UNIVERSITE HASSIBA BENBOUALI DE CHLEF
Faculté de Technologie
Département d'Electronique

MEMOIRE DE MASTER

Domaine : SCIENCES ET TECHNOLOGIES
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Design and performance measuring of an indoor optical communication system using visible-light

Par

MEKSI Hayat
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Encadreur :
M. ADARDOUR H. Errachid
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To my dear parents, to whom I owe so much,

To my brothers,

To my sister,

To my girlfriends,

To all my family,

I dedicate this modest work,

ZENDJEBIL Khadidja

First of all, my god the almighty who gave me the tenacity to complete this work, I dedicate this modest work:

My dearest parents, no dedication, no words can express my gratitude, love, and deep respect. Your affection, your inordinate sacrifices, and your support, both moral and material, have allowed me to achieve my goal,

To my dearest sisters,

To my dear brothers,

To my dear buddy Khadidja for everything she has done for the success of this project,

I thank my darling Faiza, who supported me and gave me great support for this work,

My prominent family and My Girlfriends and my colleagues,

To all those who, far or near, have contributed to the elaboration of this work,

MEKSI Hayat

Acknowledgements

First, I thank ALLAH, the almighty, for guiding me and giving me the will, the patience, and the courage to complete this work.

Before presenting the results of this modest work, I would like to thank all those who have contributed directly or indirectly to its realization.

We thank our supervising teacher "Dr. Haroun Errachid ADARDOUR" for agreeing to follow our work and for his valuable advice and guidance. We had the privilege of working with you and appreciating your qualities, values, seriousness, and competence. Great, thanks, Dr. Haroun Errachid ADARDOUR. Throughout this period, you have supervised, guided, and devoted your time while leaving us a freedom for which we are grateful.

We sincerely thank all the teachers who taught us and who, through their skills, supported us in the pursuit of our studies.

Another time, thank you.

Abstract

Visible Light Communication (or VLC) is an emerging area of research in wireless communication. The technology operates similarly to communication systems that rely on optical fibers. However, the VLC system utilizes free space as its communication medium. The advancement of LED (or Light-Emitting Diode) technology has significantly improved contemporary communication systems. When VLC is used, the LED serves as a transmitter, and when the receiver is within the direct line of sight, it transmits data in the form of light signals. The VLC system employs fast light modulation to transfer data, rendering it challenging for human vision to discern. The detector rapidly interprets the data transmitted by the LED upon receiving it. The VLC system possesses several significant benefits in comparison to alternative communication techniques. It is relatively easy to build using an LED, phototransistor, or photodiode. The VLC system is cost-effective, portable, affordable, compact, and energy-efficient, mitigates radio interference, and eliminates the need for underground cables and broadcast licenses. This study examines the design and performance evaluation of an indoor optical communication system that utilizes visible-light technology. The simulation software Optisystem is employed for this purpose. Nevertheless, we simulated the Li-Fi (or Light-Fidelity) system within a room using propagation models, including Line-of-Sight (or LoS) and Non-Line-of-Sight (or NLoS). Furthermore, the suggested model has been evaluated utilizing the LoS propagation model, employing a single direct route and a single LED as the transmitter. Conversely, the NLoS propagation model has been analyzed in several situations, considering a single LED as the transmitter. To validate our concept, we have examined the effects of the following factors on the proposed system: the variation in the Field of View (or FOV) at the recipient's end, the variation in the Transmit Half Angle (or THA) value at the transmitter end, the variation in the bit rate of a Li-Fi link, and the impact of different ambient noise sources on a Li-Fi link. The simulation findings demonstrate that the proposed system obtained a bit rate ranging from 10 Mbps to 30 Mbps at an acceptable BER of 1e-6, as simulated in this study. This was observed when the FOV and THA varied from 11.25° to 90°. The impact of noise intensity on the proposed Li-Fi system was also considered.

Keywords: Visible light communication, Light-fidelity, Field of view, Transmit half angle, Bit rate, Bit error rate, Optisystem.

