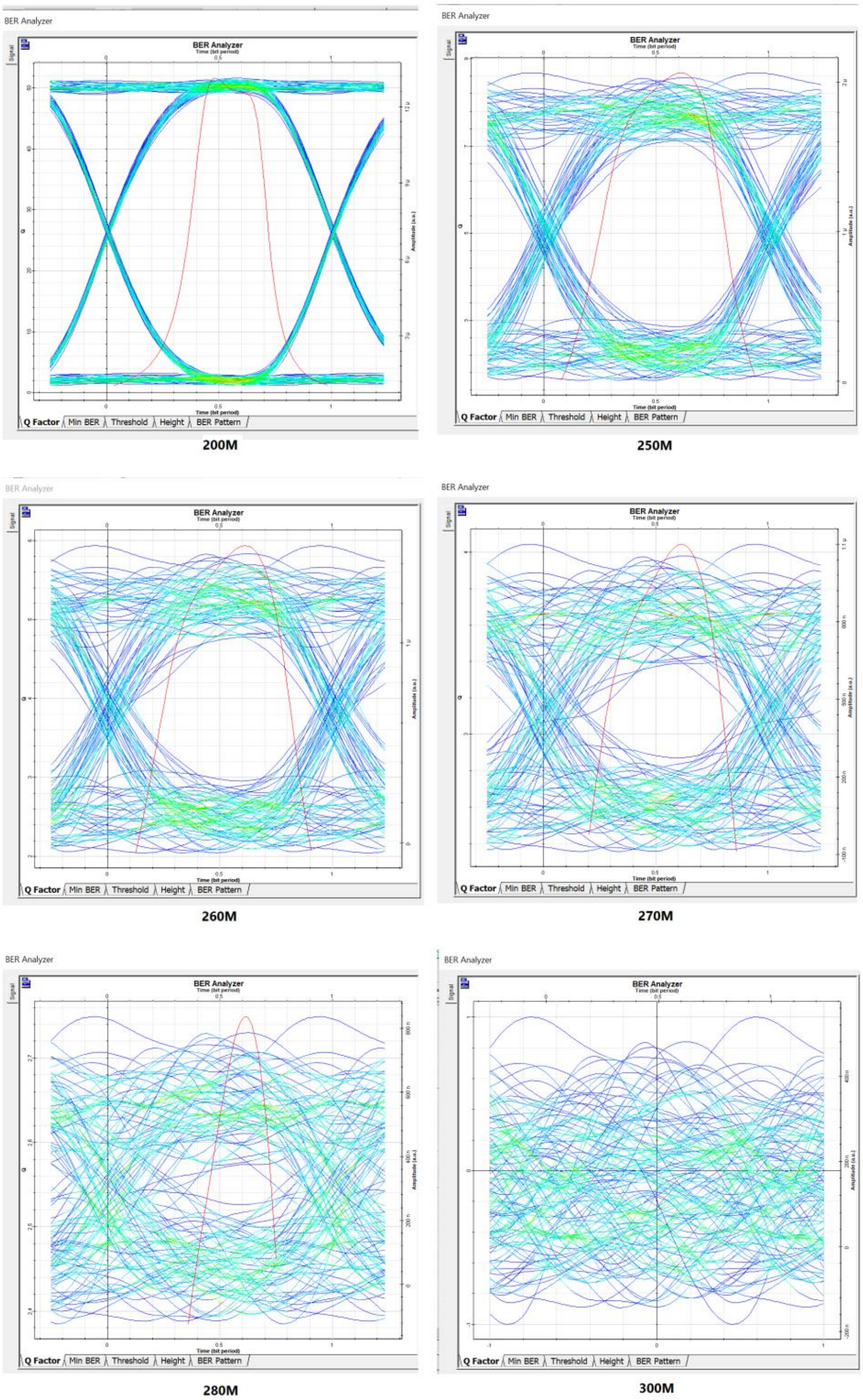


Figure III.8: Eye diagram under high attenuation (titre proposé)

Under severe attenuation, the eye diagram shows a major degradation. The signal transitions are blurred, and the eye width reduces, affecting the decision margin. Data recovery becomes challenging, especially beyond mid-range distances.

