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THEME

Optimization of an FSO System with AI

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First and foremost, I want to thank ALLAH the Almighty for granting me health, willpower, courage, and patience to complete my training and carry out this research work.

I wholeheartedly dedicate this work to:

My parents, ZERKANE ABDELKRIM and BERRAH SABRINA, my pillars, my examples, my first supporters, and my greatest strength. Thank you for your presence, support, and love, which have shaped me into who I am today.

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May God grant them happiness, health, and success.

Finally, I dedicate this work to myself, remember, it's not the end of the road.

Thanks

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Slimani Zaineb

Abstract

This master thesis examines the potential enhancements of Free Space Optics (FSO) communication systems through Particle Swarm Optimization (PSO) and Pachycondyla APIcalis Algorithm (API). FSO technology utilizes laser beams to transmit data, offering significant advantages such as high bandwidth and increased security. However, this technology faces environmental challenges like rain, fog, and atmospheric turbulence, which can affect its performance.Simulations reveal that PSO optimization can significantly increase the link margin for various deviation angles compared to the API algorithm, demonstrating the effectiveness of this optimization method. For example, for divergence angles (θ_t) of 1, 1.5, 2.4, and 3 mrad, the link margin improves by 6.4, 11.1, 9.8, and 7.6 dB, respectively, at a fixed transmitted optical power of 10 dBm. This shows that the PSO algorithm can maintain a higher link margin for the same deviation angles compared to a non-optimized scenario. PSO appears to offer a more efficient and robust optimization for FSO systems. By integrating PSO, FSO technology becomes more viable for future applications such as 5G communication networks and the Internet of Things (IoT). The adoption of PSO in FSO systems could also reduce operational costs by minimizing maintenance needs. Finally, this approach paves the way for new research on optimizing communication system parameters in varied environments.

Keywords: Optimization, Link margin, FSO, PSO, API.

Résumé

Ce mémoire examine les améliorations potentielles des systèmes de communication optique en espace libre (FSO) grâce à l'optimisation par essaims particulaires (PSO) et par l'algorithme Pachycondyla APIcalis (API). La technologie FSO utilise des faisceaux laser pour transmettre des données, offrant des avantages significatifs tels qu'une bande passante élevée et une sécurité accrue. Cependant, cette technologie est confrontée à des défis environnementaux tels que la pluie, le brouillard et les turbulences atmosphériques, qui peuvent affecter ses performances. Les simulations révèlent que l'optimisation par PSO peut considérablement augmenter la marge de liaison pour divers angles de déviation par rapport à l'algorithme API, démontrant ainsi l'efficacité de cette méthode d'optimisation. Par exemple, pour des angles de divergence (θ_t) de 1, 1.5, 2.4 et 3 mrad, la marge de liaison s'améliore respectivement de 6.4, 11.1, 9.8 et 7.6 dB à une puissance optique transmise fixe de 10 dBm. Cela montre que l'algorithme PSO permet de maintenir une marge de liaison plus élevée pour les mêmes angles de déviation, comparé à un scénario sans optimisation. PSO semble offrir une optimisation plus efficace et plus robuste pour les systèmes FSO. En intégrant PSO, la technologie FSO devient plus viable pour des applications futures telles que les réseaux de communication 5G et l'Internet des objets (IoT). L'adoption de la PSO dans les systèmes FSO pourrait également réduire les coûts opérationnels en minimisant les besoins de maintenance. Enfin, cette approche ouvre la voie à de nouvelles recherches sur l'optimisation des paramètres des systèmes de communication dans des environnements variés.

Mots clés : Optimisation, Marge de liaison, FSO, PSO, API.

ملخص

تفحص هذه المذكرة التحسينات المحتملة لأنظمة الاتصالات الضوئية في الفضاء الحر (FSO) بفضل تحسين السرب الجزيئي (PSO) وخوارزمية (Pachycondyla APIcalis (API))، تستخدم تقنية FSO أشعة الليزر لنقل البيانات، مما يوفر مزايا كبيرة مثل عرض النطاق الترددي العالي والأمان المعزز. ومع ذلك تواجه هذه التقنية تحديات بيئية مثل الأمطار والضباب والاضطرابات الجوية التي يمكن أن تؤثر على أدائها . تظهر المحاكاة أن تحسين PSO يمكن أن يزيد بشكل كبير من هامش الاتصال لزوايا انحراف مختلفة مقارنة بخوارزمية API ، مما يثبت فعالية هذه الطريقة في التحسين. على سبيل المثال، لزوايا التشتت (θ_t) من 1 ,1.5 ,2.4 و 3 (mrad)، يتحسن هامش الاتصال بنسبة 6.4 ,11.1 ,9.8 و 7.6 (dB) على التوالي عند قدرة بصرية ثابتة تبلغ 10 (dbm). هذا يظهر أن خوارزمية PSO تحافظ على هامش اتصال أعلى لنفس زوايا الانحراف مقارنةً بالسيناريو غير المحسن. يبدو أن PSO يوفر تحسينا أكثر فعالية وقوة لأنظمة FSO. من خلال دمج PSO ، تصبح تقنية FSO أكثر جدوى للتطبيقات المستقبلية مثل شبكات الاتصالات 5G وإنترنت الأشياء (IOT). ممكن أن يؤدي اعتماد PSO في أنظمة FSO أيضا إلى تقليل التكاليف التشغيلية عن طريق تقليل الحاجة إلى الصيانة. أخيراً، تفتح هذه المقاربة الباب لأبحاث جديدة حول تحسين معايير أنظمة الاتصال في بيئات متنوعة.

كلمات مفتاحية: التحسين، هامش الاتصال، أنظمة الاتصالات الضوئية في الفضاء الحر (FSO)، السرب الجزيئي (PSO)، خوارزمية Pachycondyla APIcalis (API) .

Contents

List of Figures

List of Tables

List of Abbreviations

5G	5^{th} Generation
ACAs	Ant Colony Algorithms
AI	Artificial Intelligence
APD	Avalanche Photo Diode
API	Pachycondyla APIcalis Algorithm
ARTEMIS	Advanced Relay and Technology Mission Satellite
BA	Bat-inspired Algorithm
BER	Bit Error Rate
BLA	Bee Life Algorithm
CIAC	Continuous Improved Ant Colony
CACO	Continuous Ant Colony Optimization
CACS	Continuous Ant Colony System
D2D	Device to Device
DE	Differential Evolution
ESA	European Space Agency
FA	Firefly Algorithm
FCC	Federal Communications Commission
FO	Fiber Optic
FSO	Free Space Optic
GA	Genetic Algorithm
GRASP	Greedy Randomized Adaptive Search Procedure
ICA	Imperialist Competitive Algorithm
IM	Intensity Modulation
IR	InfraRed
IoT	Internet of Things
IWO	Invasive Weed Optimization
JAXA	Japan Aerospace Exploration Agency

LASER	Light Amplification by Stimulated Emission of Radiation
LD	Laser Diode
LED	Light Emitting Diode
LiDAR	Light Detection And Ranging
LiFi	Light Fidelity
LLCD	Lunar Laser Communication Demonstration
LOS	Line Of Sight
MA	Memetic Algorithm
MB	Millimeter Base
MFA	Moth-Flame Algorithm
MRV	Marvin Rosenberg and Victor Berman
NASA	National Aeronautics and Space Administration
NSGA-II	Non-dominated Sorting GA II
OCC	Optical Camera Communication
OICETS	Optical Inter-orbit Communications Engineering Test Satellite
OWC	Optical Wireless Communication
PAV	Philips Analytical Video
PD	Photodetector
PIN	Positive Intrinsic Negative
PSO	Particle Swarm Optimization
RAD	Research And Development
RF	Radio Frequency
SA	Simulated Annealing
SNR	Signal to Noise Ratio
SONET	Synchronous Optical Network
SVM	Support Vector Machine
ULL	Ultra Low Latency
UV	Ultraviolet
VL	Visible Light
VLC	Visible Light Communication
WOA	Whale Optimization Algorithm

General introduction

Free Space Optical (FSO) communication systems represent cutting-edge technology that utilizes light beams to transmit data through the atmosphere without the need for physical cables. This method offers numerous advantages, including high bandwidth, low latency, and enhanced transmission security. However, the performance of FSO systems can be significantly affected by environmental factors such as rain, fog, and atmospheric turbulence, posing significant challenges to their reliability and efficiency.

The growing importance of FSO systems in modern communications drives researchers to explore various methods to optimize their performance. Optimizing the parameters of these systems is crucial to minimize the effects of adverse conditions and maximize transmission quality. This thesis focuses on studying and improving the performance of FSO systems using different optimization techniques and integrating artificial intelligence approaches.

This thesis is composed of three distinct chapters:

The first chapter introduces the fundamentals of free space optical communication technology. We explore the history of optical communication, highlighting the key milestones that led to the development of modern FSO systems. The key components of FSO systems, such as transmitters, receivers, and propagation channels, are examined in detail. Additionally, we discuss the integration of FSO technology into telecommunications systems and industrial applications, comparing the advantages and disadvantages of FSO links with other wireless communication technologies.

The second chapter is dedicated to the different optimization techniques used to enhance the performance of FSO systems. We present a classification of optimization problems, distinguishing them according to various criteria such as continuous vs discrete problems, constrained vs unconstrained, deterministic vs stochastic, and linear vs nonlinear. We then explore the key elements of optimization, including objective functions, variables, and constraints. The optimization techniques discussed include heuristic and metaheuristic algorithms, with a particular focus on the Pachycondyla Apicalis algorithm (API) and Particle Swarm Optimization (PSO).

The third chapter focuses on the application of artificial intelligence techniques to optimize FSO systems in the context of future generations of wireless communications, such as 5G and beyond. We discuss the ideal parameters of FSO systems, losses, and link margins, and present simulation results illustrating how the Particle Swarm Optimization algorithm (PSO) and Pachycondyla Apicalis algorithm (API) can be used to improve the reliability and efficiency of FSO transmissions under various conditions. This chapter highlights upcoming challenges and potential solutions for effectively integrating FSO technology into next-generation communication networks.

Finally, we conclude this thesis by summarizing the main results and drawing significant conclusions from our study, while proposing future research directions to continue improving free space optical communication systems.

Chapter 1

GENERAL OVERVIEW OF FSO TECHNOLOGY

1.1 Introduction

Free Space Optics (FSO) is an innovative wireless data transmission technology that uses laser beams to transmit signals without the need for fiber optics cables or radio frequency licenses. This innovative approach provides high bandwidth and secure communication while avoiding the costs typically associated with spectrum licensing. With its exceptional performance, FSO has become a key technology in various industrial applications and telecommunication networks. In this chapter we will explore the basics of Free Space Optics (FSO) technology. We'll look into its history, key components, integration into telecommunications systems, and practical applications in different industrial. Additionally, we will address the advantages and limits of FSO links, as well as the distinctions between this technology and other forms of optical and radio based communications.

1.2 Free Space Optics Technology

1.2.1 Brief History

The history of optical communication dates back to ancient times when humans used hand and arm signals for long-distance communication, which later more complex methods like beacons, smoke signals, and lighthouses. One notable milestone was Chappe's optical telegraph system, developed in the 1790s, this system could transmit messages over 135 kilometers in one minute greatly extending the range of communication [1]. Although it was eventually replaced by the electromagnetic telegraph, the optical telegraph remained in use in remote areas until the early 1900s.

In the late 19th century, optical telegraph systems were widely used on European and American railroad systems.At the same time, Graham Bell produced his photophone in 1880[2], which can be considered a precursor to modern free space optical (FSO) communication.

In 1955, Zenith introduced the Flash Matic, the first wireless TV remote control, which evolved into infrared remote-control systems[3].

However, it was the invention of the laser in 1960 that truly ignited interest in FSO technology, especially within military organizations. The introduction of fiber optics in the 1980s shifted the focus away from FSO, but it remained a subject of research and development[4].

In recent years, technological advancements and renewed interest have led to a resurgence in FSO technologies. These technologies have gained traction due to high bandwidth, quick setup times, low cost, and demonstrated performance, with applications in various enterprises. FSO has been used in intersatellite communications, such as the JAXA OICETS 'KIRARI' and the ESA ARTEMIS satellite in 2005 [5], and in NASA's Lunar Laser Communication Demonstration (LLCD) in 2013 [6].Moreover, FSO and millimeter-wave technologies are expected to play an important role in next-generation wireless backhauling.

Figure 1.1: A photophone receiver [4].

1.2.2 Optical Wireless Communication

Wireless communication uses radio waves to transmit data across a frequency range from 30 kHz to 300 GHz, this form of communication often faces challenges such as congestion, which can lead to lower throughput and increased interference. As radio frequency (RF) increases, issues like propagation loss and line of sight (LOS) limitations become more apparent. However, wireless communication isn't limited to radio waves. It also includes the optical spectrum, which comprises ultraviolet, visible, and infrared wavelengths, offering more bandwidth allowing for high speed communication[7]. Optical Wireless Communication (OWC) systems take advantage of this broader spectrum to develop innovative wireless technologies and services.

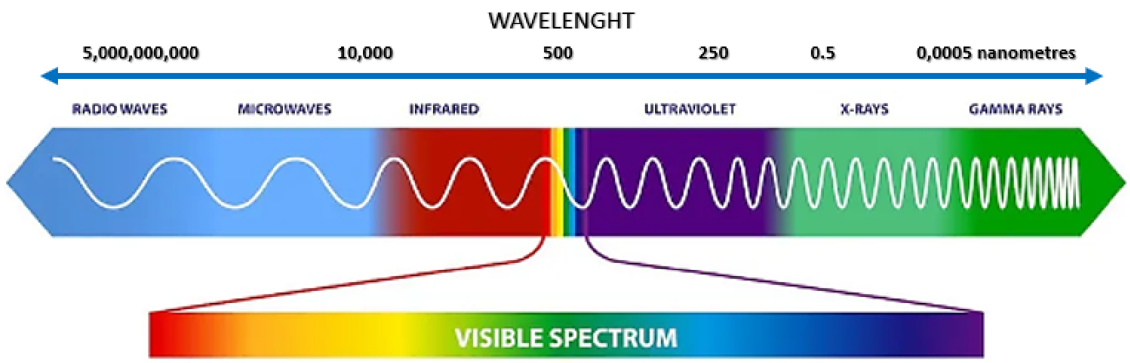


Figure 1.2: Electromagnetic Spectrum.