Résumé

La communication par lumière visible (ou VLC) est un domaine de recherche émergent dans le domaine des communications sans fil. Cette technologie fonctionne de la même manière que les systèmes de communication qui s'appuient sur des fibres optiques. Cependant, le système VLC utilise l'espace libre comme support de communication. Les progrès de la technologie des diodes électroluminescentes (ou LED) ont considérablement amélioré les systèmes de communication contemporains. Lorsque le système VLC est utilisé, la LED sert d'émetteur et, lorsque le récepteur se trouve dans la ligne de mire directe, elle transmet les données sous la forme de signaux lumineux. Le système VLC utilise une modulation rapide de la lumière pour transférer les données, ce qui les rend difficiles à discerner pour la vision humaine. Le détecteur interprète rapidement les données transmises par la LED dès qu'il les reçoit. Le système VLC présente plusieurs avantages significatifs par rapport aux autres techniques de communication. Il est relativement facile à construire en utilisant une LED et un phototransistor ou une photodiode. Le système VLC est rentable, portable, abordable, compact et économe en énergie, il atténue les interférences radio et élimine le besoin de câbles souterrains et de licences de radiodiffusion. Cette étude examine la conception et l'évaluation des performances d'un système de communication optique intérieur qui utilise la technologie de la lumière visible. Le logiciel de simulation Optisystem est utilisé à cette fin. Néanmoins, nous avons simulé le système Li-Fi (ou Light-Fidelity) à l'intérieur d'une pièce en utilisant des modèles de propagation, y compris la ligne de vue (ou LoS) et la non-ligne de vue (ou NLoS). En outre, le modèle proposé a été évalué à l'aide du modèle de propagation LoS, en utilisant une seule route directe et une seule LED comme émetteur. Inversement, le modèle de propagation NLoS a été analysé dans plusieurs situations, en considérant une seule LED comme émetteur. Pour valider notre concept, nous avons examiné les effets des facteurs suivants sur le système proposé : la variation du champ de vision (ou FOV) du côté du destinataire, la variation de la valeur du demi-angle d'émission (ou THA) du côté de l'émetteur, la variation du débit binaire de la liaison Li-Fi et l'impact de différentes sources de bruit ambiant sur la liaison Li-Fi. Les résultats de la simulation montrent que le système proposé a obtenu un débit binaire allant de 10 Mbps à 30 Mbps avec un BER acceptable de 1e-6, comme simulé dans cette étude. Cela a été observé lorsque le FOV et le THA variaient de 11.25° à 90°. L'impact de l'intensité du bruit sur le système Li-Fi proposé a également été pris en compte.

Mots-clés : Communication par lumière visible, Fidélité de la lumière, Champ de vision, Demi-angle de transmission, Débit binaire, Taux d'erreur binaire, Optisystem

ملخص

تُعد الاتصالات بالضوء المرئي (أو VLC) مجالاً ناشئاً للبحث في مجال الاتصالات اللاسلكية. تعمل هذه التقنية بشكل مشابه لأنظمة الاتصالات التي تعتمد على الألياف الضوئية. ومع ذلك، يستخدم نظام VLC الفضاء الحر كوسيط اتصال. وقد أدى تقدم تكنولوجيا الصمام الثنائي الباعث للضوء (أو الصمام الثنائي الباعث للضوء) إلى تحسين أنظمة الاتصالات المعاصرة بشكل كبير. عند استخدام نظام VLC، يعمل الصمام الثنائي الباعث للضوء كجهاز إرسال، وعندما يكون جهاز الاستقبال داخل خط الرؤية المباشر، فإنه ينقل البيانات في شكل إشارات ضوئية. ويستخدم نظام VLC التعديل الضوئي السريع لنقل البيانات، مما يجعل من الصعب على الرؤية البشرية تمييزها. يقوم الكاشف بتفسير البيانات المرسلة بواسطة الصمام الثنائي الباعث للضوء بسرعة عند استقبالها. يمتلك نظام VLC العديد من المزايا المهمة مقارنةً بتقنيات الاتصال البديلة. من السهل نسبيًا بناؤه باستخدام الصمام الثنائي الباعث للضوء والترانزستور الضوئي أو الصمام الثنائي الضوئي. نظام VLC فعال من حيث التكلفة ومحمول وميسور التكلفة وصغير الحجم وموفر للطاقة، ويخفف من التداخل اللاسلكي، ويغني عن الحاجة إلى كابلات تحت الأرض وتراخيص البث. تتناول هذه الدراسة تصميم وتقييم أداء نظام اتصالات بصري داخلي يستخدم تقنية الضوء المرئي. تم استخدام برنامج المحاكاة Optisystem لهذا الغرض. ومع ذلك، فقد قمنا بمحاكاة نظام Li-Fi (أو الدقة الضوئية) داخل غرفة باستخدام نماذج الانتشار، بما في ذلك خط الرؤية (أو LoS) وغير خط الرؤية (أو NLoS). علاوةً على ذلك، تم تقييم النموذج المقترح باستخدام نموذج انتشار خط البصر (LoS)، باستخدام مسار مباشر واحد ومصباح LED واحد كجهاز إرسال. وعلى العكس من ذلك، تم تحليل نموذج الانتشار غير المباشر في عدة حالات، مع الأخذ في الاعتبار وجود مصباح LED واحد كجهاز إرسال. وللتحقق من صحة مفهومنا، قمنا بفحص تأثيرات العوامل التالية على النظام المقترح: التباين في مجال الرؤية (أو FOV) في طرف المستلم، والتباين في قيمة زاوية نصف الإرسال (أو THA) في طرف المرسل، والتباين في معدل البت لوصلة Li-Fi، وتأثير مصادر الضوضاء المحيطة المختلفة على وصلة Li-Fi. تُظهر نتائج المحاكاة أن النظام المقترح حصل على معدل بت يتراوح بين 10 ميغابت في الثانية و30 ميغابت في الثانية بمعدل الخطأ في البت المقبول يبلغ 1e-06، كما تمت محاكاته في هذه الدراسة. وقد لوحظ ذلك عندما تراوح مجال الرؤية وTHA من 11.25 درجة إلى 90 درجة. كما تم النظر في تأثير شدة الضوضاء على نظام Li-Fi المقترح.