Attenuation: 200 dB/km

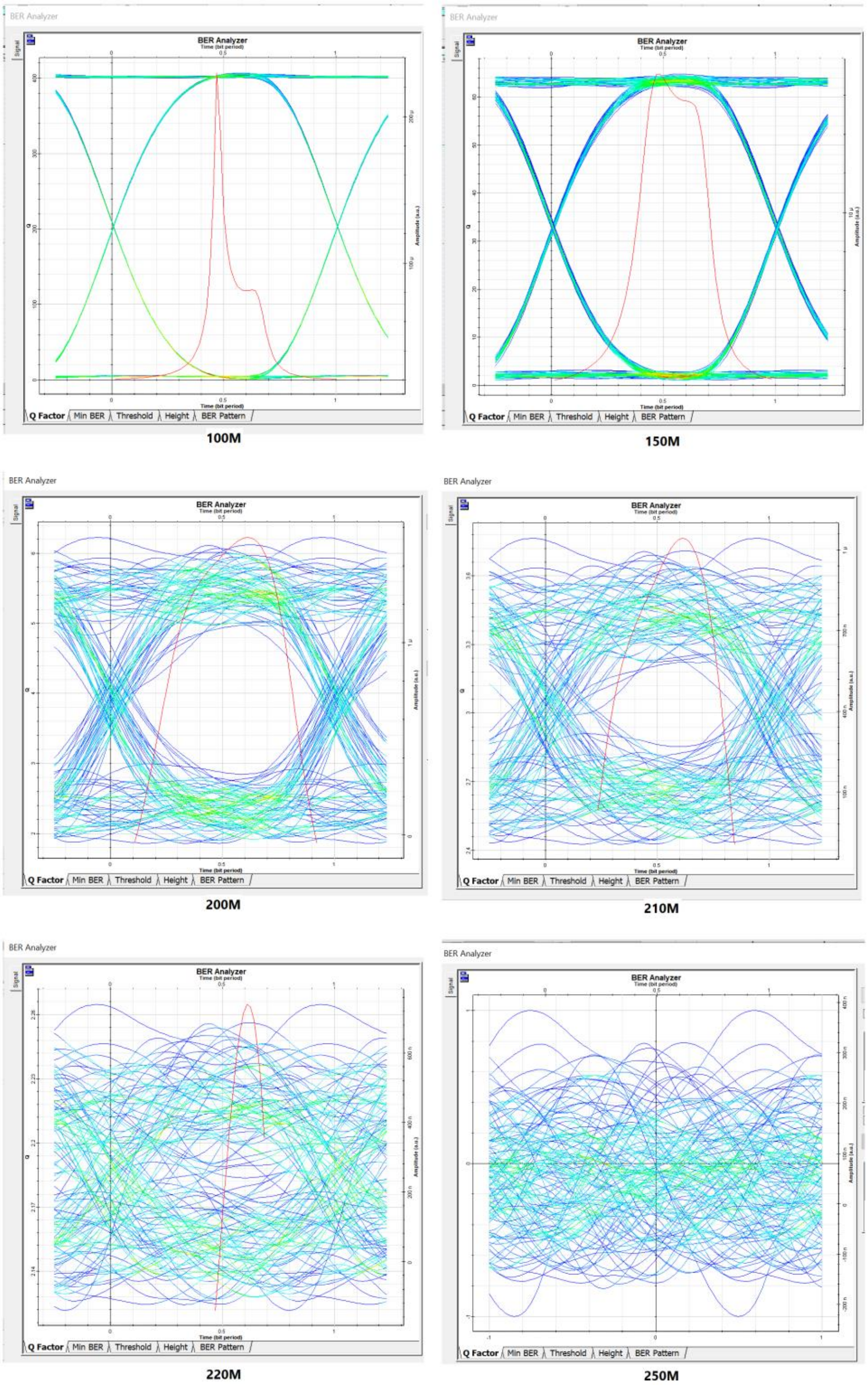


Figure III.9: : Constellation diagram with low BER (titre proposé)

The eye diagram is almost completely closed for long distances. The system becomes unreliable, with heavy noise, overlapping symbols, and a clear indication that the FSO link is no longer viable under these conditions without amplification or compensation mechanisms.

2.4 Quantitative Performance: Q-Factor and BER

In addition to visual inspection, quantitative metrics were extracted for deeper analysis.

For each attenuation level, the Q-factor and BER were calculated for a range of distances.

Attenuation: 50 dB/km

Distance (m)	Q Factor	BER
50	1978.16	0
100	1682.72	0
150	1309.73	0
300	463.899	0

Observations:

- Q-factor remains high (e.g., >1000) at distances below 100m.
- BER is virtually zero up to 150m.
- Beyond 200m, slight degradation begins to appear.

Attenuation: 100 dB/km

Distance (m)	Q Factor	BER
50	1813.78	0
100	1192.29	0
150	633.817	0
200	289.431	0
300	34.8546	1.7946×10^{-266}

Observations:

- Q-factor declines faster compared to 50 dB/km.
- BER remains low until ~150m, then starts increasing.
- At 300m, BER becomes significant, showing a steep drop in reliability.

Attenuation: 150 dB/km

Distance (m)	Q Factor	BER
50	1599.04	0
100	735.152	0
150	237.853	0
200	51.5888	0
250	8.67741	2.01661×10^{-7}
260	5.93375	1.47542×10^{-9}
280	2.74916	2.97823×10^{-3}
300	0	1

Observations:

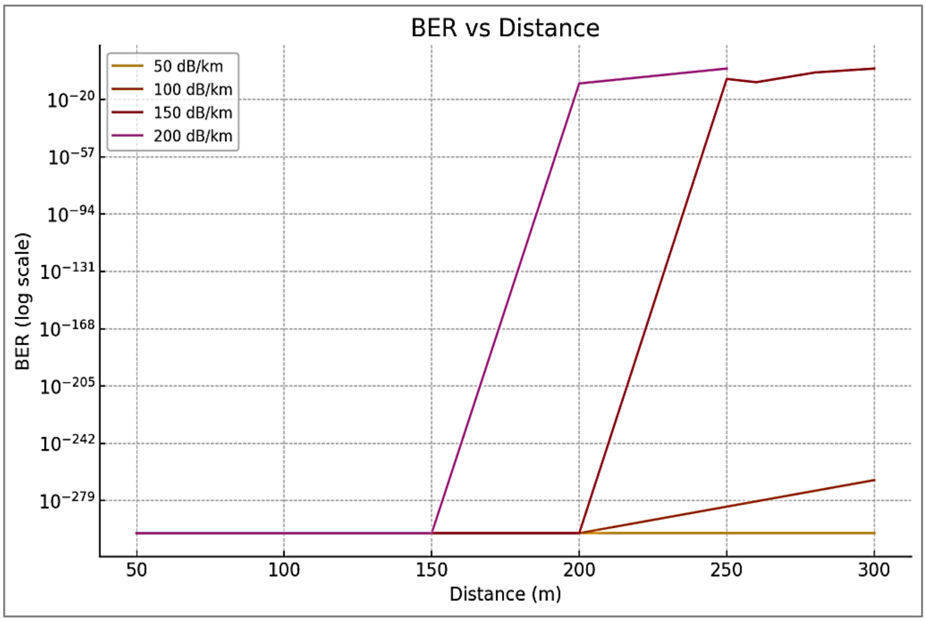
- Rapid degradation in Q-factor, even at 100m.
- BER increases substantially beyond 150m.
- Indicates system failure without compensation beyond this point.