Optical wireless communication is a method that involves modulating a light source to send an electrical signal across the atmosphere or free space for data transmission. The optoelectronic conversion process uses light sources such as light-emitting diodes (LEDs) or laser diodes (LDs). After the signal is received, a photodetector is used to extract the transmitted information, as illustrated in Figure 1.3. OWC presents a wide array of potential applications, wish are visually depicted in Figure 1.4.

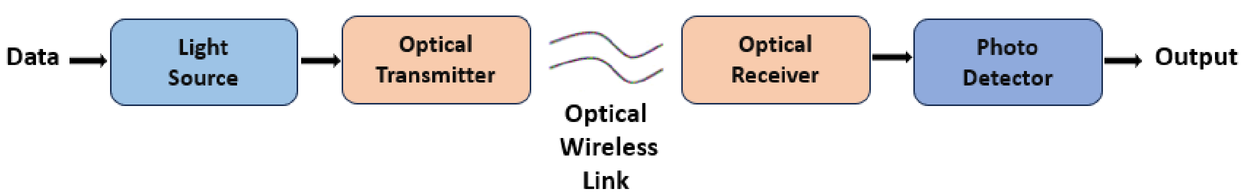


Figure 1.3: General principle of OWC.

Figure 1.4: OWC applications.

Optical Wireless Communications encompass various technologies classified in Figure 1.5, which helps to differentiate between OWC systems based on their distinctive features. Table 1.1 provides a brief comparison of different wireless communication systems, offering a structured summary of their key differences.

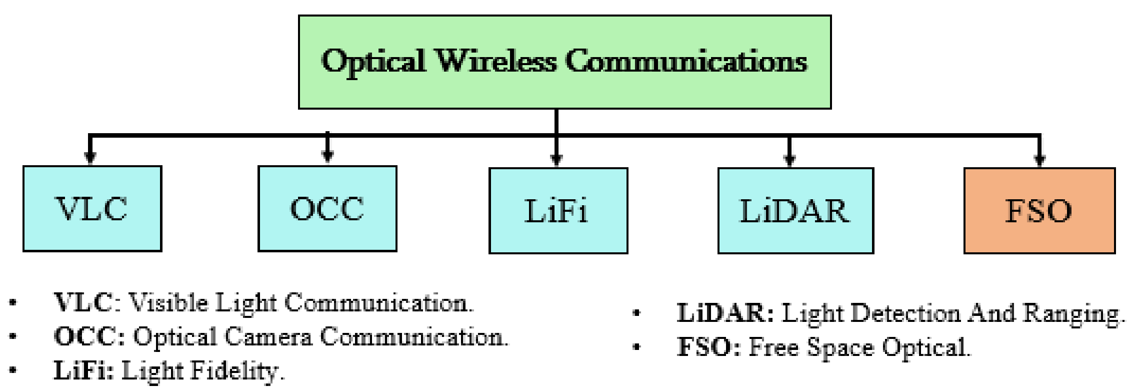


Figure 1.5: Classification of OWC technologies.

Table 1.1: Comparison of different wireless communication systems.

	LIFI	VLC	OCC	FSO	RF
Transmitter	LED/LD	LED/LD	LED	LED/LD	Antenna
Receiver	PD	PD/Camera	Camera	PD	Antenna
Communication distance	<10 m [8]	20 m	1 to 4 m [9]	>1000 m [7]	> 100 km [7]
Interference Level	Low	Low	Low	Low	Very high
Environmental effect	Indoor: No Outdoor: Yes	Indoor: No Outdoor: Yes	NO	YES	YES
Data rate	1 Gbps [10]	4.22 to 5.6 Gbps [11]	38.4 kbps [9]	10 Gbps [12]	∼6 Gbps [7]
Security	High	High	High	High	Low

1.2.3 Free Space Optical Communications

Free Space Optical (FSO) communications, a subset of OWC technologies, are particularly suitable choice for outdoor long-range applications. FSO is a critical technology for high-rate wireless data transmission, utilizing a line-of-sight (LOS) approach to convey information through a modulated light beam from one point to another in free space. An FSO communication system utilizes the visible light (VL), infrared (IR), and ultraviolet (UV) portions of the electromagnetic spectrum [13]. Although ultraviolet light is generally not preferred due to atmospheric limitations, technical complexities and safety concerns.

The term "Free space" refers to media like air, outer space, or vacuum, which have similar propagation properties [14]. One of the significant advantages of FSO is that it doesn't require a license from the Federal Communications Commission (FCC) for installation and operation [15]. Commercial FSO systems can offer significantly higher data rates, less than or equal to 10 Gbps, over link spans of up to 1.5 km [12]. However, weather conditions and physical obstructions can impact the reliability of FSO links, particularly for long-distance communications. An FSO system has three main components:

- **The transmitter:** Converts electrical signals into optical signals, which are then sent as a light beam through free space.

- **The free space transmission channel:** This is the path along which the light beam propagates, usually through the atmosphere.
- **The receiver:** Converts the received optical signals back into electrical signals for further processing.

These components illustrated in Figure 1.6, work together to facilitate the transmission of data over long distances using light-based communication methods. Despite its benefits, FSO technology's reliability can be influenced by environmental factors like weather and physical blockages.

Figure 1.6: FSO communication system.

1.3 FSO Systems

The performance of an FSO system depends on its design and atmospheric conditions, utilizing light beams for data transmission without physical infrastructure. Critical components such as transmitters, receivers, and propagation channels play a significant role, with atmospheric factors impacting signal transmission and requiring adaptive strategies. Understanding the characteristics of Free Space Optical (FSO) systems is essential for their customized deployment. The majority of FSO systems are designed to operate within specific wavelength ranges, typically between 780–850 nm and 1520–1600 nm [16].

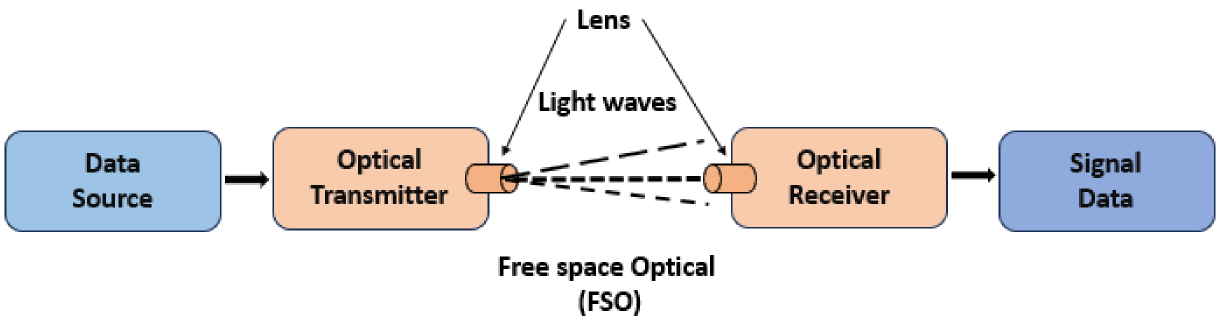


Figure 1.7: FSO communication system in line-of-sight.

1.3.1 Transmitter

The primary function of this component is to modulate the data source onto an optical carrier, allowing the signal to propagate toward the receiver.

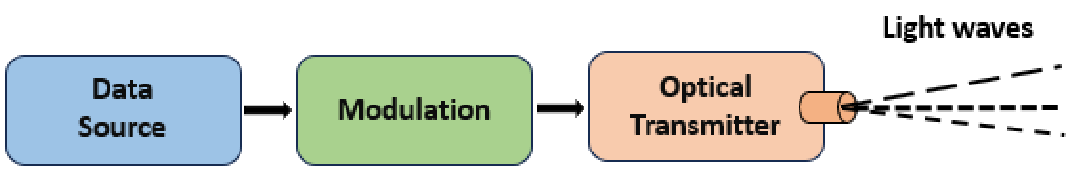


Figure 1.8: Optical transmitter block diagram.

Optical Source

A key component in any optical communication system is the optical source, which must support efficient modulation and high data throughput. Optical sources used in wireless optical communications predominantly rely on semiconductors technology and can be classified into two types:

Light-emitting diodes (LEDs): These semiconductor devices emit light when a voltage is applied across their terminals. LEDs are built around of a p-n junction, formed by joining a p-type semiconductor with an n-type semiconductor. When a voltage is applied to the p-n junction, electrons and holes recombine, releasing energy in the form of photons. The color of the light emitted by an LED is determined by the materials used to make in the p-n junction with a range from ultraviolet to infrared [17].

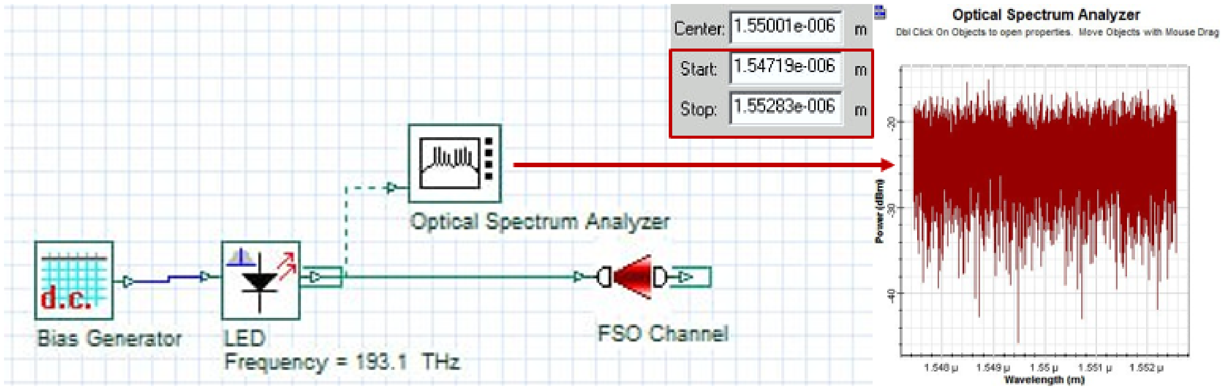


Figure 1.9: FSO transmitter using LED diode.

Light Amplification by Stimulated Emission of Radiation (LASER): is a device that produces a beam of coherent light through the process of stimulated emission. A laser consists of three key components: a gain medium (which can be a solid, liquid, or gas) and an optical cavity formed by two mirrors. When energy is applied to the gain medium, it excites atoms or molecules, causing them to release photons These photons bounce between the mirrors, stimulating the emission of more photons in the same phase and direction. The photons that eventually exit through one of the mirrors form a coherent light beam, characterized by a very narrow bandwidth and a high degree of spatial and temporal coherence [18].

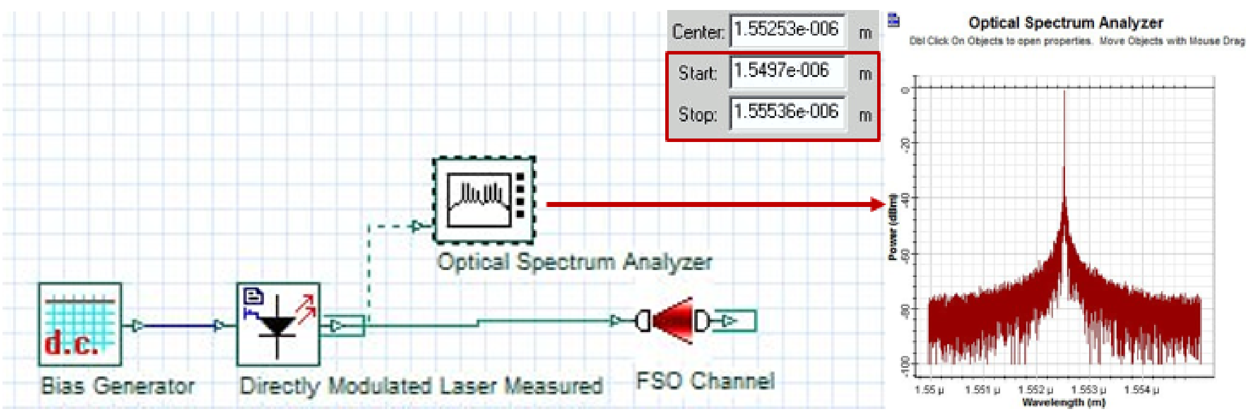


Figure 1.10: FSO transmitter using LASER diode.