كلمات المفتاحية: الاتصال بالضوء المرئي، دقة الضوء، مجال الرؤية، زاوية نصف الإرسال، معدل البت، معدل الخطأ في البت، نظام البصريات.

Chapter 1 : Visible Light Communication Technology

Chapter 2 : Components of a Li-Fi Communication Network

Chapter 3 : Simulation Results and Interpretations

ADC	Analog Digital Converter
APD	Avalanche Photodiode
AWGN	Additive white Gaussian noise
BER	Bit Error Rate
FOV	Field of view
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical and Electronics Engineers
IES	Interference between Symbols
IR	Infra-Red
IRDA	International Infrared Data Association
LED	Light Emitting Diode
Li-Fi	Light-Fidelity
LoS	Line of Sight
LPF	Low-Pass Filter
LTE	Long Term Evolution
MAC	Media Access Control
MCM	Multi-carrier modulation
NLoS	Non-Line-of-sight
NRZ	Non-Return-to-Zero
OCC	Optical Camera Communication
OFDM	Orthogonal Frequency Division Multiplexing
OLO	Local Optical Oscillator
OOK	On-Off Keying
OT	Operation Theatres
OWC	Optical Wireless Communications
PD	Photodiode
PHY	Physical-layer
P-I-N	Positive Intrinsic Negative Diode
PPM	Pulse Position Modulation
PWM	Pulse width modulation
RF	Radio Frequency
RGB	Red Green Blue
ROV	Remotely Operated Vehicles
SCM	Single Carrier Modulation
SMD	Surface Mounting Device

SNR	Signal to Noise Ratio
THA	Transmitter half angle
TIA	Trans-Impedance Amplifier
VLC	Visible Light Communications
VPPM	Variable Pulse Position Modulation
WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless-Fidelity
WLAN	Wireless Local Area Network

Chapter 1

Chapter 2

Chapter 3

Chapter 1

Chapter 2

Chapter 3

General introduction

VLC technology, also known as Visible Light Communication, is a wireless communication system that utilizes light signals to transfer data in a broader scope. It provides benefits compared to conventional wireless communication technologies like Wi-Fi, specifically regarding velocity, security, and dependability. Nevertheless, the utilization of VLC technology in home automation systems is still limited due to specific technical obstacles.

Li-Fi, also known as Light Fidelity, is a wireless communication technology that utilizes light as a medium for data transmission. Its development addressed the issues faced by conventional wireless communication, such as the saturation of the radio spectrum and security concerns. Li-Fi provides enhanced data transfer speed, heightened security, and improved resistance to interference. Optical communication employs light signals for data transmission, reducing susceptibility to interference and enabling two-way transmission.