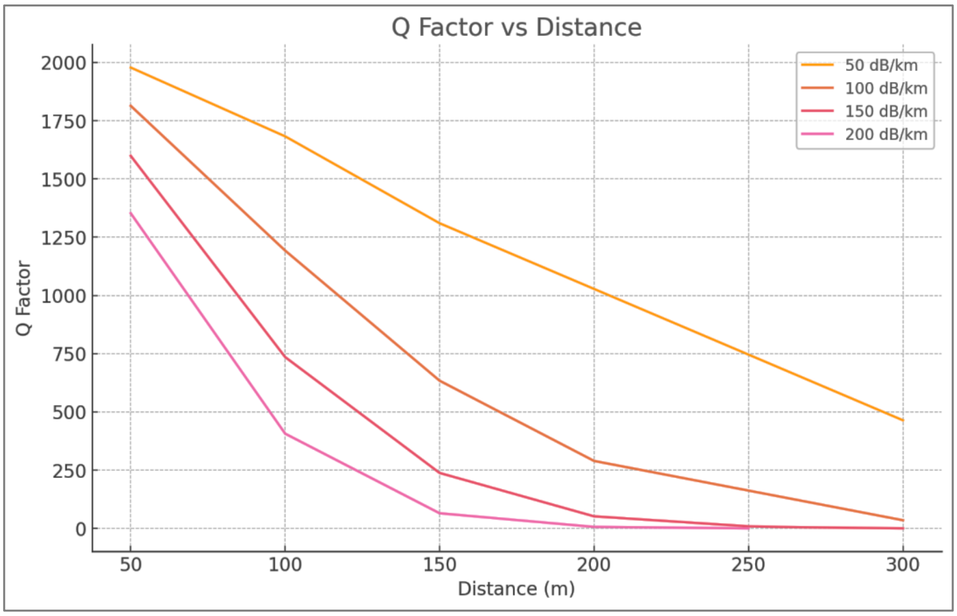
Attenuation: 200 dB/km

Distance (m)	Q Factor	BER
50	1352.6	0
100	406.467	0
150	64.7822	0
200	6.2277	2.358×10^{-10}
250	0	1

Observations:

- Q-factor is poor across all distances.
- BER exceeds acceptable limits even at short distances.
- Not practical under these conditions for this architecture.





2.5 Conclusion for Architecture 1

This experiment clearly demonstrates the fragility of a basic FSO link when exposed to high attenuation. Eye diagrams visually reflect the signal degradation, while Q-factor and BER quantify the severity. Under ideal weather, up to 100–150m communication is reliable for attenuation values up to 100 dB/km. However, higher attenuation drastically reduces performance, especially over longer distances.

3. Architecture 2: Multi-User FSO System (512 Users)

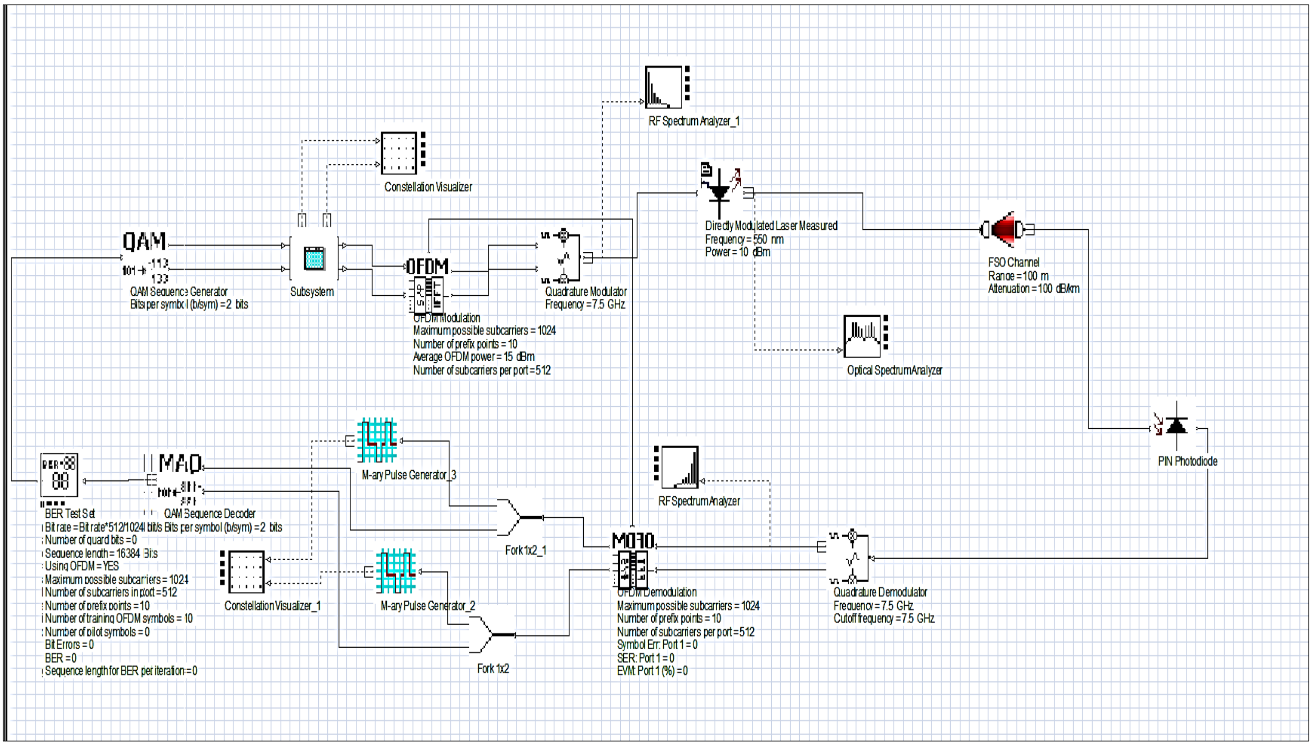


Figure III.10: Constellation diagram under degraded conditions (titre proposé)

3.1 Objective and Scope

This second simulation models a more advanced and realistic deployment scenario capable of supporting multiple users (512), and evaluates the impact of:

- Atmospheric attenuation
- Laser transmitter power
- Transmission distance

Performance is measured using **constellation diagrams**, which are crucial for assessing modulation fidelity in complex systems.