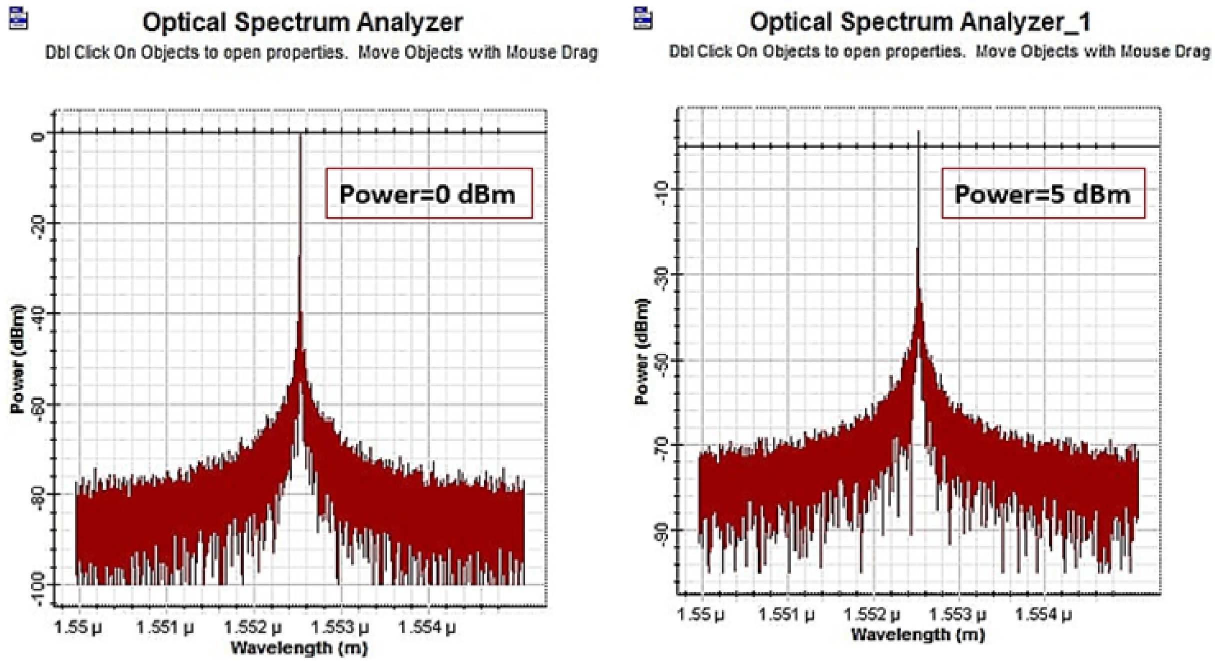


Figure 1.11: Optical Spectrum of laser diode.

- **Criteria for selecting laser diodes in FSO systems:**
  - The laser source's transmission wavelength must align with the atmospheric windows, typically found around 850 nm and 1550 nm in the shorter IR wavelength range [19].
  - The narrow linewidth of the laser diode indicates it is a single-mode laser diode. Single-mode laser diodes produce a more focused light beam that is less susceptible to dispersion.

The relatively high-power output of the laser diode is crucial for FSO systems that require long-distance data transmission.

Additional factors influencing the selection of laser diodes in FSO [19]:

- Cost and availability of commercial components.
- Transmission power.
- Lifetime.
- Modulation capabilities.
- Eye safety.
- Physical dimensions and compatibility with other transmission media.

Signal Modulation

- **Intensity Modulation (IM):** is a data transmission technique in which information is encoded by varying the power level of the carrier signal. This is achieved by adjusting the operating current of the optical source in direct proportion to the data being transmitted. The basic concept of direct modulation, which is central to this method, is illustrated in Figure 1.12.

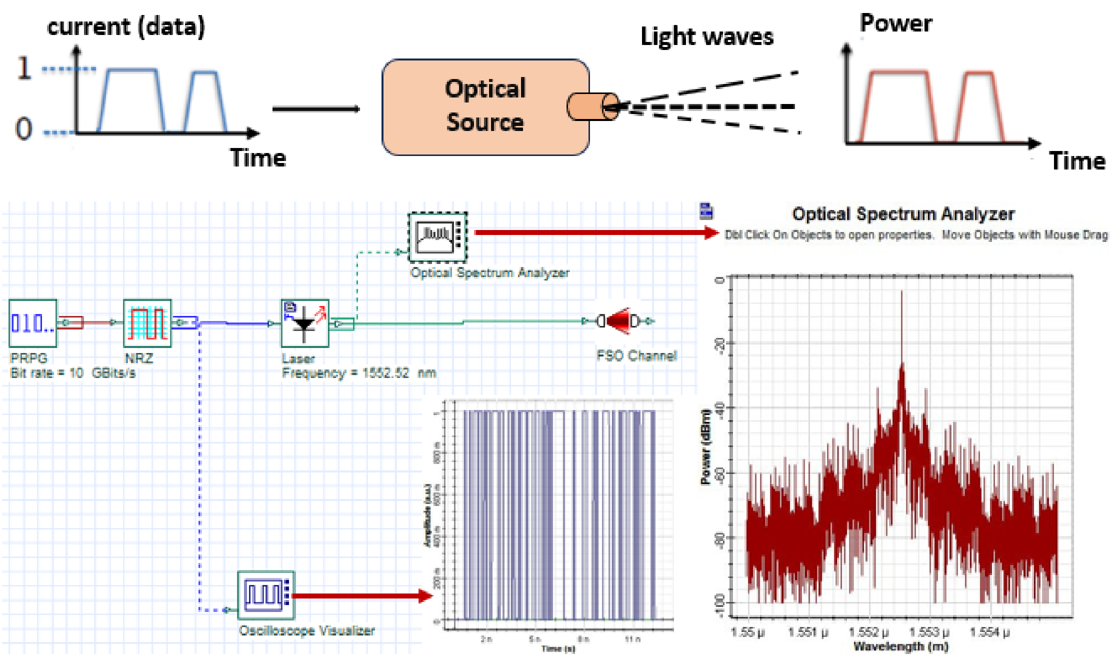


Figure 1.12: Fundamental concept of direct modulation.

- **External modulation:** In this type of modulation, the optical source remains unmodulated, receiving a continuous supply of electrical power. Instead, a separate device is used to perform the intensity modulation, allowing for greater control and flexibility in signal processing. This approach can offer advantages in terms of stability and reduced risk of signal distortion compared to direct modulation.

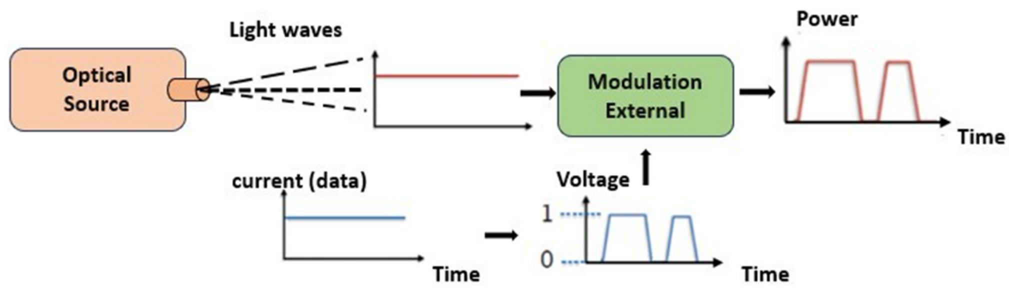


Figure 1.13: Fundamental concept of external modulation.

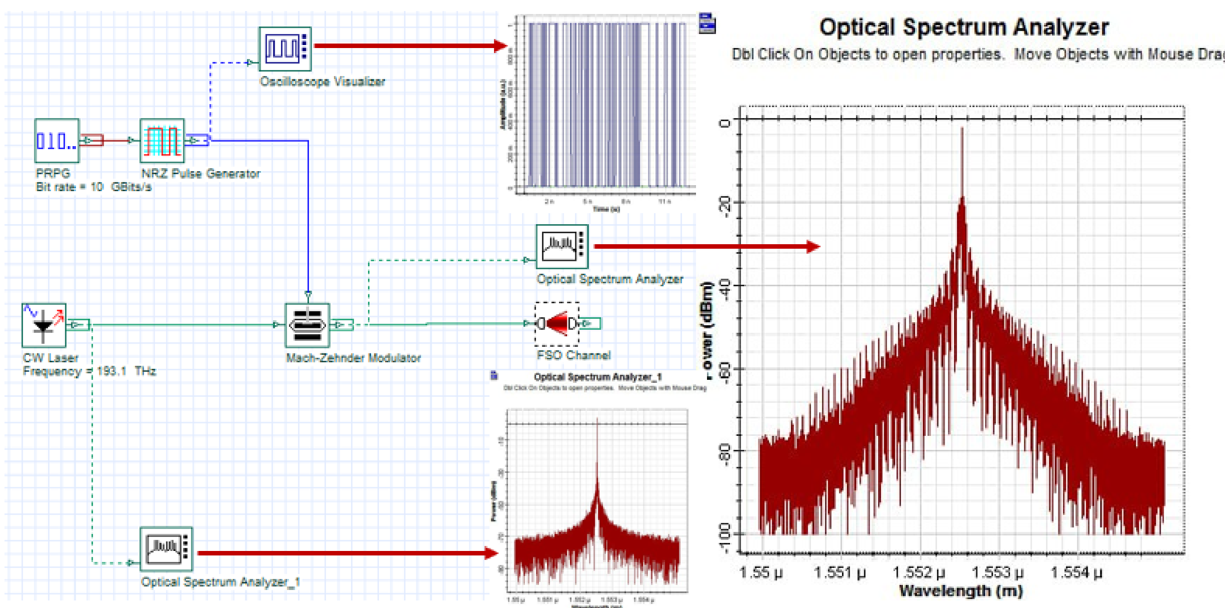


Figure 1.14: External modulation using mach-zehnder modulator.

1.3.2 Receiver

The receiver's primary function is to extract and retrieve data transmitted through an optical field. Photodetection is essential in this process as it converts optical radiation into an electrical signal, thereby enabling the recovery of information transmitted via the channel.

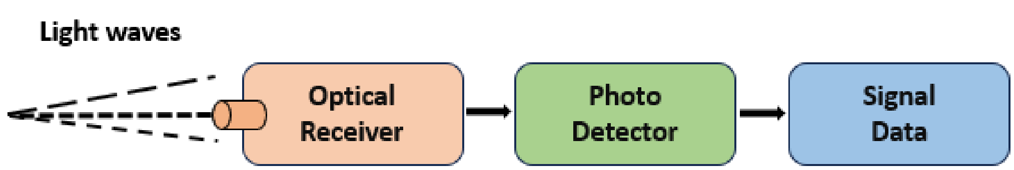


Figure 1.15: Optical receiver block diagram.

Photodetectors

The photodetector, specifically the photodiode, is a semiconductor device featuring a PN junction that is reverse-biased, facilitating the conversion of optical signal (photons) into electrical signals via the photoelectric effect. Photodiodes are categorized into main types:

Positive Intrinsic Negative photodiodes (PIN): These are semiconductor devices comprising an intrinsic (lightly doped) layer nestled between a P-type region and an N-type region. When these photodiodes are reverse-biased, they produce a current proportional to the incident optical power. PIN photodiodes are favored for their affordability, ease of use, and adequate performance.

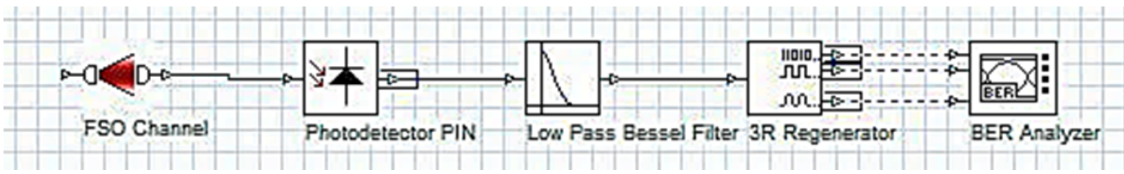


Figure 1.16: FSO receiver using PIN photodetector.

Avalanche Photo Diode (APD): These devices operate when photons enter the PN, initiating an electronic avalanche a process that significantly amplifies the electric current from a minimal number of incident photons. APDs are valued for their high sensitivity, rapid response and superior performance. Although they are more costly, challenging to operate, and require strong reverse polarization.

Figure 1.17: FSO receiver using APD photodetector.

- Criteria for selecting photodetectors in FSO systems:

The parameters used are:

Table 1.2: Simulation parameters of FSO system using PIN and APD.

Range	**Data Rate**	**Optical Source Type**	**Modulator**	**Photodetector Type**
[0–2] Km	10 Gbps	LD	Mach-Zehnder	PIN/APD

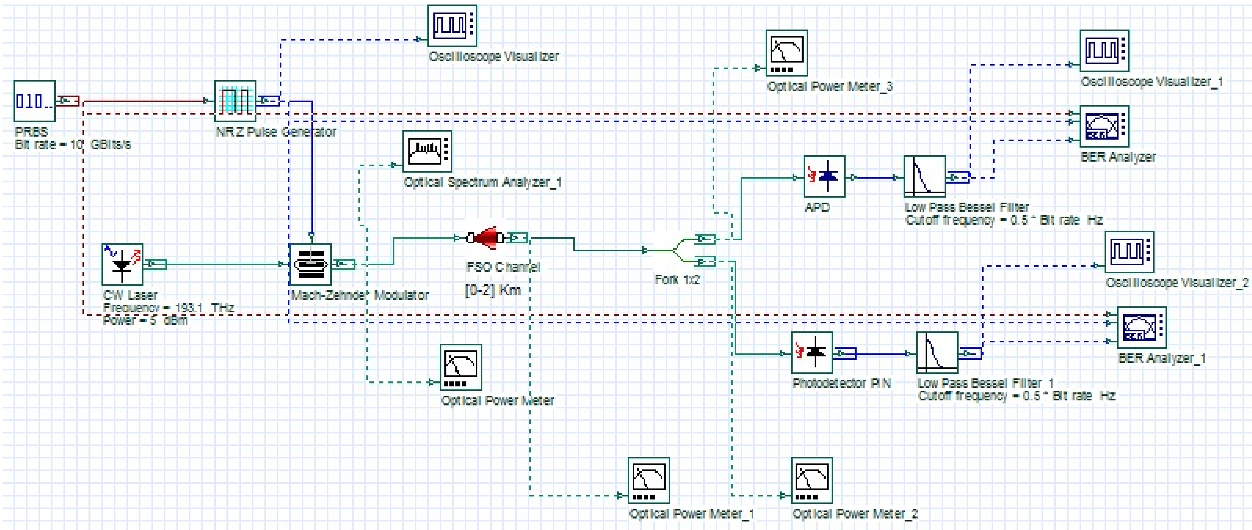


Figure 1.18: FSO system using PIN and APD.