This study investigates the potential application of Li-Fi technology in developing a highly efficient transmission system. The first chapter will begin with an introductory overview of VLC and Li-Fi technology. In addition, we will examine the present obstacles confronting conventional wireless communication technologies, such as Wi-Fi. This chapter presents an overview and features of visual communications using light. This document comprehensively explains this technology's operational principle and structural requirements for communication. It then proceeds to describe the characteristics of Li-Fi technology, including its conceptual and functional principles, the structure of the Li-Fi network, its applications, advantages, and limits.

The second chapter will examine the various elements of a communication network and the specific attributes of the LED and photodetector. The channel modeling section will discuss noise, transmission channel capacity, and three wireless optical channels. In addition, we will discuss the modulations related to VLC transmissions and the various encoding methods used.

In the third chapter, we will establish a prototype of a Li-Fi system and assess its performance and usability. We will also explain the potential of Li-Fi technology.

Ultimately, this work aims to illustrate the efficacy of Li-Fi communication as a viable substitute for conventional wireless communication technologies in the VLC system. In this discussion, we will examine the benefits and difficulties associated with Li-Fi communication and the most effective strategies for designing and implementing such a system.

CHAPTER 1

Visible light communication technology

1.1. Introduction

Solid-state lighting (SSL) device development has grown significantly, especially with regard to light-emitting diodes (LEDs). These days, LEDs are incredibly dependable and efficient, and they last significantly longer than traditional light sources. Because of these benefits, LEDs are being employed in more lighting applications, and it's anticipated that they will soon completely replace conventional light sources.

LEDs have other unique qualities. They can flip on quickly, making them useful for communication and illumination. Because of this property, a brand-new communication method called Visible Light Communication (or VLC) was developed, enabling high-speed data transfer via LED lights.

Wi-Fi is presently the most famous wireless technology globally. However, this technology has specific drawbacks, including interference, a restricted frequency range, and saturation.

The newest technology, Li-Fi (see Figure 1.1), might be an excellent substitute for addressing these restrictions. Although Wi-Fi and Li-Fi technologies are employed for wireless communication, they differ greatly in that Li-Fi uses visible light, whereas Wi-Fi uses radio waves. Professor Harald Haas coined the name "Li-Fi" in 2011 when he showed how data could be transmitted using an electroluminescent diode (or LED) that modulated its intensity at a high frequency that was invisible to the human eye.

Figure 1.1. Overview of technology Li-Fi [1].

Because it uses visible light and the infrared spectrum, which has a bandwidth roughly 2600 times greater than the radio spectrum, this technology holds great promise for the future. When data transmission is required, it may serve as a replacement for RF communication (such as Wi-Fi or cellular networks). At 224 gigabits per second, Li-Fi is around 100 times faster than some Wi-Fi applications.

This chapter presents the generalities and features of visual communications by light. The working idea of this technology and the framework required for this kind of communication are explained in depth. Potential applications range from visible light to light fidelity. The attributes of Li-Fi technology include its conceptual and functional principles, network structure, applications, benefits, and limitations [1].

1.2. Generalities

A portion of optical wireless communications is known as VLC (or OWC). While VLC communications only cover the visible portion of the wavelength spectrum between 380 and 750 nm [2], which corresponds to a frequency range from 430 THz to 790 THz [3], as shown in Figure 1.2, OWC communications include all three visible, infrared, and ultraviolet light wavelengths.

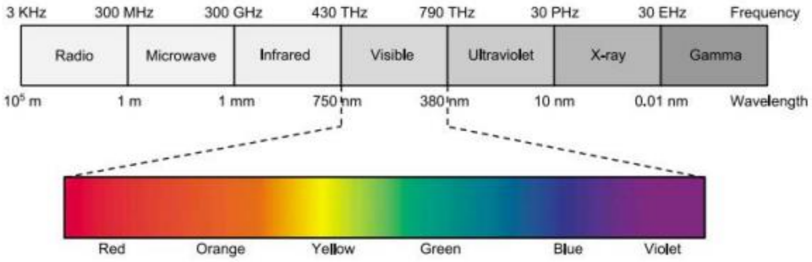


Figure 1.2. Electromagnetic spectrum [4].