3.2 Simulation Setup

- **Number of users**: 512
- **Attenuation values**: 10, 20, 30, 40 dB/km
- **Laser Power**: Varied from -15 dBm to +15 dBm
- **Distances**: Multiple (fixed per attenuation level)
- **Modulation Format**: QAM
- **Atmosphere**: **Idealized (no fog, rain, turbulence)**

3.3 Constellation Diagrams per Attenuation Level

Constellation diagrams visually represent the symbol quality and noise effect on modulated signals.

Attenuation: 10 dB/km

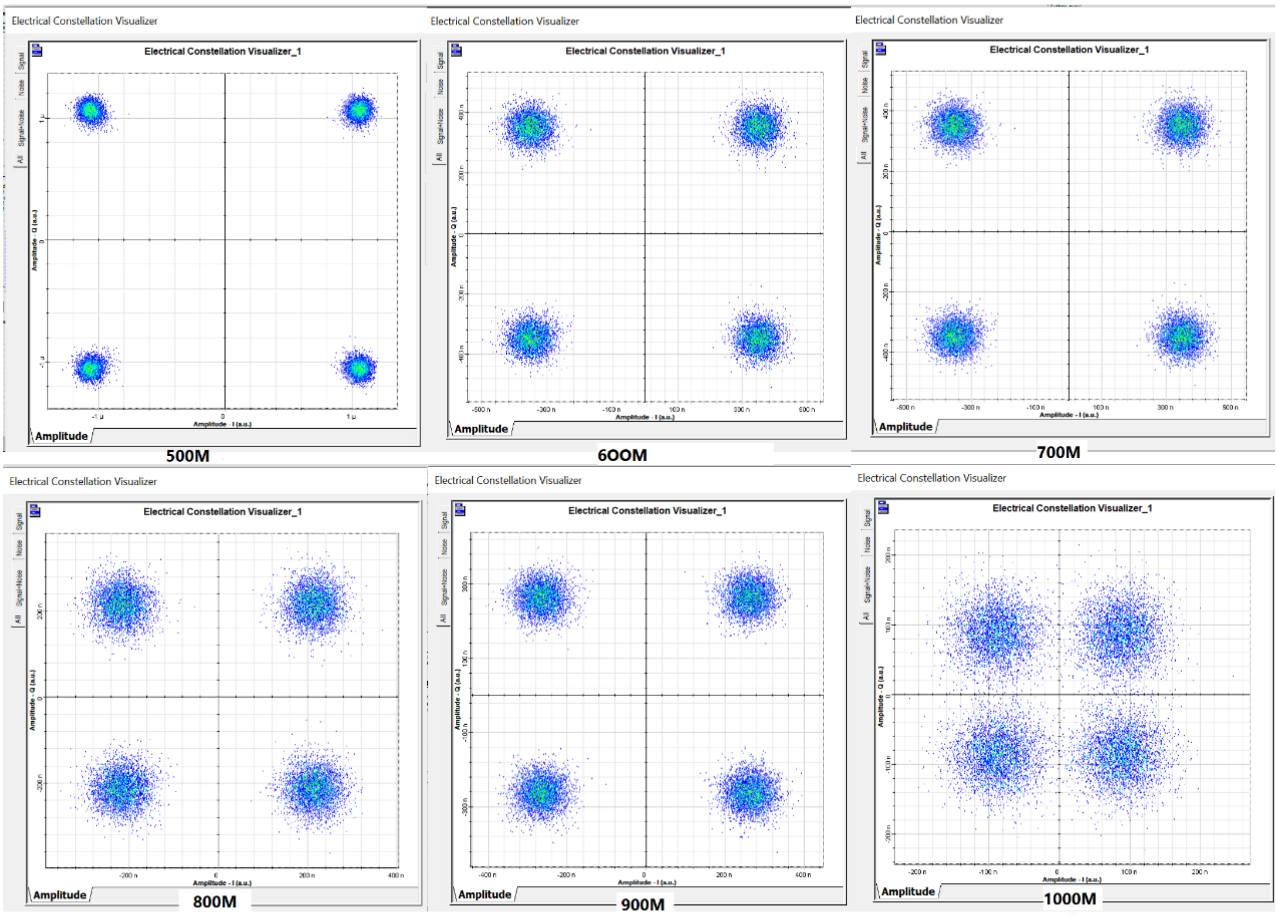


Figure III.11 : Q-factor variation by distance (titre proposé)

Observations:

- Well-defined constellation points
- Minimal phase/amplitude noise
- Ideal for long-range transmission