In Free Space Optical (FSO) systems, the selection of photodetectors is crucial and depends on the specific application requirements, similar to the choice of optical sources. The detector must have a sensitivity that aligns with the transmission wavelength of the emitter. Here are the criteria for choosing between Avalanche Photodiode (APD) and Positive Intrinsic Negative (PIN) photodiodes:

1. APD photodiodes are often preferred for their increased sensitivity, which helps compensate for signal attenuation over long distances.

2. APD photodiodes require a higher and more stable polarization voltage. If stability poses a challenge, PIN diodes might be a better option.

3. PIN diodes are generally more cost-effective and should be considered unless the enhanced sensitivity offered by APDs is essential.

4. The choice of photodetector can also be influenced by environmental conditions. PIN diodes may offer greater robustness, whereas APDs might necessitate more controlled conditions.

5. For applications requiring high data rates, the higher bandwidth of APDs provides an advantage. In contrast, PIN diodes are a more economical choice for lower data rate applications.

These criteria guide the selection process, ensuring that the photodetector chosen is best suited for the operational demands of the FSO system.

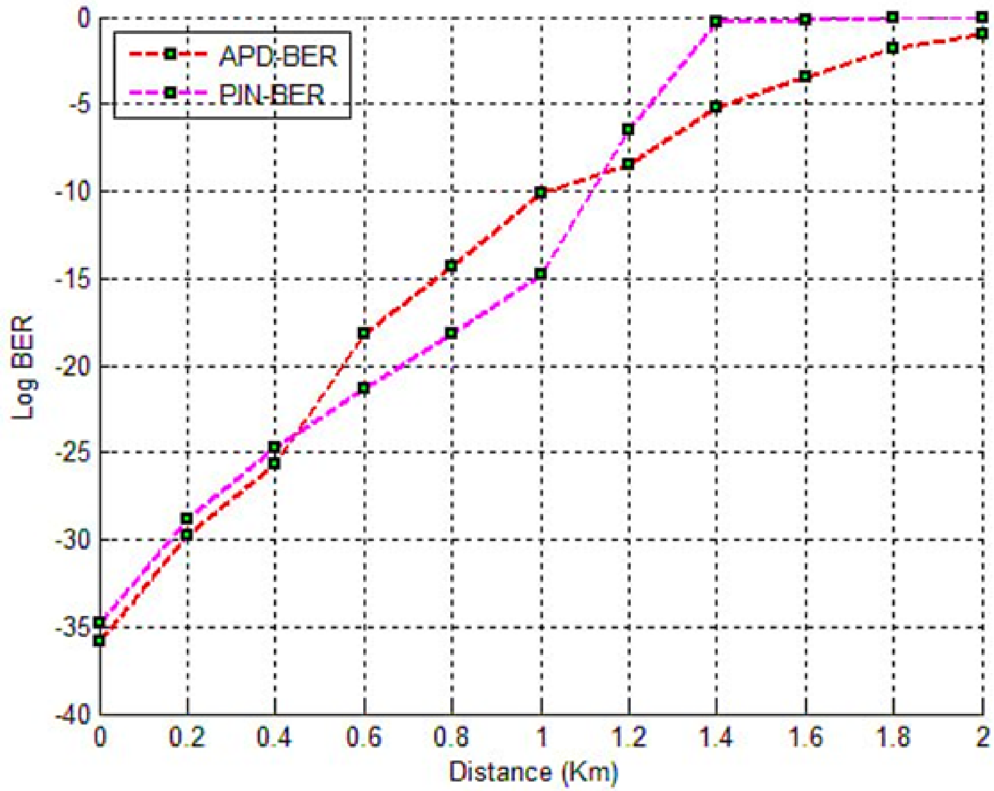


Figure 1.19: APD BER and PIN BER vs Distance.

The graph compares the Bit Error Rate (BER) of Avalanche Photodiodes (APDs) and (PIN) diodes over different distances. In more accessible terms and based on the results of existing studies, we could say that Avalanche Photodiodes (APDs) have a lower Bit Error Rate (BER). This means they are higher-performing, making them suitable for long-distance or high-speed communications. However, this advantage comes with greater complexity and more demanding operational requirements. On the other hand, PIN diodes offer satisfactory performance with benefits in terms of cost, simplicity, and potentially better durability, making them a practical choice for less stringent applications. System designers must assess and compare sensitivity, cost, ease of use, and environmental suitability when choosing between APD and PIN photodiodes, taking into account the detailed performance trends shown in the graph (Figure 1.19).

1.3.3 Propagation Channel

The propagation channel under consideration is the atmospheric medium. which is inherently complex and significantly influences the characteristics of the emitted light beam. FSO links are particularly vulnerable to the variabilities of this medium, which impose several constraints on signal transmission.

These challenges often manifest as attenuation or extinction of the optical signal as it travels through the atmosphere, consequently restricting the effective range between the transmitting and receiving units. Atmospheric extinction of the signal is primarily attributed to multiple wavelength-selective phenomena, as illustrated in Figure 1.20.

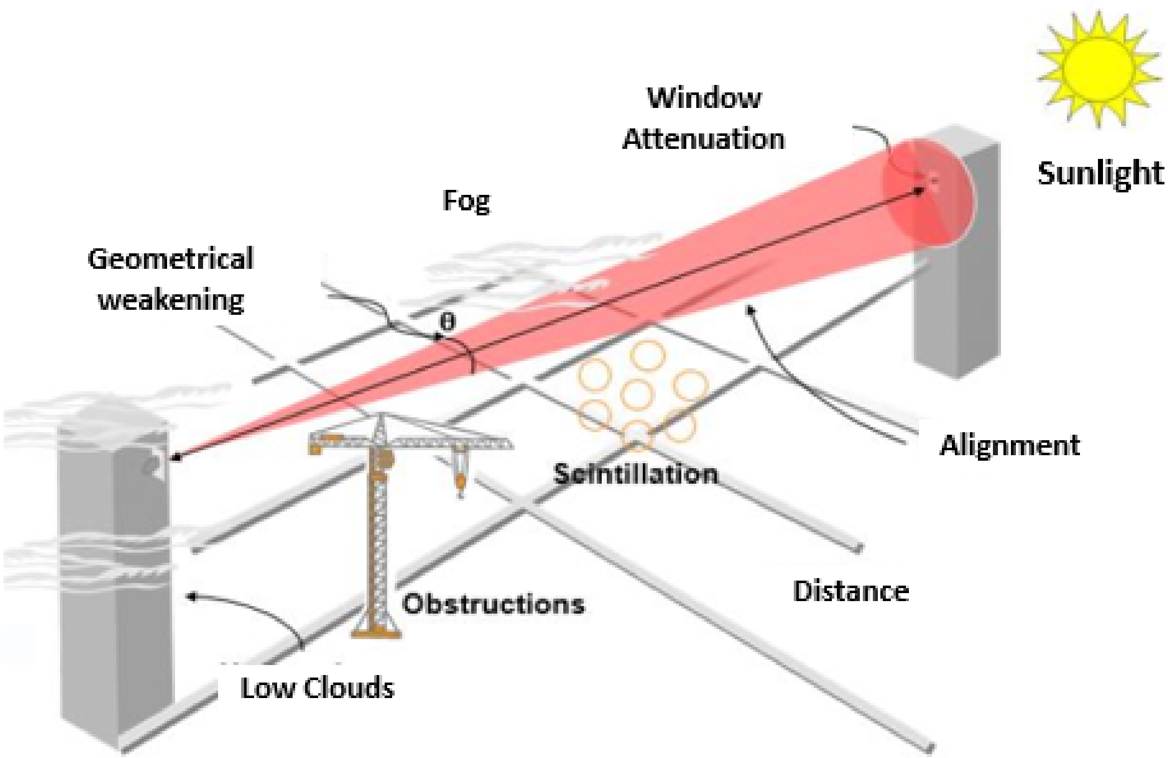


Figure 1.20: Phenomena that affect the optical beam.

Geometric attenuation

This form of attenuation is time-independent and occurs due to the divergence of the light beam along its propagation path. It will be computed based on the divergence angle, the link range, and transmitter and receiver aperture [20].

$$A_{geo}\,(dB) = 10lg\left(\frac{d_2^2}{(d_1 + Z\theta_t\,)^2}\right) \tag{1.1}$$

Where:

- d_1: Diameter of the transmitter aperture (m).

- d_2: Diameter of the receiver aperture (m).

- θ_t: Angle of divergence in (mrad).

- Z: Distance between the transmitter and receiver in (Km).

Fog effect

Measuring the density of fog and obtaining statistical data is challenging, and typically, it can only be estimated based on the number of particles present (fog density). The attenuation effect of fog, measured in decibels per kilometer (dB/km), correlates with atmospheric visibility V in kilometer (km) and the factor $\in$ in the research indicates that typically ranges between (0.02 and 0.05). This relationship is expressed with the following equation [21]:

$$A_{fog}\,(dB/Km) = |10lg_{10}(\in)/V| \tag{1.2}$$

Equation (1.2) is a rule that's been checked and works for any kind of fog, for light of any color, when you can see less than 3 kilometers ahead in the fog. There's also another way to figure out how much fog weakens the light, and that's by using something called the "Kim model". This model has its own math rule to describe this [22]:

$$\alpha_{fog}\,(dB/km) = \frac{3.912}{V}\left(\frac{\lambda}{550nm}\right)^{-q} \tag{1.3}$$

Where:

- V: Visibility in (km).

- λ: Wavelength in (nm).

- q: Particle size in (nm).

The values needed to use in Equation (1.3) are illustrated in Table 1.3 [22]:

Table 1.3: Relationship between Visibility and Particle Size .

V (km)	V > 50	6 <V < 50	1 <V < 6	0.5 < V < 1	V < 0.5
q (nm)	1.6	1.3	0.16*V +0.34	V-0.5	0

Equation (1.3) is used to calculate attenuation with:

- V(km): [0.2, 0.9, 4, 20, 60].
- λ(nm): 1550.
- q(nm): from Table 1.3.

Results:

Table 1.4: Visibility Mitigation using Kim's Formula.

V (km)	0.2	0.9	4	20	60
q (nm)	0	0.4	0.98	1.3	1.6
Attenuation (dB/km)	19.56	2.87	0.354	0.051	0.0124

The operational range of the communication link is intrinsically dependent on climatological factors. The attenuation values, which are key indicators of signal degradation due to these conditions, are tabulated and used as referenced in the table below [23]:

Table 1.5: Climatic conditions and their attenuation.

Climatic conditions	**Attenuation (dB/Km)**
Clear climate	0.19
Heavy rain	4.69
Dense fog	18.3

The parameters used are:

Table 1.6: Simulation parameters.

Range	[0–2] Km
Data Rate	10 Gbps
Optical Source Type	LD
Coding Type	NRZ
Optical Source Power	5 dBm

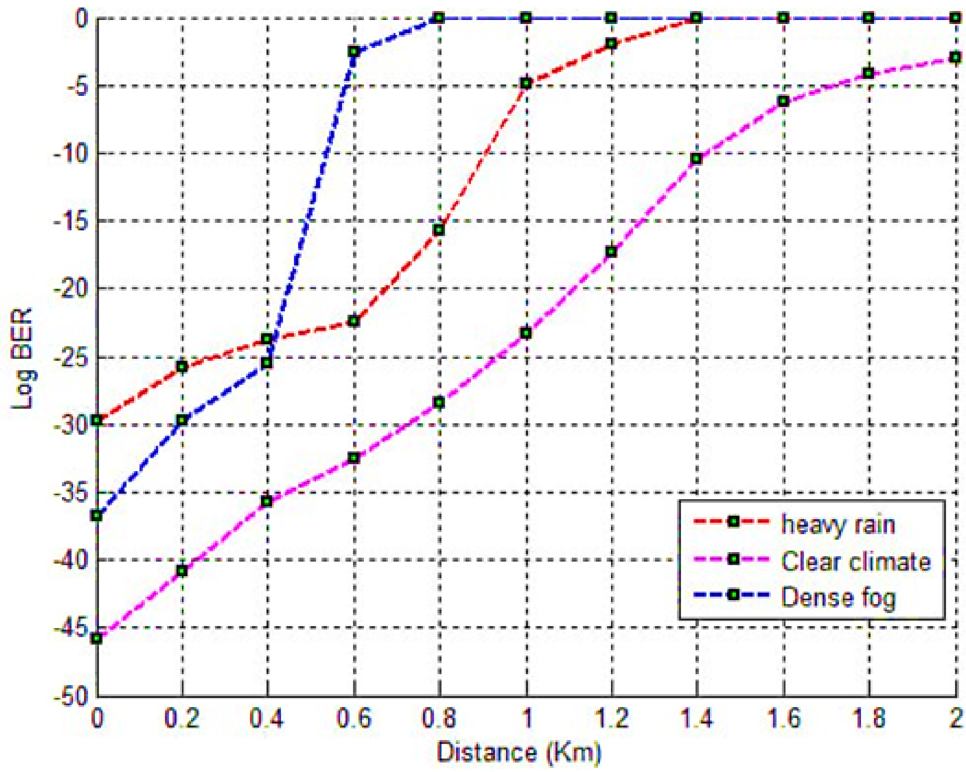


Figure 1.21: BER of climatological conditions vs distance.

This graph portrays the impact of climatological conditions on the Bit Error Rate (BER) for a FSO communication system over a range of distances up to 2 kilometers. The graph compares the log BER under three distinct atmospheric conditions: heavy rain, a clear climate, and dense fog. It is evident from the graph that a clear climate results in the lowest BER, suggesting optimal signal integrity. In contrast, heavy rain and dense fog induce higher BERs, indicating a decline in transmission quality with dense fog showing the most significant impact. The steepness of each line illustrates how each environmental condition progressively deteriorates the signal quality as the distance increases.