VLC has transitioned from being a component of OWC to a standalone technology. Unlike traditional OWCs, which are primarily used for communication, VLC's unique characteristic of being visible to the human eye has opened up new applications, such as illumination, making it a versatile technology. The whole visible light spectrum is usable by VLC systems. The excellent availability of broadband (more than 10,000 times the bandwidth of the RF spectrum) in these communications solves the issue of the low bandwidth of RF communications [5].

1.3. History of VLC technology

The concept of exploiting visible light for data transfer is not entirely novel. Smoking signals were employed to transmit messages dating back several millennia and were used by several civilizations, such as the Native Americans and Romans. Lighthouses assist ships in navigating treacherous coastal regions by emitting visible beams of light at regular intervals. The "Pharos of Alexandria" is widely considered to be the inaugural tower that functioned as a lighthouse and was among the Seven Wonders of the World. The construction of this structure can be traced back to 300 BC. Alexander Graham Bell, a Scottish scientist and inventor, is credited with creating the photophone, the first advanced endeavor to utilize visible light for data transmission. The photo-phone, invented by Alexander Graham Bell and his helper Charles Tainter, was a device that enabled the transmission of data using beams of sunlight. It was completed in February 1880. Figure 1.3 depicts a schematic illustration of the photo-phone, clearly describing its functioning. The sunlight is directed through a lens *(a)* onto *(b)* thin mirror, which is then vibrated by the user's voice transmitted through a mouthpiece. The light beams reflected from the vibrating mirror carry the modulated voice signal. The light subsequently passes through lens *(c)* and is directed towards a parabolic mirror *(e)*, where a selenium cell *(d)* is positioned at its focal point. The conductivity of Selenium is inversely proportional to the intensity of light incident upon it, making it a convenient feature of this material. A connected telephone *(g)* can convert the signal back into audible waves by demodulation. In April 1880, Bell and Tainter achieved the first instance of wireless communication in history when they were positioned 213 meters apart. Tainter instructed Bell to wave his hat intermittently, demonstrating their device's functionality [6].

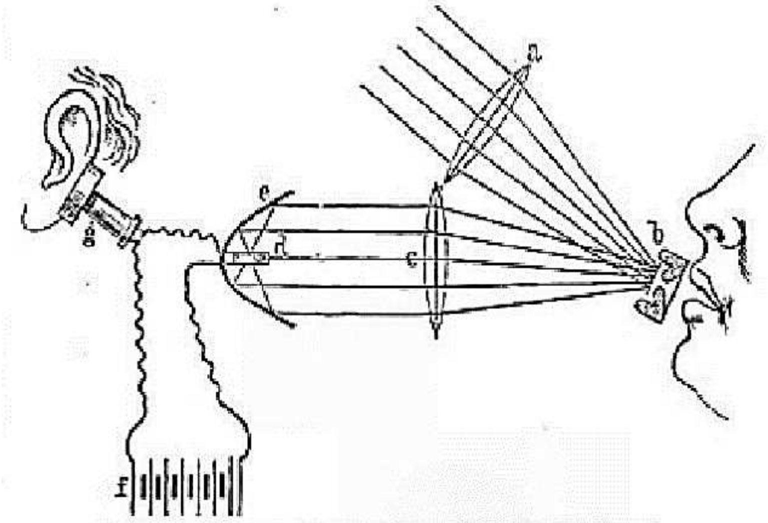


Figure 1.3. Schematic view of the photophone [6].

1.4. Architecture of a VLC system

The two primary components of a VLC system are a transmitter that modifies the light generated by LEDs and a receiver that uses a photodetector to extract the modulated signal from the light. As seen in Figure 1.4, the transmitter and receiver are physically apart but connected via the VLC channel [7].