Attenuation: 20 dB/km

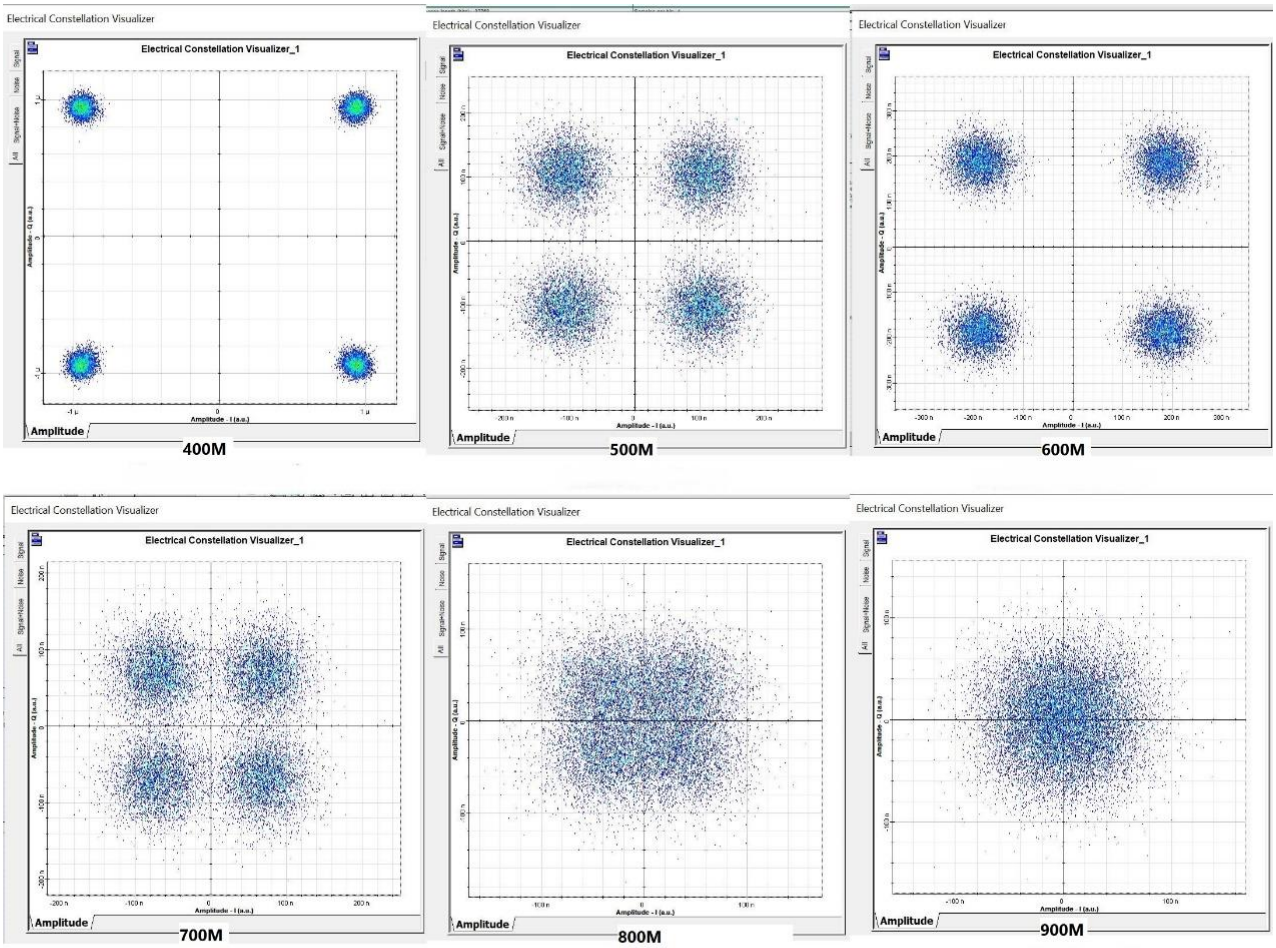


Figure III.12 : BER vs distance curve (titre proposé)

- Slight spreading of points
- Still within acceptable modulation margins

Attenuation: 30 dB/km

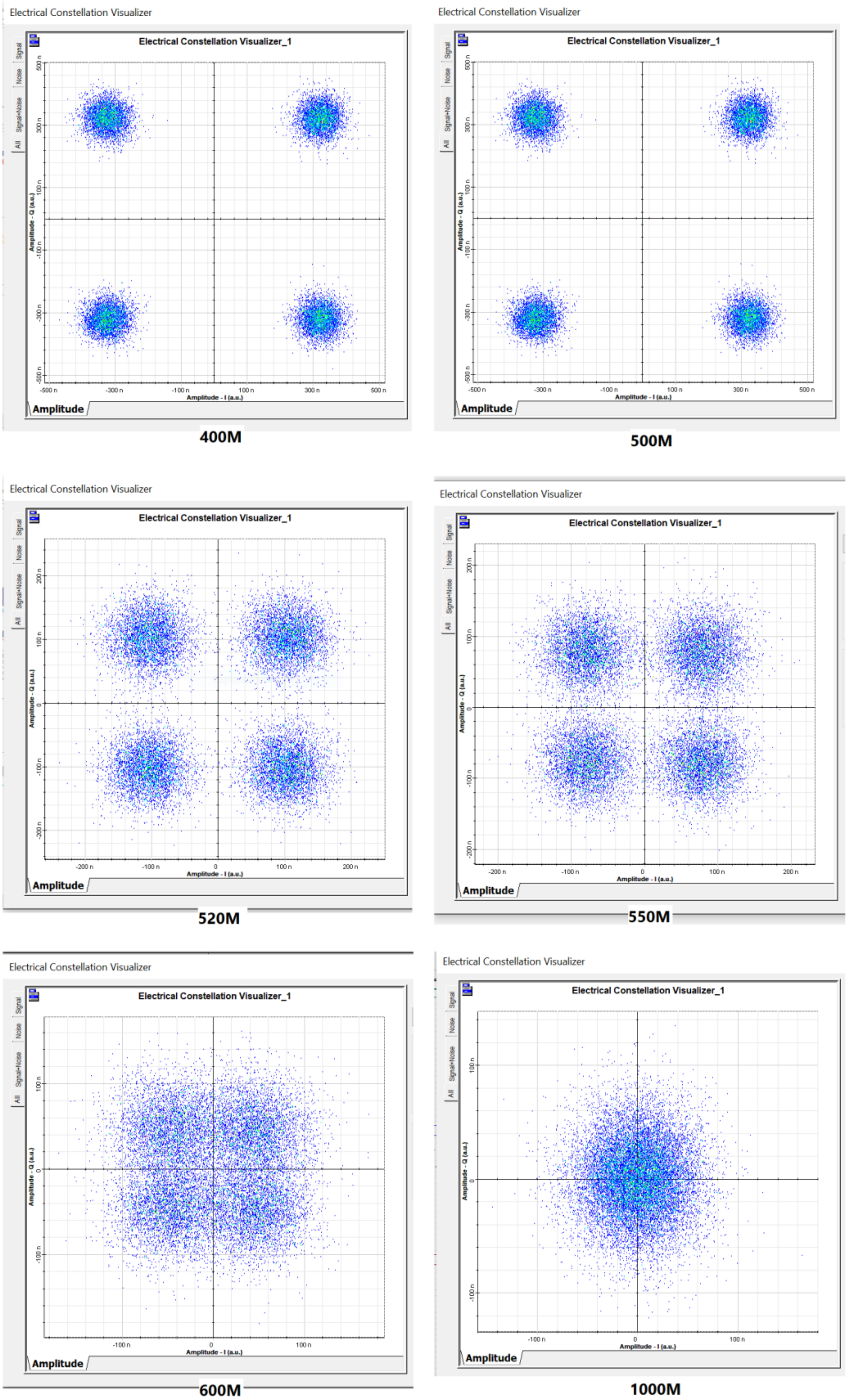


Figure III.13: Performance comparison of QAM and OFDM (titre proposé)