Rain effect

Attenuation of optical signals due to rain is attributed to geometric scattering, which arises from the interaction of the signal with raindrops. Such scattering effects are significant and cannot be overlooked. The rain droplets lead to the reflection and refraction of the light beam, which diminishes the signal strength. The extent of signal weakening due to rainfall, measured in decibels per kilometer (dB/km), is quantified using the subsequent equation[24]:

$$\alpha_{rain}\,(dB/km) = 1.076(R^{0.67}) \tag{1.4}$$

Where:

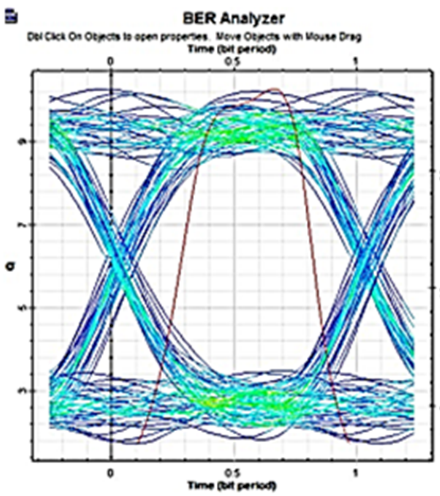
- R: Rate of rain precipitation in (mm/h).

We take this table as an example of rain attenuation:

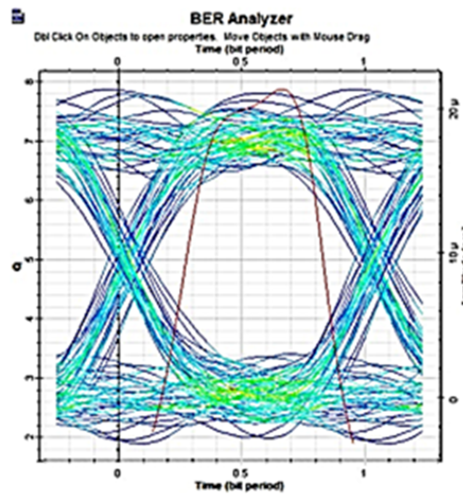
Table 1.7: Attenuation level values based on rainfall.

Rain	**low (1 mm/h)**	**moderate (3 mm/h)**	**Heavy (9 mm/h)**
Attenuation (dB/Km)	1.076	2.24	4.69

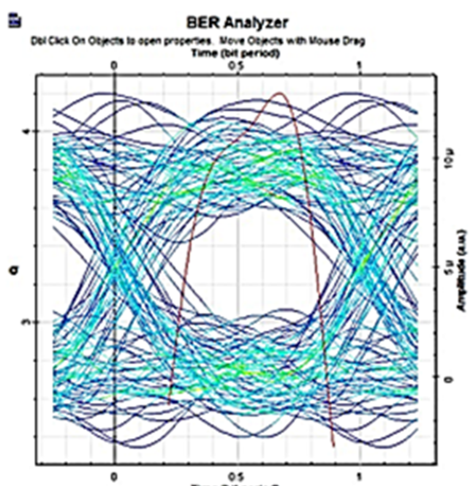
Results:



(a) Low rain :Q=10.2597



(b) Moderate rain :Q=7.87056



(c) Heavy rain : Q=4.20224.

Figure 1.22: FSO system with rain effect in 1Km.

Figure 1.22 illustrates the effect of rain on Free Space Optical (FSO) communication at a distance of 1 kilometer. The Q-factor is a measure of signal quality; a higher value indicates better signal performance. These eye diagrams visualize the time-domain degradation of signal quality, with the closing of the "eye" indicating increased signal distortion and error rates. In heavy rain, the eye is most closed, highlighting the significant impact of such adverse weather conditions on signal clarity.

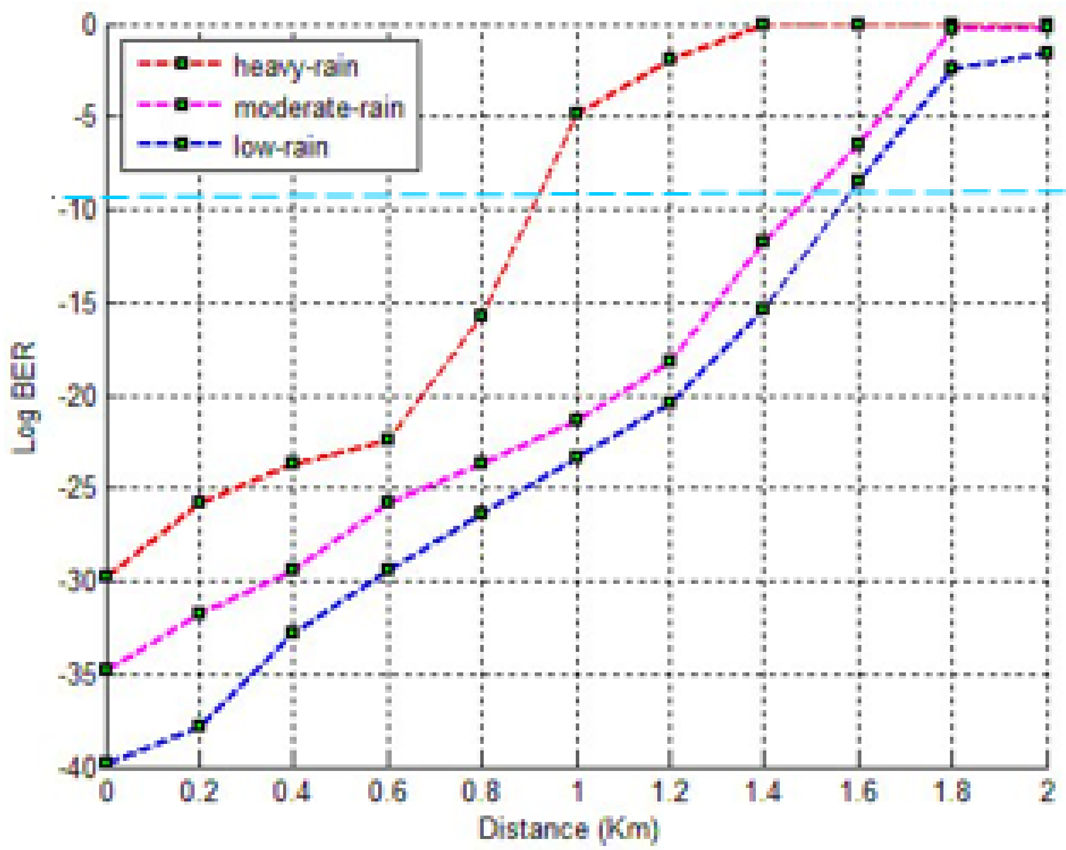


Figure 1.23: BER of rain vs distance.

Figure 1.23 shows the relationship between the bit error rate (BER) and the distance for three different weather conditions: heavy rain, moderate rain, and low rain. Here is a detailed analysis:

- The curve for heavy rain shows that the BER increases rapidly with distance, reaching high values of BER at a distance of about 0.9 km. To reach a BER higher than 10^{-9} under moderate rain, the distance does not exceed 1.5 km. The BER remains relatively low over longer distances for low rain, reaching high values beyond 1.6 km.

- The more intense the rain, the faster the BER increases with distance. This is explained by the greater attenuation of communication signals under unfavorable weather conditions.

In conclusion, the figure clearly illustrates how weather conditions impact the performance of communication systems, with a BER that increases proportionally to distance and rain intensity.

Snow effect

The attenuation caused by snow is influenced by to the precipitation (S, measured in millimeters per hour) and the wavelength according to the following relationships [24]:

1. Wet snow altitude below 500 m:

$$A_{snow}\,(dB\ /\ Km) = (0.0001023\ .\ \lambda + 3.7855466)\ \ .\ S^{0.72} \tag{1.5}$$

2. Dry snow altitude above 500 m:

$$A_{snow}\,(dB/\ Km) = (0.0000542\ .\ \lambda + 5.4958776)\ \ .\ S^{1.38} \tag{1.6}$$

Where:

- λ: Wavelength in (nm).
- S: Snowfall rate in (mm/h).

1.3.4 Characteristics of FSO Equipment

The following parameters must be considered in FSO link:

- **Range:** The distance FSO links can cover varies from just a few tens meters of up to several kilometers. Some manufacturers provide a maximum range, while others list a typical range that can be expected under various weather conditions.

- **Security:** The security level of FSO equipment is indicated by the laser class depicted in Table 1.8[24]. This is a key aspect to think about when designing wireless optical telecommunication systems because it affects how easy or difficult it is to install and maintain the laser link. Factors that help determine the laser class include the transmission wavelength, the power of the emission, and the shape of the beam.

- **System Margin and Quality of Service:** The quality of service, which includes the system's reliability and performance, is affected by the transmission wavelength. The system's ability to handle challenges, like atmospheric disturbances, can also depend on how many optical emitters are used; systems with multiple emitters are generally more stable.
- **Cost:** The cost of the system, which is obviously a very important criterion for operators to ensure maximum economic efficiency from the connection.

Table 1.8: Laser Category for 850 and 1550 nm.

Laser Classification	**Power (mW)**	**Opening size (mm)**	**Distance (m)**	**Power density (mW/cm^2)**
Wavelength 850 nm				
Class 1	0.78	7	14	2.03
		50	2000	0.04
Class 1M	0.78	7	100	2.03
		7	14	1299.88
	500	50	2000	25.48
Wavelength 1550 nm				
Class 1	10	7	14	26.00
		25	2000	2.04
Class 1M	10	3.5	100	103.99
	500	7	14	1299.88
		25	20.00	101.91

The primary suppliers of FSO equipment in the market are: BridgeWave, fSONA, LightPointe, MRV, Canon, PAV, RAD, and CableFree. The Table 1.9 outlines several instances of FSO equipment.

Table 1.9: Instances of FSO equipment.

Equipment Name	Description	Equipment Image
SONAbeam 2500Z	The SONAbeam Z series offers an economical solution for short-distance links up to 500 meters and provides up to 2.5Gbps of full-duplex bandwidth. Operating at a wavelength of 1550 nm enables it to penetrate harsh atmospheric conditions [25].	
Flight Spectrum	A pioneering Optical Wireless product inside a prominent telecommunication network, currently deployed across 60 nations. It utilizes a dual transmitter/receiver configuration to enhance performance, delivering 40 Mbps over a distance of 4 km [26].	
Intellimax systems	Exemplified by ULL-3000 and MB2000, combine Free Space Optics (FSO) and millimeter wave tech. The ULL-3000 models is designed to offers FSO with extremely ultra-low latency (<1 μs), which means it optimizes the path through the air to minimize delays. Both systems are capable of transmitting data at a speed of 2 Gbps over a distance of 10 kilometers, and they can do this reliably in all weather conditions with 99.999% availability [4].	

1.4 Integration of FSO Technology in Telecommunications

1.4.1 Applications Across Industries for FSO Links

- **Inter-Building Connectivity:** FSO technology is great for creating fast and cost-effective data links between buildings in various settings, even when the amount of data being transferred fluctuates[27].
- **Video Surveillance:** FSO systems are effectively used for wireless video monitoring in military, commercial, and public safety environments, providing better speed and quality than traditional methods.
- **Backhaul for Cellular Networks:** Adept at implementing FSO technology as an alternative path for extended bandwidth-intensive high-speed cellular services, enhancing connectivity within city infrastructure and SONET rings.
- **Broadcasting and Disaster Monitoring:** Experienced in the application of FSO systems are used for broadcasting live events and news, as well as for monitoring disasters, ensuring high-quality transmission in both regular and emergency scenarios.
- **Security:** FSO technology is employed to ensure secure data transfers, which is increasingly important with the emergence of quantum computing.
- **Last Mile Solution:** FSO communication serves as a crucial link for remote end-users who don't have access to optical fiber, particularly in rural areas.
- **IoT and 5G Integration:** Proficient in integrating FSO technology with IoT over 5G connectivity to support high bandwidth, low latency, and interference-free data transmission, which is essential for extensive IoT deployments.
- **Satellite Communications:** Skilled in efficiently implementing FSO technology in space applications, delivering power-efficient long-distance inter-satellite orbital links with improved system capacity and spectral efficiency.
- **Device-to-Device (D2D) and Multipoint Communication:** Proficient in applying FSO technology to diverse communication mechanisms such as D2D, machine-to-machine, vehicle-to-infrastructure, and multipoint-communications in settings like in healthcare facilities, railway stations, shopping malls, and industrial areas.

1.4.2 Comparing FSO Technology with Fiber Optics and Radio Technology

Table 1.10: FSO vs Fiber Optics and Radio Frequency.

	FSO	FO	RF
Transmission Speed	$\leq$ 10 Gbps[12]	100 Gbps to $\sim$ Tbps [28]	$\sim$ 6 Gbps[7]
Licensing Requirement	No permission required	Requires permission for digging	Often requires permits
Weather Dependency	Affected by rain, fog, dust, and heat	Not affected	Less affected
Applications	Between buildings (short distance)	Point-to-Point (long distance)	Longer coverage
Installation Time	Easy and fast	Difficult and time-consuming	Longer setup time
Immunity to Interference	Yes	Can be intercepted (less secure)	No
Security	Moderate	High	Moderate
Cost	Moderate	High	High

1.5 Benefits and Drawbacks of FSO Links

Advantages of FSO:

- License free operation.
- Moderate costs.
- Higher data rates and lower bit error rates.
- Immunity to electromagnetic interference.
- Secure communication due to line-of-sight requirement.
- Easy installation and maintenance.

- Suitable for indoor and outdoor applications.
- Potential for a high bandwidth-to-cost ratio.