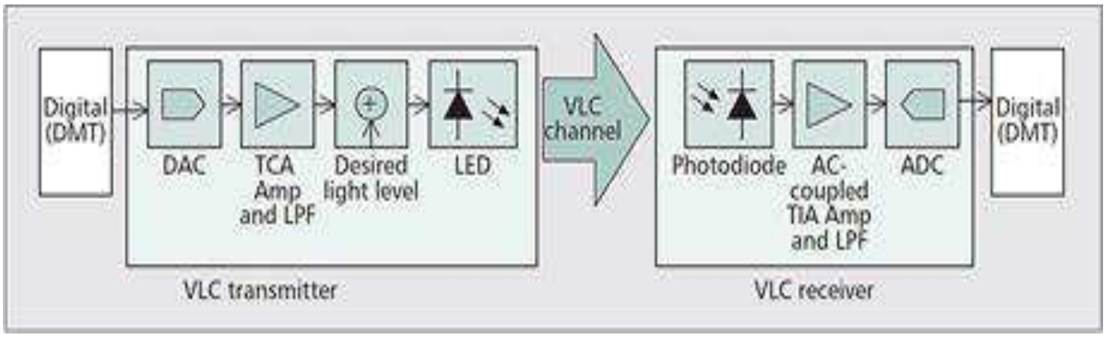


Figure 1.4. Block diagram of a VLC system [7].

1.4.1. VLC transmitter

A VLC transmitter is an electro-optical transducer that transmits data using visible light waves and a wireless transmission medium [8]. The transmitter consists of a transduction amplifier (TCA) and a digital-analog converter (DAC, Digital to Analogue Convertor). It may modulate information bits and convert them into an analog current signal.

High-speed LEDs, transconductance amplifiers, and pass-bass filters (LPF or low pass filter) [9]. The LED transforms an electric signal into optical energy, enabling both communication and lighting. Online encoding and modulation of the information by the DAC is followed by transmission of the information to the optical signal through modulation of the LED light's amplitude or other characteristics [10].

1.4.2. VLC receiver

An LPF pass-bass filter is placed after the photodiode, transforming the optical power received into an electrical signal at the receiver level. Subsequently, a trans-impedance amplifier (or TIA) amplifies, demodulates, and decodes this electrical signal. The analog current signal is converted into a digital signal using an analog-digital converter (ADC, Analogue to Digital Convertor) to obtain the bits of the user's message.

Among the numerous varieties of photodetectors, each with its own unique properties, photodiodes stand out. Their compact size, high sensitivity, and quick reaction make them the most well-liked photodetectors. The two most common types of photodiodes used as photodetectors are P-I-N (or Positive Intrinsic Negative Diode) and APD (or Avalanche Photodiode) [11].

1.5. Applications of VLC

VLC has naturally been taken into consideration for applications in both indoor and outdoor contexts, given all of the benefits and downsides mentioned above [12]:

- Indoor orientation: The position of a receiver is triangulated using multiple light sources with centimeter accuracy.
- Limited coverage areas: VLC, including hospitals, can be utilized where RF systems are prohibited. It can also be used as a data access solution underwater or in other locations without RF service.
- Personal network: The goal is to enable wireless communication like Wi-Fi. As a result, the infrastructure's LED light sources become access points.
- Transport communication: New vehicle applications like platooning and self-driving cars can be supported by VLC technology [13].

1.6. Visible light to light fidelity

To ensure the smooth integration of VLC technologies, it is imperative to establish standardized protocols for the physical layer (PHY) and the MAC layer. These protocols will facilitate the efficient implementation of VLC technologies in various applications and have garnered interest from international and national standardization organizations. The initial global standard for Visible Light Communication (VLC), specifically known as IEEE 802.15.7, was officially released in 2011 by the Working Group for Wireless Personal Networks. This standard explicitly defines the physical (PHY) and media access control (MAC) layers for short-range wireless optical communications that utilize visible light for indoor and outdoor applications.

The IEEE 802.15.7 specification [14] allows for the utilization of gradients to regulate light brightness and electricity consumption. Employing a gradient and the Li-Fi transmission circuit will enhance the light efficiency of the bulbs. Regarding infrastructure, substituting incandescent lights with current LED bulbs will create a network for illumination and communication. Due to the significant difference between visible light and the RF band, 33 other RF devices can't interfere with Li-Fi. This makes Li-Fi suitable for use in hospitals and airplanes. The communication range of VLC is constrained, in contrast to Li-Fi technology, which utilizes the entire range of light spectrum for communication. Various wireless communication applications include Wi-Fi, GSM, satellite, and LTE. Li-Fi is a specific use of Visible Light Communication (VLC). In contrast to VLC apps, Li-Fi utilizes infrared light for communication. A speed of around 40 Gbps is attained. Nevertheless, RF is far less susceptible to noise than Li-Fi. Li-Fi serves as a supplement to RF communications rather than a replacement for them.