- Increased symbol dispersion
- Decision boundaries less clear

Attenuation: 40 dB/km

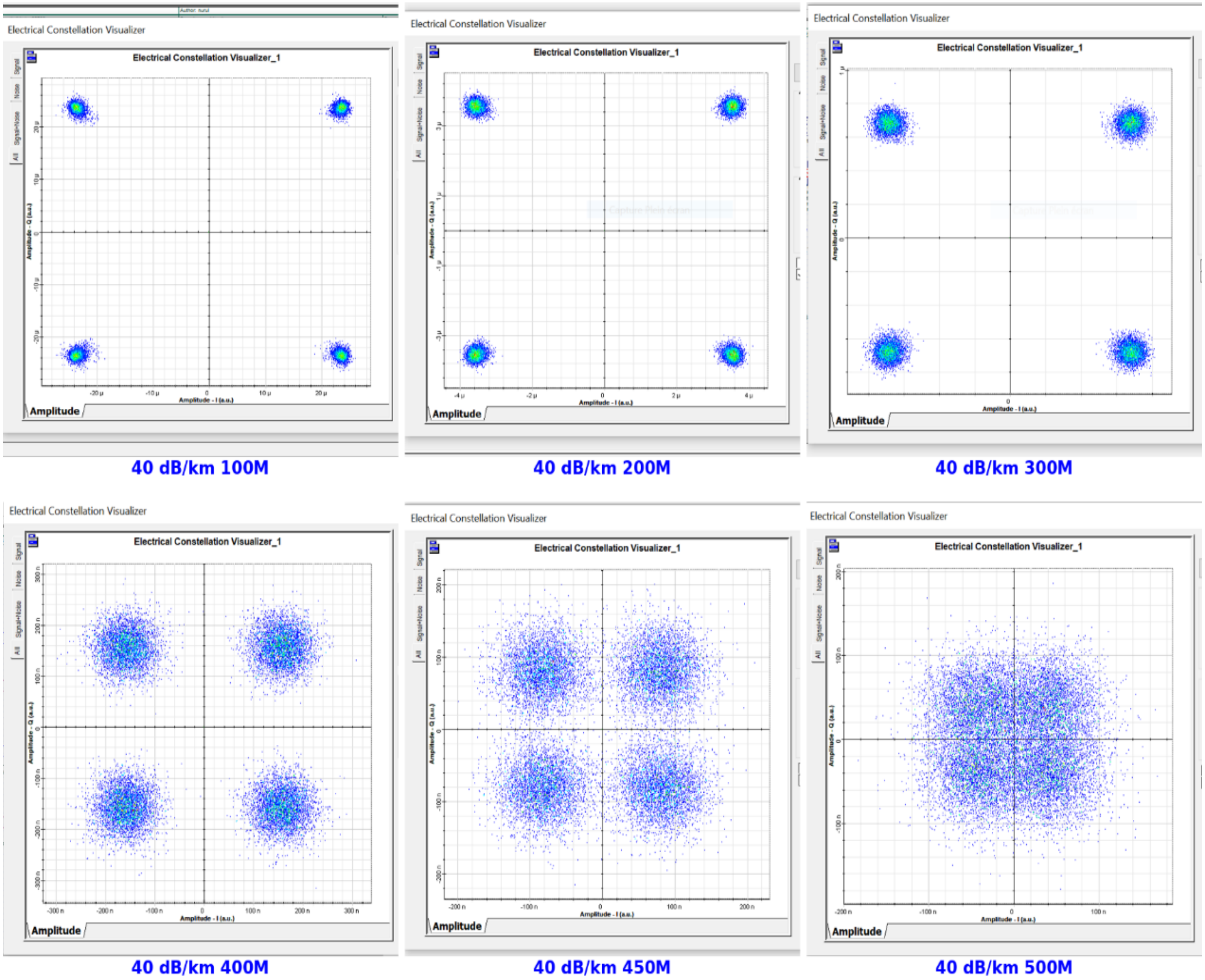


Figure III.14: Spectral efficiency of different modulation schemes (titre proposé)

- Severe degradation
- Symbols blur into each other
- High error probability

3.4 Constellation Diagrams per Laser Power Level

Laser power critically impacts signal clarity. Seven power levels were tested:

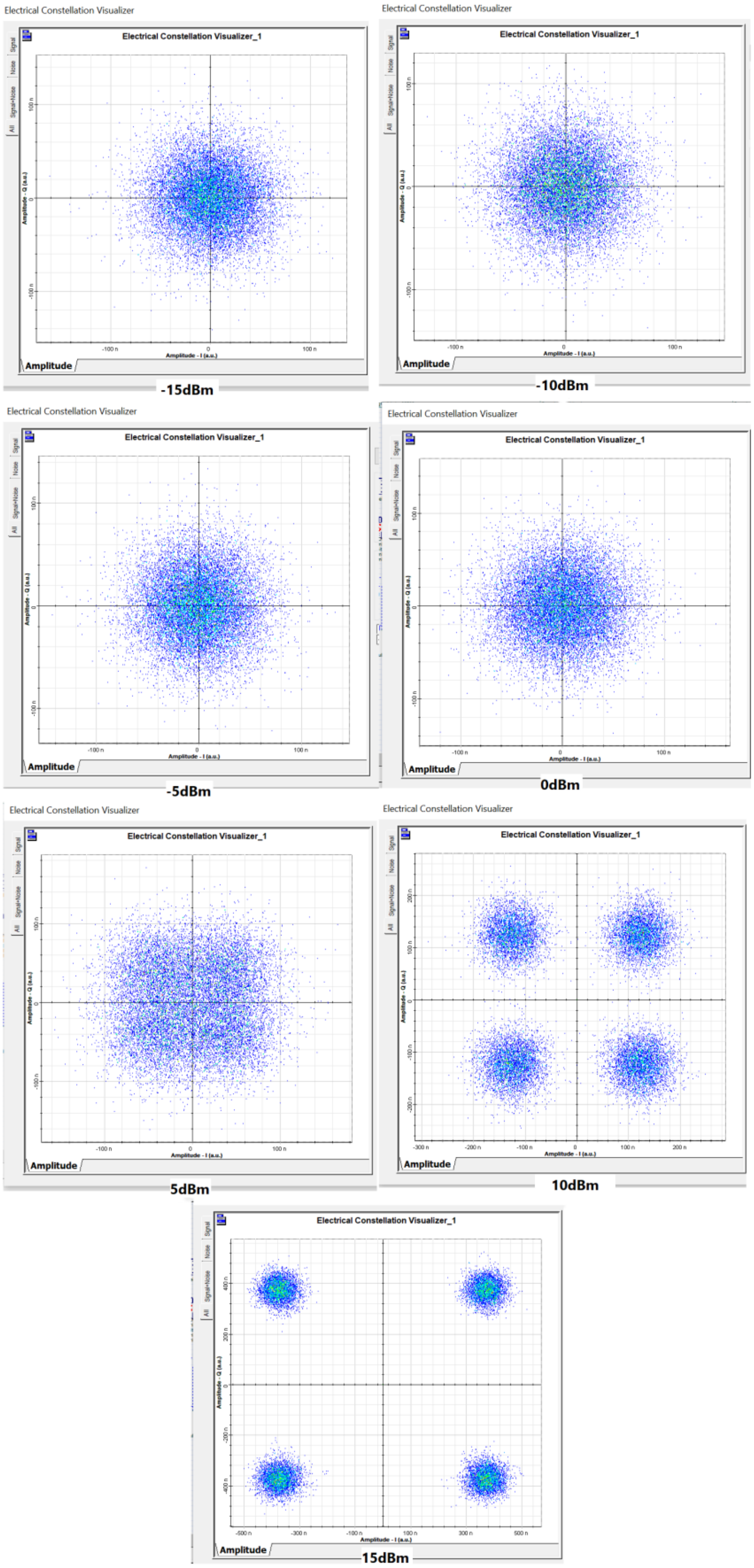


Figure III.15: Impact of attenuation on transmission power (titre proposé)

Observations:

- At **-15 and -10 dBm**, symbols are scattered, indicating low received power and high error.
- Best clarity at **5 to 10 dBm**, where constellation points are tight and clearly separated.
- Slight nonlinear distortion may appear at **+15 dBm**, potentially due to receiver saturation.

3.5 Conclusion for Architecture 2

The multi-user system behaves predictably: increased attenuation and insufficient laser power degrade signal fidelity. However, the system is robust under moderate conditions with properly tuned power levels. Optimizing laser power and receiver sensitivity is key for supporting large user bases.

4. General Practical Conclusions

Both simulations confirm the high sensitivity of FSO systems to environmental and system parameters. Under **ideal atmospheric conditions**, performance remains excellent up to certain thresholds of distance and attenuation. However, FSO systems—especially at higher user densities—require precise tuning of transmission power and careful architectural planning.

5. Consideration of Atmospheric Conditions: Limitations and System Adaptations

Although the simulations presented in this study were conducted under **idealized conditions**—neglecting the effects of the atmosphere on optical propagation—it is crucial to acknowledge that **real-world deployment of FSO systems is heavily influenced by weather**.

5.1 Real-World Weather Challenges

In practice, the **atmospheric channel** introduces several impairments due to:

- **Dry weather scattering** (fog, haze, mist): fine particles cause **Mie scattering**, leading to attenuation.
- **Precipitation** (rain, snow): large droplets lead to **geometric scattering**, which can significantly obstruct the beam.
- **Clouds**: dense cloud types (e.g., cumulonimbus, altostratus) contribute to **absorption and diffusion**, reducing transmission quality.

These phenomena result in **increased attenuation**, reduced **link availability**, and potential **communication outages**.

5.2 OptiSystem's FSO Weather Condition Component

To simulate real-world weather impacts, OptiSystem includes the **FSO Weather Condition** component. This tool estimates the **attenuation of optical signals** due to various atmospheric scenarios, including **clear sky**, **fog**, **rain**, **snow**, and **cloud types**.

Figure III.16: *Attenuation under dry weather conditions for various visibility levels (e.g., clear air, fog, haze). The component uses Mie scattering models (Kim or Kruse) to compute losses based on visibility range.*

This component allows the selection of calculation type (e.g., Dry Weather, Precipitation, or Clouds), and automatically determines the **scattering regime** (Rayleigh, Mie, or Geometrical) based on the **particle size parameter** and **wavelength** used.

5.3 Key Modeling Parameters

In the case of **cloud coverage**, different cloud types are associated with varying particle densities and liquid water contents, which directly influence the attenuation. The Kim and Kruse models estimate the **extinction coefficient** for each cloud type.

Figure III.17: *Attenuation values for different cloud types simulated using the FSO Weather Condition component in OptiSystem. Each cloud type (e.g., Cumulus, Stratus, Cirrus) affects transmission differently due to variation in water content (L) and particle density (N).*

5.4 Atmospheric Adaptation Strategies

When poor weather conditions significantly degrade link performance, **several equipment-level adjustments** can be applied to preserve communication:

- **Increase transmitter power** (if within safe and linear operating range)
- **Reduce link distance** or deploy **repeaters** for long paths
- **Use spatial diversity**: multiple transmitters to reduce fading
- **Adaptive optics** to correct beam distortion
- **Wavelength selection**: Prefer 1550 nm due to lower atmospheric absorption
- **Backup hybrid RF link** to ensure availability during extreme conditions

5.5 Summary

While our practical results demonstrate FSO performance under **clear-sky scenarios**, it is essential to consider **weather-aware system design**. OptiSystem's **FSO Weather Condition component** provides a scientific basis for evaluating the attenuation due to various climate effects. Future simulations can incorporate this component to model real-world deployments and validate the **resilience of the system architecture** against atmospheric challenges.