Drawbacks of FSO:

- Limited by weather conditions (rain, fog, snow,etc.).
- Beam dispersion.
- Beam alignment requiring direct visibility.
- Atmospheric attenuation linked to composition, scintillation effects, and aerosol presence.
- Sensitivity to physical obstructions.
- Impact of adverse weather conditions.
- Limited lifespan of laser diodes.
- Higher power consumption.

1.6 Conclusion

To wrap up this chapter, it's clear that Free Space Optics (FSO) technology represents a significant advancement in wireless communications technology. However, it's not without its challenges, mainly from atmospheric conditions that can affect transmission quality. We've laid the groundwork to understand how FSO works and its implications. In the next chapter, we'll explore how to improve FSO systems, particularly through the use of Artificial Intelligence (AI) and metaheuristic methods.

Chapter 2

OPTIMIZATION TECHNIQUES

2.1 Introduction

This chapter provides an in-depth look at the basic principles of these techniques. We start by defining different types of optimization problems and reviewing their critical components. Then, we move on to examine a range of optimization methods, including simpler approaches like heuristics and more complex strategies known as metaheuristics. Additionally, we discuss two particular techniques: the Pachycondyla APIcalis algorithm (API) and Particle Swarm Optimization algorithm (PSO). Gaining an understanding of these methods will prepare individuals to effectively address complex problems and make well-informed decisions across a variety of disciplines.

2.2 Identifying Optimization Problems

Understanding how to classify optimization problems is key to solving a wide range of challenges effectively. These Problems are sorted into different categories depending on various factors such as the kind of constraints they involve and the characteristics of the decision variables.

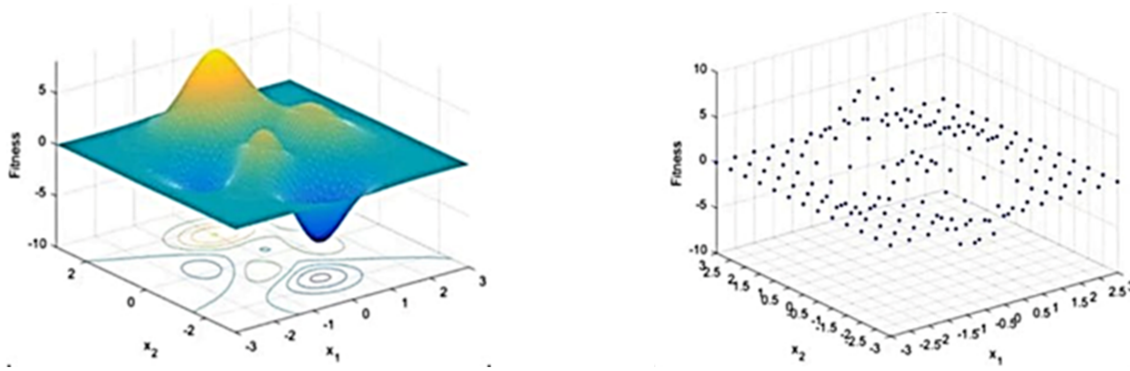
2.2.1 Continuous Vs Discrete

Optimization problems are broadly categorized into two types:

- **Discrete problems:** In these problems, variables are constrained to discrete values, such as integers or specific objects from a finite set.

- **Continuous problems:** Here, variables can assume any real value within a specified range.

Understanding this distinction is crucial as it informs the selection of appropriate optimization techniques tailored to each problem type.



(a) Continuous. (b) Discrete.

Figure 2.1: Continuous Vs Discrete problem.

2.2.2 Constrained Vs Unconstrained

- **Constrained:** This approach involves finding the best solution by either maximizing or minimizing a goal, known as the objective function, while adhering to specific restrictions or constraints.

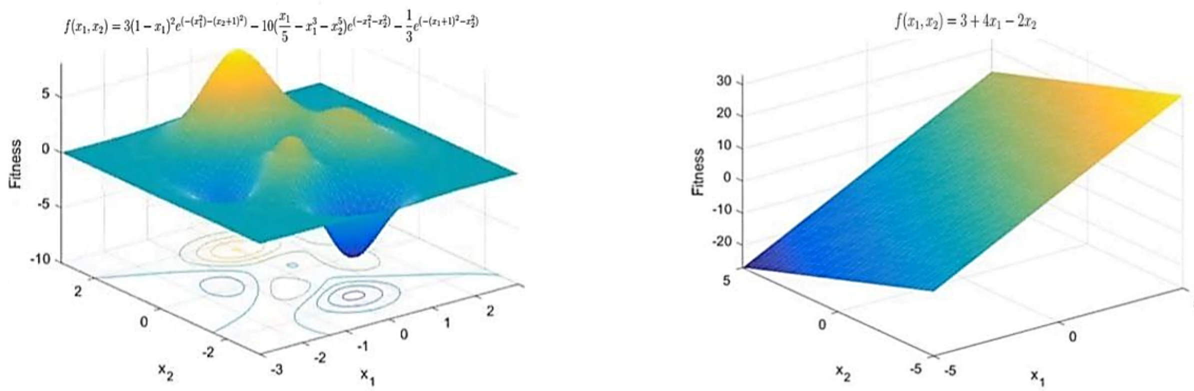
- **Unconstrained:** This method does not impose any restrictions on the decision variables, which allows for straightforward analysis using differential calculus to explore possible solutions.

2.2.3 Deterministic Vs Stochastic

In a deterministic optimization problem, all model data is exact and there's no uncertainty involved. This means every decision is based on known variables that do not change. Conversely, a stochastic optimization problem incorporates randomness or elements of probability, which means there's inherent uncertainty in the model data, affecting the decision-making process.

2.2.4 Linear Vs Non-Linear

- **Linear optimization problems:** In these problems, both the objective function and constraints are expressed as linear relationships.
- **Nonlinear optimization problems:** Here, either the objective function or the constraints, or both, involve nonlinear relationships.



(a) Non-linear. (b) Linear.

Figure 2.2: Objective function; Linear Vs Non-Linear.

2.2.5 Static vs Dynamic

- **Static optimization problems:** The objective function and constraints do not change over time.
- **Dynamic optimization problems:** The objective function or constraints change over time.

2.3 Optimization Elements

2.3.1 Objective Functions

Objective function play a pivotal role in mathematical optimization by either minimizing or maximizing a real-valued function across feasible alternatives. These functions, dependent on decision variables serve to gauge solution quality, striving for the most favorable solution.

2.3.2 Variables

Decision variables serve as the variables whose values can be adjusted within feasible ranges or alternatives. These adjustments directly influence the objective function's behavior and ultimately determine the feasibility and quality of solutions.

2.3.3 Constraints

Constraints in optimization define the permissible range of decision variables, delineating the feasible region and directing the decision-making process.

2.3.4 Optimization Metrics

Optimization metrics serve as vital tools for evaluating the efficacy of optimization endeavors. They gauge the performance of the objective function within imposed constraints, providing insights into the success of optimization strategies.

2.4 Optimization techniques

Optimization techniques encompass specialized algorithms crafted to address optimization challenges. These algorithms, integral to machine learning applications, aim to identify the optimal solution among multiple alternatives while adhering to predefined constraints. They fall into two principal categories:

- **Deterministic Optimization Algorithms:** These algorithms adhere to predefined rules, ensuring a consistent path towards solutions without incorporating randomness. Consequently, given identical starting points, deterministic algorithms consistently converge to the same final solution.
- **Stochastic Optimization Algorithms:** In contrast, stochastic algorithms leverage probabilistic rules, introducing randomness into the optimization process. Consequently, even with identical starting conditions, stochastic algorithms can yield diverse final solutions due to their inherent stochastic nature.

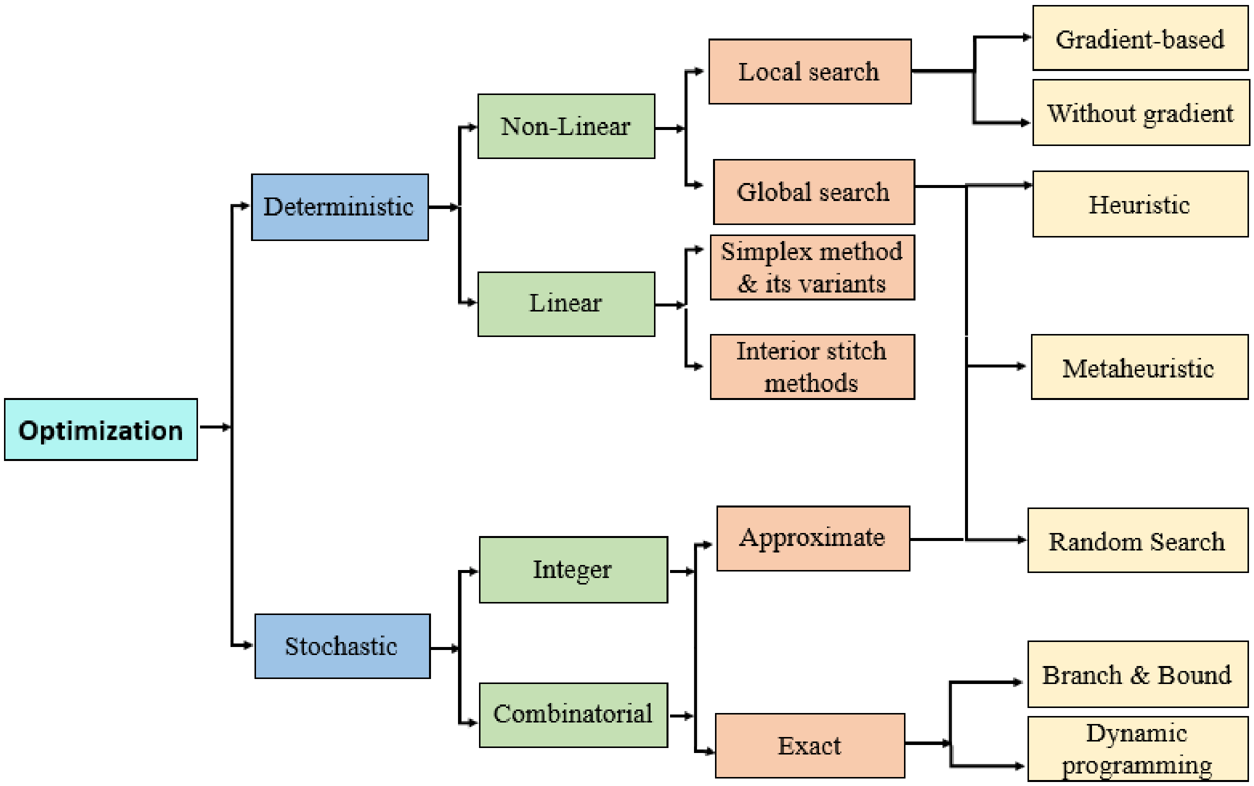


Figure 2.3: Different classes of optimization algorithms.

2.5 Heuristics

Heuristics are problem-solving techniques aimed at discovering satisfactory solutions, often close to optimal, within a reasonable computational effort, although without guaranteeing optimality or feasibility [29]. They fall into three main categories [30]:

- **Construction-based Heuristics:** These methods construct a solution step by step, typically starting with an empty or partial solution and gradually adding elements until a complete solution is achieved. This iterative process builds the solution from scratch, incrementally incorporating components until the entire problem is addressed.

- **Improvement-based Heuristics:** In contrast, improvement-based heuristics begin with an initial solution, which may be suboptimal, and iteratively refine it by making incremental adjustments. These adjustments aim to enhance the solution's quality, iteratively seeking improvements until reaching a satisfactory level where further enhancements are no longer feasible.

- **Hybrid Heuristics:** Hybrid heuristics integrate aspects of both construction-based and improvement-based approaches. By combining the strengths of these two methodologies, hybrid heuristics leverage the systematic construction process while also incorporating iterative improvements. This amalgamation allows for a comprehensive exploration of the solution space, exploiting the benefits of both strategies.

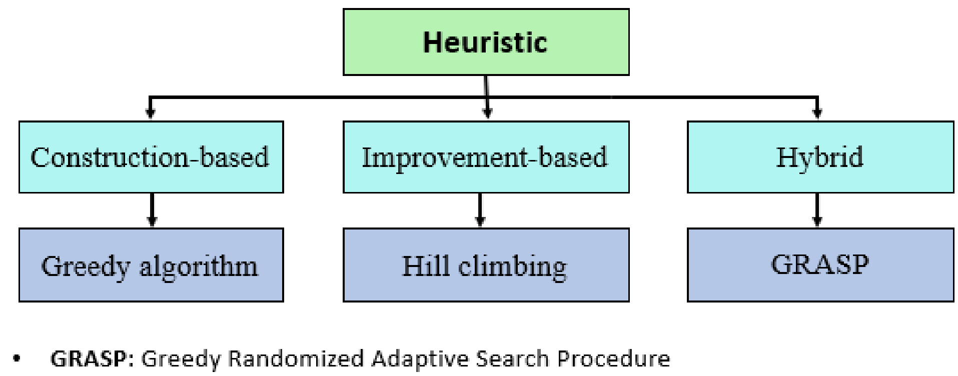


Figure 2.4: Different classes of a heuristic algorithms.

2.6 Metaheuristics

2.6.1 Overview of Metaheuristic Structures

The words of “meta” and “heuristic” are Greek where, “meta” is “higher level” or “beyond” and heuristics means “to find”, “to know”, “to guide an investigation” or “to discover” [31].

Metaheuristic algorithms are advanced optimization techniques designed to tackle complex problems that elude conventional problem-solving methods. These algorithms draw inspiration from various natural processes, including genetics, the behavior of swarms, and evolutionary principles. Common examples of metaheuristic algorithms are genetic algorithms, particle swarm optimization, ant colony optimization, simulated annealing, and tabu search. They find extensive applications across diverse domains such as engineering, finance, and computer science, providing solutions to intricate challenges that are otherwise difficult to solve using standard methods.