General Conclusion

This thesis has thoroughly explored the design, modeling, and performance evaluation of Free Space Optical (FSO) communication systems, particularly in the context of their integration with 5G and future wireless networks. The work has been structured into three main chapters, each addressing specific aspects of FSO systems, from fundamental principles to advanced techniques and practical simulations.

In **Chapter 1**, we introduced the basic concepts and components of FSO systems. We explained the operating principle of FSO communication, which involves transmitting optical signals through the atmosphere using lasers or LEDs. The chapter detailed the architecture of the system, including the transmitter, propagation channel, and receiver. Special focus was placed on the types of light sources used, such as Fabry-Perot and VCSEL lasers, as well as the characteristics of photodetectors like PIN and avalanche photodiodes (APDs). We also addressed key atmospheric factors such as fog, rain, and turbulence, and their impact on signal quality. Mathematical models including geometric attenuation, scintillation variance, and channel capacity were presented to quantify the effects of these phenomena.

Chapter 2 focused on the modeling of FSO systems within the framework of 5G and beyond. We discussed how FSO links can complement existing infrastructures by providing high-speed, secure, and cost-effective wireless backhaul, especially in urban areas or environments where fiber deployment is challenging. The chapter introduced advanced communication techniques such as QAM, QPSK, OFDM, and MIMO, and provided mathematical formulations and diagrams to support their implementation. We analyzed how each technique enhances spectral efficiency, reduces error rates, and improves resilience under atmospheric disturbances. The potential of FSO in supporting applications such as IoT, smart cities, emergency communications, and satellite links was also emphasized.

In **Chapter 3**, we turned to the practical evaluation of FSO systems using simulation tools, particularly OptiSystem. Two architectures were simulated: a single-user FSO link and a large-scale multi-user system supporting up to 512 users. By varying parameters such as transmission distance and atmospheric attenuation (ranging from 50 dB/km to 200 dB/km), we assessed the system's performance using eye diagrams, constellation diagrams, Bit Error Rate (BER), and Q-factor metrics. The simulations clearly illustrated how increased attenuation and longer distances degrade signal quality. Results also confirmed that advanced modulation and optimized system parameters can significantly improve performance under challenging conditions.

To conclude, this research demonstrates that FSO technology is a viable and strategic solution to meet the increasing demands for high-speed, low-latency, and secure communication in next-generation networks. While atmospheric conditions remain a limitation, the combination of robust modulation techniques, precise modeling, and adaptive signal processing can effectively mitigate these effects. FSO systems are not only relevant for 5G but are also expected to play a critical role in 6G and beyond, particularly for applications requiring fast deployment, high throughput, and strong security.

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Résumé

Ce mémoire explore les systèmes de communication optique en espace libre (FSO), une technologie prometteuse qui utilise des faisceaux lumineux (laser/LED) pour transmettre des données à haut débit sans câble, adaptée aux exigences des réseaux 5G et futurs (6G). Les avantages des systèmes FSO incluent une grande vitesse, une sécurité renforcée, une flexibilité d'installation et une immunité aux interférences électromagnétiques. Toutefois, ces systèmes sont sensibles aux conditions atmosphériques comme le brouillard ou la pluie.

Le travail combine une étude théorique approfondie (modulation QAM/OFDM, effets atmosphériques, turbulence, absorption) avec des simulations pratiques sur OptiSystem. Des résultats ont été obtenus sur le débit, le facteur Q, le BER, et les performances en environnement dégradé. Ce mémoire conclut que les systèmes FSO sont essentiels pour étendre les réseaux 5G, notamment dans les zones rurales, les villes intelligentes et les situations d'urgence.

Abstract

This thesis investigates Free Space Optical (FSO) communication systems—an emerging high-speed, wireless technology that uses laser or LED beams to transmit data without physical cables. FSO systems are well suited for the high bandwidth and low latency demands of 5G and future 6G networks. They offer key advantages such as high data rates, secure narrow beams, fast deployment, and immunity to electromagnetic interference. However, they are highly affected by atmospheric factors like fog and turbulence.

The study includes a detailed theoretical analysis (QAM/OFDM modulation, atmospheric modeling, noise, attenuation) combined with practical simulations using OptiSystem. Results focus on key metrics such as BER, Q-factor, and performance under varying weather conditions. The thesis concludes that FSO is a critical technology to complement 5G infrastructure, particularly in remote areas, smart cities, and emergency networks.

الملخص

تبحث هذه الأطروحة في أنظمة الاتصالات الضوئية الفضائية الحرة، وهي تقنية لاسلكية ناشئة عالية السرعة تستخدم أشعة الليزر أو الثنائيات الباعثة للضوء لنقل البيانات دون الحاجة إلى كابلات مادية. تُعد أنظمة الاتصالات البصرية في الفضاء الحر مناسبة تمامًا لمتطلبات النطاق الترددي العالي وزمن الاستجابة المنخفض لشبكات الجيل الخامس والجيل السادس المستقبلية. وتوفر هذه الأنظمة مزايا رئيسية مثل معدلات نقل بيانات مرتفعة، وأمان عالٍ بفضل ضيق الحزمة الضوئية، وسهولة وسرعة في النشر، ومناعة ضد التداخلات الكهرومغناطيسية. ومع ذلك، فإن أداءها يتأثر بشدة بالعوامل الجوية مثل الضباب والاضطرابات في الغلاف الجوي.

تتضمن هذه الدراسة تحليلًا نظريًا مفصلًا لتقنيات التعديل ونمذجة القنوات البصرية والضوضاء والتوهين، إلى جانب محاكاة عملية باستخدام برنامج أوبتي سيستم. وقد ركزت النتائج على مؤشرات أداء رئيسية مثل معدل الخطأ في البيانات، ومعامل الجودة، ومدى كفاءة النظام في ظروف جوية مختلفة. وتخلص الأطروحة إلى أن أنظمة الاتصالات البصرية في الفضاء الحر تُعد تقنية حيوية لتدعيم البنية التحتية لشبكات الجيل الخامس، وخاصة في المناطق النائية، والمدن الذكية، وشبكات الاتصال في حالات الطوارئ.