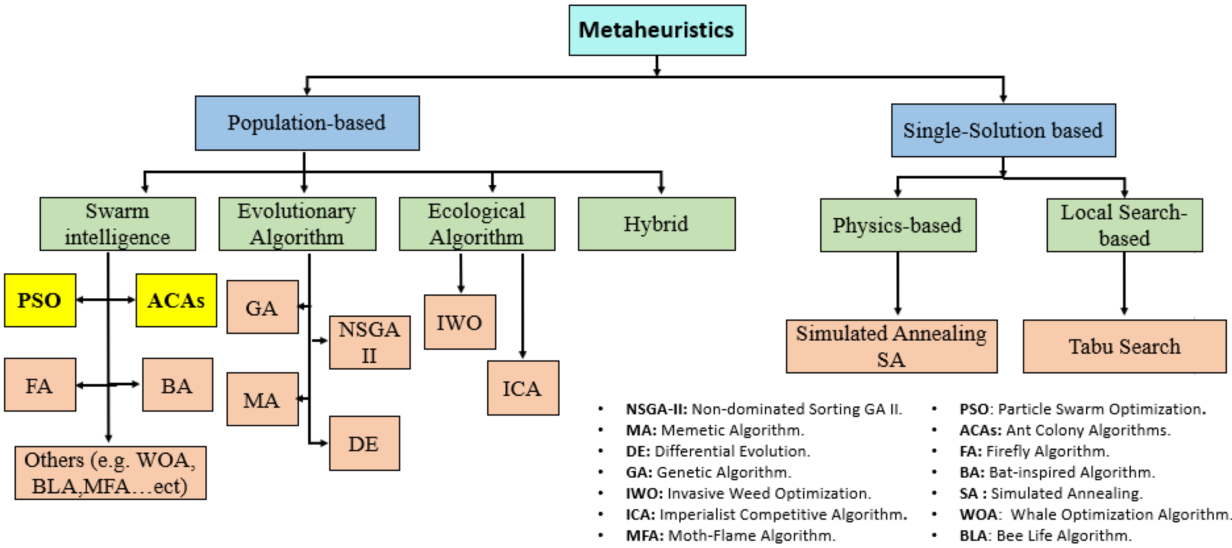


Figure 2.5: Classification of metaheuristic optimization algorithms.

2.6.2 Ant Colony Algorithms

The ant system represents an innovative type of cooperative search algorithm, inspired by the behaviors observed in real ant colonies. Ants demonstrate remarkably efficient strategies in solving shortest path problems between their food sources and the colony. The key mechanism for communication and decision-making about paths among ants is the use of pheromone trails. These pheromones allow ants to collectively optimize their routes and efficiently manage their navigation and resource allocation [32].

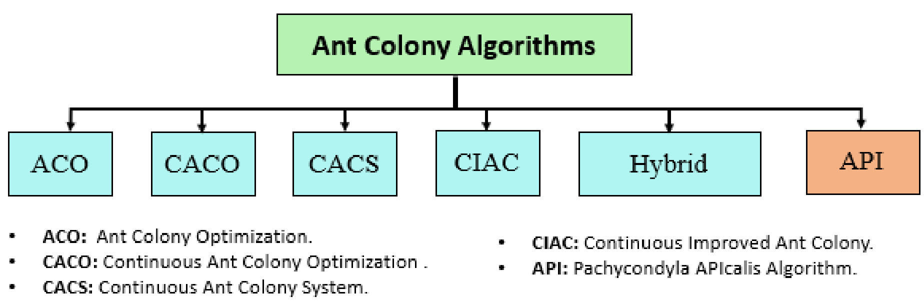


Figure 2.6: Classification of Ant Colony Algorithms..

Behavior of Ant Colonies

Ant behavior is characterized by sophisticated communication systems that rely heavily on pheromones. Ants navigate and coordinate their activities by depositing pheromones along their trails, which is a principle known as stigmergy. Within and around their colonies, this stigmergic system helps guide their movements. As ants travel between their nest and food sources, they leave behind a chemical substance called pheromone on the ground. This substance is detectable by other ants, whose path choices are influenced by the strength of the pheromone concentration, stronger concentrations generally attract more ants. These pheromone trails enable ants to efficiently locate and return to food sources previously discovered by other colony members. Over time, the paths used by ants tend to evolve, typically converging towards the shortest route between the nest and food sources [33]. This adaptive behavior showcases the ants' ability to optimize their routes based on collective, chemical signaling as depicted in Figure 2.7.

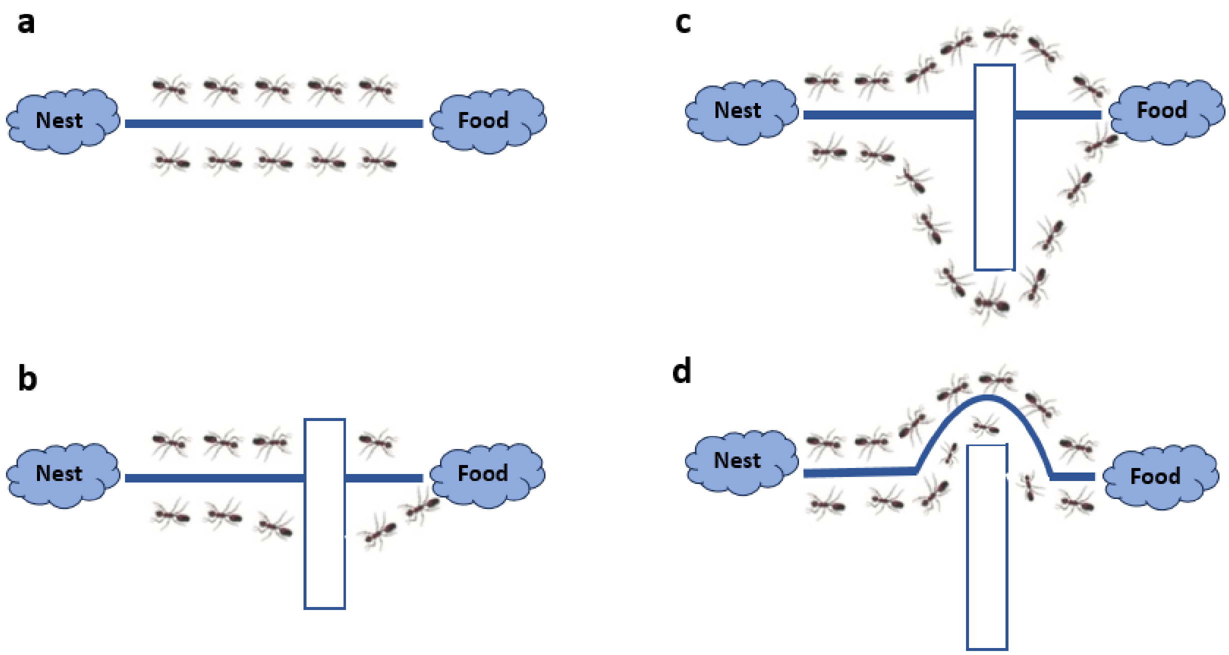


Figure 2.7: Ant Behavior (a) Ants in a pheromone trail between nest and food, (b) An obstacle interrupts the trail, (c) Ants find two paths to go around the obstacle, (d) A new pheromone trail is formed along the shorter path.

Impact of Pheromone Trails

- **Path selection and communication:** Ants employ chemical signals, specifically pheromone trails, to communicate the locations of food sources to their nest mates and guide them effectively. These pheromone trails are composed of chemical deposits left by ants as they move. An effective trail, characterized by stronger pheromone deposits, serves as a robust signal that attracts a larger number of ants, thereby enhancing the efficiency of foraging activities. This system allows ants to optimize their foraging routes, leveraging collective intelligence to find and harvest food resources efficiently.

- **Positive Feedback Loop:** An increased amount of pheromone left behind by following ants makes a trail even more attractive to other ants. This produces a beneficial feedback system that aids in the colony's convergence on ideal pathways by rewarding clever ideas.
- **Collaborative Learning and Optimization:** By means of pheromone exchange, the colony acquires collective knowledge on optimal pathways. Pheromone trails that are stronger direct the colony to the best places to look for food or return to the nest.
- **Adaptation to Obstacles:** Ants' decision-making processes are significantly affected by the intensity of residual pheromones whenever an obstacle disrupts a previously established pheromone trail. The presence of stronger pheromone deposits on shorter alternative routes increases the probability that these paths will be followed by other ants. This adaptive behavior allows the colony to efficiently navigate and adjust to sudden environmental changes, thereby maintaining the effectiveness of their foraging activities despite new obstacles.

2.6.3 Applications of Metaheuristic algorithms

- Metaheuristic optimization algorithms like Whale Optimization, Artificial Bee Colony, and Grey Wolf Optimizer enhance human activity recognition and fall detection using wearable sensors, boosting accuracy and efficiency [34].
- Metaheuristics excel where traditional optimization methods fall short, delivering high-quality solutions efficiently for complex problems in finance, planning, scheduling, and engineering design [35].
- Metaheuristic optimization enhances Support Vector Machine (SVM) parameter optimization for data classification, improving SVM accuracy and efficiency [36].
- Metaheuristics optimize system parameters in engineering, physics, and chemistry, enhancing system accuracy and efficiency through data-driven parameter identification [37].

- Metaheuristics tackle real-world challenges like scheduling, space allocation, and clustering, balancing optimal solutions with speed, addressing various practical problems effectively [38].

2.7 Pachycondyla APIcalis Algorithm

In the realm of ant colony algorithms, the term "ant colonies" typically refers to the utilization of stigmergy as a method for information exchange among the colony members.

However, the Pachycondyla Apicalis Algorithm (API) represents a departure from this traditional approach. Inspired by the foraging behavior of the primitive ant species Pachycondyla Apicalis, this algorithm uniquely omits the use of pheromone trails for communication. Instead, it explores alternative mechanisms of coordination and optimization, which diverge from the standard pheromone-based strategies commonly observed in other ant colony optimization algorithms.

2.7.1 Foraging strategy of Pachycondyla APIcalis

The foraging strategy of Pachycondyla Apicalis ants involves creating a network of hunting sites around their nest, extending up to ten meters away, with each site spanning a radius of approximately 2.5 meters. This strategic placement forms a "mosaic" that comprehensively covers a large territory. Notably, these ants may periodically relocate their nest due to factors like comfort or depletion of prey in the vicinity. Each ant undertakes an individual foraging mission, guided primarily by visual memory to navigate and identify hunting sites. Initially, the choice of site is random, but once a prey is captured, the location is memorized, and the ant returns using visual landmarks. This method contrasts markedly with species that rely on pheromone trails, illustrating a distinctly individualistic approach. As the ant continues to explore and revisit sites, it refines its understanding of which areas are most productive. Failure to find prey leads to exploring new areas or revisiting previous ones, thus optimizing the hunt for regions with abundant prey. When successful, an ant returns directly to the nest, prioritizing efficient prey delivery. Their minimal communication and reliance on individual memory and visual cues underscore a unique adaptive foraging technique distinct from other ant species [39].

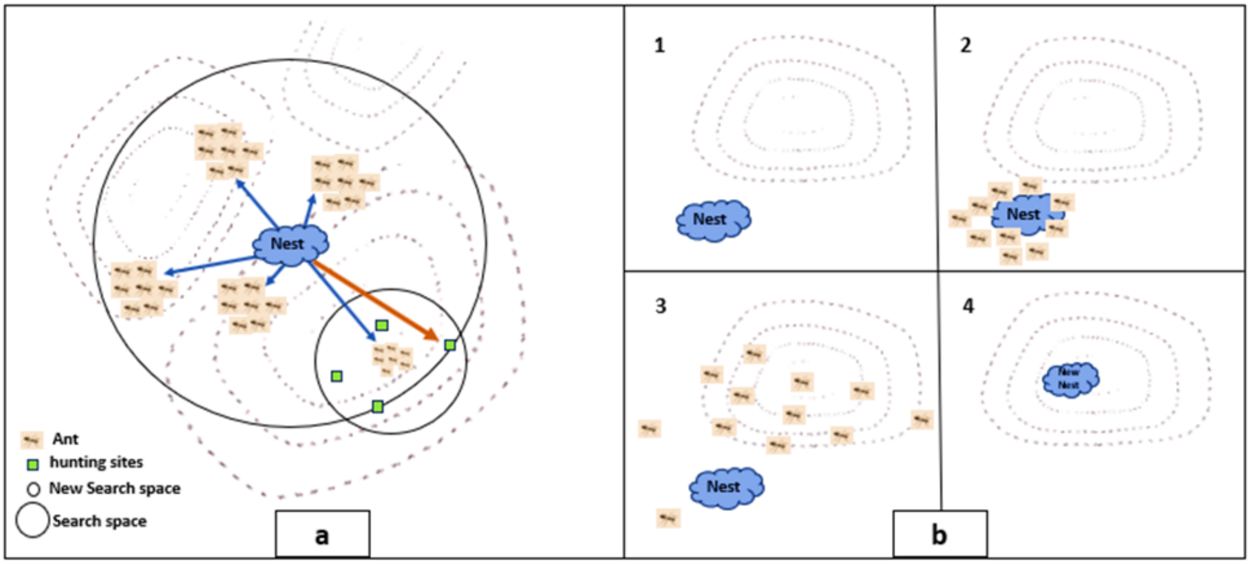


Figure 2.8: Foraging strategy of Pachycondyla APIcalis (a) Search for hunting sites, (b) the search steps for hunting sites..

2.7.2 API Algorithm

The API algorithm's procedures are methodically detailed as follows [35, 40]:

1. Initialization: Set the initial parameters for the algorithm.

2. Generation of New Nest (Exploration): Initiate the creation of new sites for resource gathering.

3. Exploitation: This stage includes several sub-steps:

   - 3.1 Intensification Search: Each ant evaluates the number of sites it remembers. If an ant remembers fewer than the set threshold of sites, it creates and explores a new site nearby. If the previous exploitation was successful, the ant revisits and exploits the same site. Otherwise, the ant chooses a new site from its memory at random for exploitation.

   - 3.2 Information Sharing: Sites in an ant's memory are probabilistically updated with the most successful site found during the current cycle.

   - 3.3 Nest Movement: If certain predefined conditions are met (e.g., resource depletion or environmental changes), the nest is relocated. If not, the process returns to the intensification search phase.

4. Termination Test: The algorithm checks if the end conditions are satisfied (such as a maximum number of iterations or achievement of goal state). If yes, the process stops; if no, the memories of all ants are cleared, and the cycle restarts from the second step.

This structured approach ensures that each ant intensively explores and utilizes available resources, sharing information to optimize collective success. The diagram below demonstrates how each ant intensifies its search efforts:

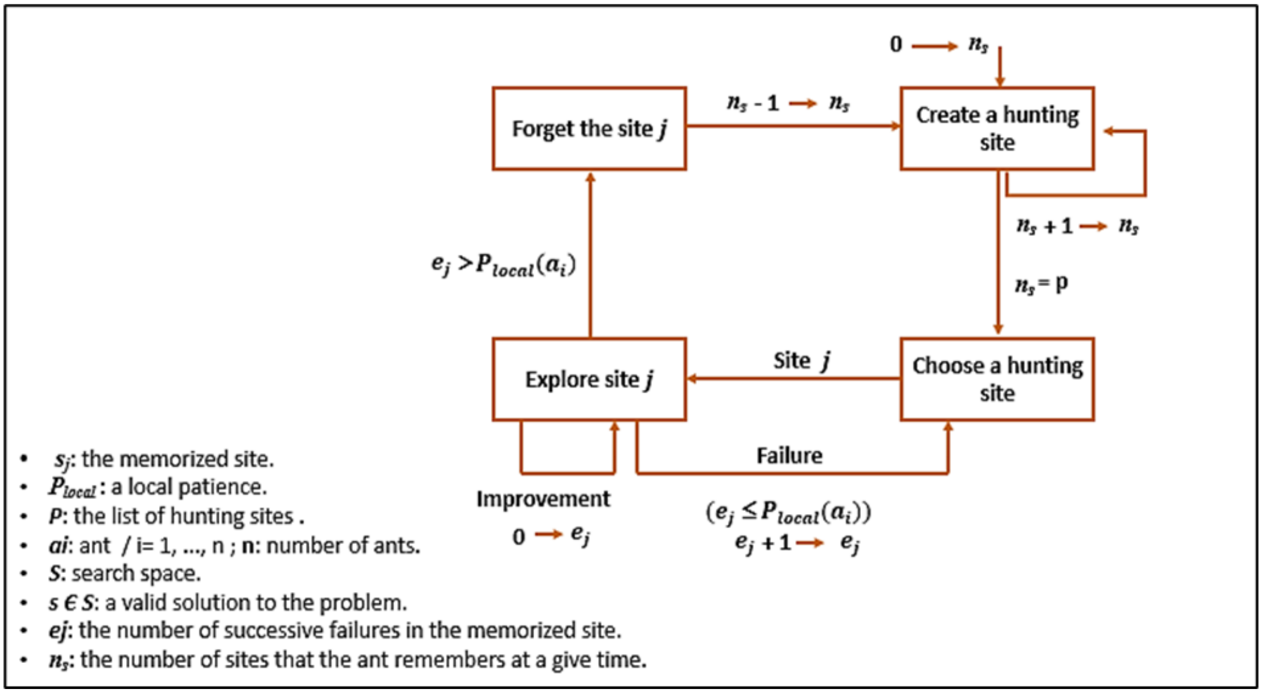


Figure 2.9: Basic structure of Pachycondyla APIcalis optimization (API) algorithm.

2.8 Particle Swarm Optimisation

Particle Swarm Optimization (PSO) is a computational method categorized under swarm intelligence, a concept originally introduced by Kennedy and Eberhart (1955) [30]. PSO mimics the social behaviors observed in natural organisms such as birds and fish. In these groups, individuals work collaboratively, learning from one another and their environment to find optimal resources. PSO operates as a stochastic optimization technique where multiple 'particles' explore potential solutions within a defined problem space [40], aiming to converge on the most effective solution. The algorithm has been applied across various sectors including healthcare, environmental science, industrial processes, commerce, and smart city development [41]. The behavior of each particle within the swarm is dictated by three primary components and depict in Figure 2.10:

- Inertia Component: This drives the particle to continue in its existing trajectory.
- Cognitive Component: It propels the particle towards the best position it has previously encountered.
- Social Component: This encourages the particle to head towards the best position discovered by its peers in the swarm.

These components collectively guide the swarm towards optimal solutions, balancing individual discovery and social learning.

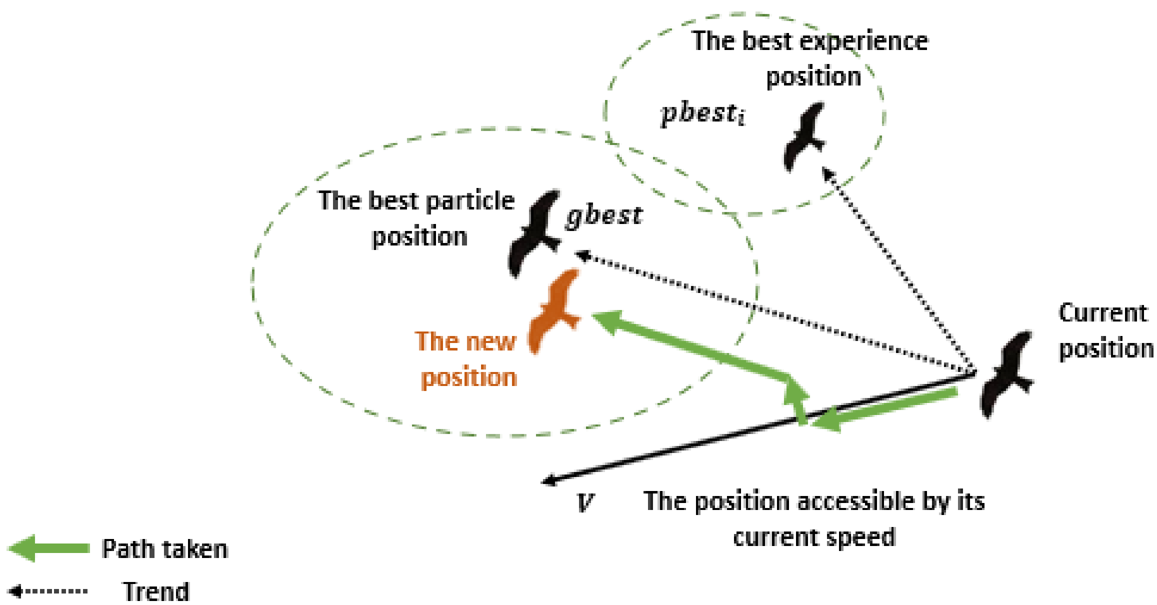


Figure 2.10: Movement of a particle.

2.8.1 PSO Algorithm

The Particle Swarm Optimization (PSO) algorithm is a well-regarded method in computational science , designed to mimic the collective behavior observed in natural swarms like birds or fish. It is employed to iteratively enhance solutions for complex optimization problems. Below is a structured breakdown of its workflow [40, 42]:

1. Initialization: Start by initializing a swarm of particles. Each particle in this swarm represents a potential solution within a multidimensional space.

2. Position and Velocity Definitions:

   - Each particle is defined by a position vector X_i in a D-dimensional space. For instance, particle i in a 3-dimensional space could have a position vector:

   $$X_i = [X_{i_1}, X_{i_2}, X_{i_3}] \tag{2.1}$$

   - Each particle also has a corresponding velocity vector V_i which dictates the rate and direction of movement through the solution space.

3. Personal and Global Bests:

   - Personal Best (Pbest): The best position a particle has achieved on its own.
   - Global Best (Gbest): The best position achieved by any particle in the swarm.

4. Velocity and Position Update:

   - Velocity Update: Each particle's velocity is adjusted based on its personal best and the global best, incorporating randomness for exploration:

   $$V_i(t+1) = \omega \cdot V_i(t) + c_1 \cdot r_1(P_{\text{best},i}(t) - X_i(t)) + c_2 \cdot r_2(G_{\text{best}}(t) - X_i(t)) \tag{2.2}$$

   where:

     - ω: Inertia weight.
     - c_1: Cognitive coefficient.
     - c_2: Social coefficient.

   - Position Update: The particle's position is updated by adding the new velocity to the current position:

   $$X_i(t+1) = X_i(t) + V_i(t+1) \tag{2.3}$$

5. Evaluation and Optimization Criteria:

   - After updating positions, evaluate the fitness of each particle against the problem's criteria.
   - Save the new personal and global best positions if improvements are found.

6. Loop until Convergence:

- The algorithm iterates through the velocity and position updates until the optimization criteria are met or a maximum number of iterations is reached, leading to the optimal solution.

  This iterative process effectively utilizes the social and cognitive components of swarm behavior to navigate towards the most favorable solutions in a given problem space.

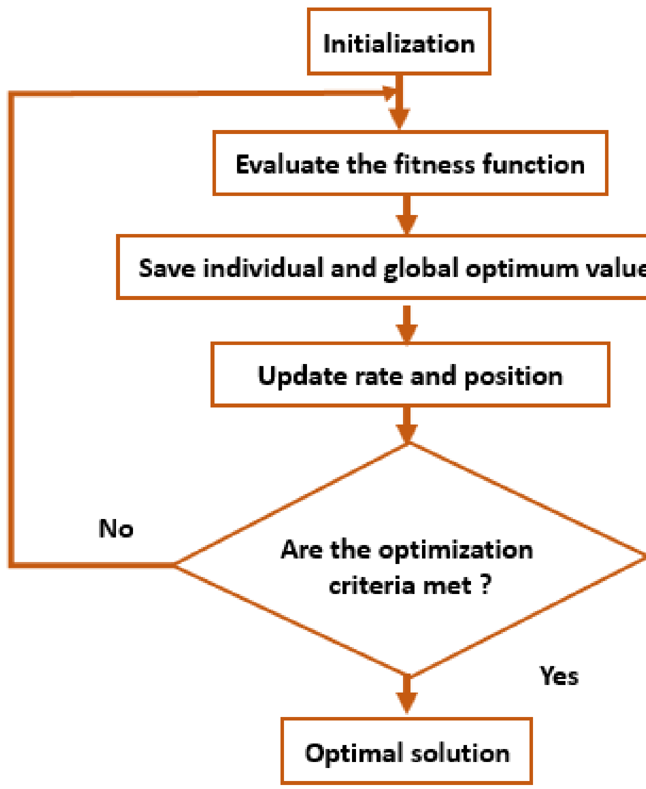


Figure 2.11: Basic structure of the particle swarm optimization (PSO) algorithm.

2.9 Conclusion

Chapter 2 provides an in-depth look at optimization techniques, discussing various types, including continuous, discrete, constrained, unconstrained, deterministic, and stochastic problems. It elaborates on the critical components such as objective functions, variables, constraints, and optimization metrics, offering a well-rounded understanding of the field.

The chapter places particular focus on advanced metaheuristic strategies, such as Particle Swarm Optimization (PSO) and Ant Colony Optimization, which are inspired by natural processes and capable of addressing complex challenges beyond traditional methods. It also introduces the API Pachycondyla Apicalis Algorithm, a novel approach that diverges from conventional pheromone-based strategies in ant colony optimization.

Moving forward, the next chapter will explore the practical implementation of these sophisticated optimization strategies, particularly the API and PSO methods, within the context of Free Space Optical (FSO) systems. This application aims to enhance the efficiency and effectiveness of FSO systems, demonstrating the real-world capabilities of these advanced optimization techniques in optimizing communication technologies.

Chapter 3

EVALUATIONS AND OUTCOMES OF SIMULATIONS

- **Contact Dr. Djellab Hanane regarding this chapter at the email address:** hanane.djellab@univ-tebessa.dz

General conclusion

This master's thesis examined the potential improvements in free-space optical (FSO) communication systems through particle swarm optimization (PSO) and Pachycondyla APIcalis (API) . The results show that FSO technology, which uses laser beams for data transmission, offers significant advantages such as high bandwidth and enhanced security. However, this technology faces environmental challenges such as rain, fog, and atmospheric turbulence, which can affect its performance.

PSO optimization has demonstrated significant improvements in link margin. Simulations have revealed that PSO can notably increase this margin for various deviation angle values, proving the effectiveness of this optimization method. Moreover, PSO helps maintain high signal quality despite environmental disturbances, thus proving its robustness. Similarly, the Pachycondyla Apicalis algorithm (API) has been analyzed for its potential in improving FSO systems. The results indicate that API, while effective, generally offers lower gains in link margin compared to PSO. API optimization still contributes to enhancing the system's robustness and reliability under adverse conditions, but PSO shows superior performance in maintaining higher and more stable link margins across different divergence and deviation angles.

In summary, this research makes a significant contribution to the advancement of next-generation wireless communication technologies. The techniques and results presented pave the way for further research aimed at continually improving the reliability and efficiency of FSO systems. Future perspectives include:

- Integrating more advanced artificial intelligence techniques to further optimize the performance of FSO systems.

- Exploring new industrial applications for free-space optical communication systems.

- Extending studies to more varied environments and real-use scenarios to test the robustness and effectiveness of PSO optimizations.

Thus, this master's thesis demonstrates that using PSO can make FSO technology more viable for future applications such as 5G communication networks and the Internet of Things (IoT), significantly improving the performance and reliability of free-space optical communication systems.

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