1.7. Definition of Li-Fi technology

Li-Fi, short for Light Fidelity, is a term that is reminiscent of Wi-Fi or the superior sound quality of Li-Fi [15]. The system is a completely connected, high-speed wireless communication that uses visible light in both directions. Li-Fi is a technique that enables data transmission using the visible part of the electromagnetic spectrum, specifically light, as opposed to Wi-Fi, which uses radio waves. LED lamps, known for their energy efficiency, exhibit exceptional responsiveness. They can be activated or deactivated at an undetectable rate to the human eye. The Li-Fi technology rapidly adjusts light brightness to generate a signal that a receiver can understand.

1.8. Origins and development of Li-Fi

The concept of Li-Fi was conceived in 2011 by Professor Harald Haas, an expert in mobile communications at the University of Edinburgh. During a TED Global conference, Haas presented his visionary concept titled "Wireless data from every light bulb." The presentation was pivotal in developing and growing enthusiasm for Li-Fi in the wireless communications industry. Since then, numerous organizations have dedicated themselves to promoting the development of broadband wireless optical communication technologies. Below is a timeline outlining the key events that have shaped the development of the Li-Fi idea [1]:

In 2004, Japan demonstrated LED lighting systems to showcase their ability to rapidly transmit data to portable and in-vehicle computing devices.

In 2005, experimental tests were conducted in Japan to send data to mobile phones using VLC (Visible Light Communications) technology. The testing utilized fluorescent light and LEDs, achieving estimated speeds of 10 kbps and several Mbps.

In 2007, a demonstration occurred in Japan where an LCD TV with an LED backlight transferred information to a PDA using light. In the same year, Japan's Visible Light Communications Consortium (VLCC) put forward standards for visible light communication systems and the visible light identification system. These standards, known as JEITA CP-1221 and JEITACP-1222, were subsequently accepted by JEITA (Japan Electronics and Information Technology Industries Association).

In 2008, international guidelines were established for local networks utilizing Optical Wireless Communications (OWC), incorporating infrared (IR) and Visible Light

Communication (VLC) technology. Using a direct target line, VLC demonstrations utilizing five LEDs obtained data speeds exceeding 100 Mbps across short distances of a few meters.

In 2009, the VLCC introduced its initial specification standard, which incorporated and enhanced the fundamental standards of the International Infrared Data Association (IRDA). This standard also established a range of wavelengths inside the visible light spectrum for practical applications.

In 2010, VLC technology was created to facilitate communication among various electronic devices, including high-definition TVs, information kiosks, personal computers, personal digital assistants, cell phones, and more.

In 2011, the University of Edinburgh, United Kingdom, conducted a practical demonstration of a VLC (Visible Light Communication) system that utilized an OFDM (Orthogonal Frequency Division Multiplexing) technique. The device achieved a data transmission rate of 124 Mbps and employed a commercially available phosphorescent white LED.

In 2014, StinsComan, a Russian firm, introduced a local wireless Li-Fi network called BeamCaster. This network can carry data at an impressive speed of 1.25 gigabytes per second (Gbps) [16].

In 2016, Lucibel, a French business, conducted a trial of a prototype of bi-directional and high-speed Li-Fi illumination at the offices of property producer Sogreprom in France [17].

In 2018, Oledcomm, a French startup, unveiled MyLiFi, an LED desktop lamp that utilizes Li-Fi technology to transmit a wireless Internet connection using light.

In 2019, Oledcomm unveiled the LiFiMax, which provides a maximum download speed of 100 Mbit/s and an upload speed of up to 40 Mbps.

In 2023, Oledcomm, a French business, introduced an upgraded version of its Li-Fi technology, which now offers a doubled speed of 2 Gbps. This advancement targets data transmission applications in future factories and transportation systems [18].

1.9. Architecture of a Li-Fi network

The Li-Fi architecture incorporates many LED lights that utilize a constant voltage and constant current for optical transmission. The fundamental elements of such a system are as previously described:

- Several LED lights are used to transmit data.

- An optical sensor is designed to receive and detect data by measuring light intensity. This can be accomplished with a photodetector or a camera, such as a camera found on a mobile phone. In the second scenario, we refer to it as Optical Camera Communication (or OCC) [1]

Figure 1.5 demonstrates that terminals can connect to the Internet through an LED bulb. The lamp driver enables the adjustment of LED brightness based on environmental conditions and received data.

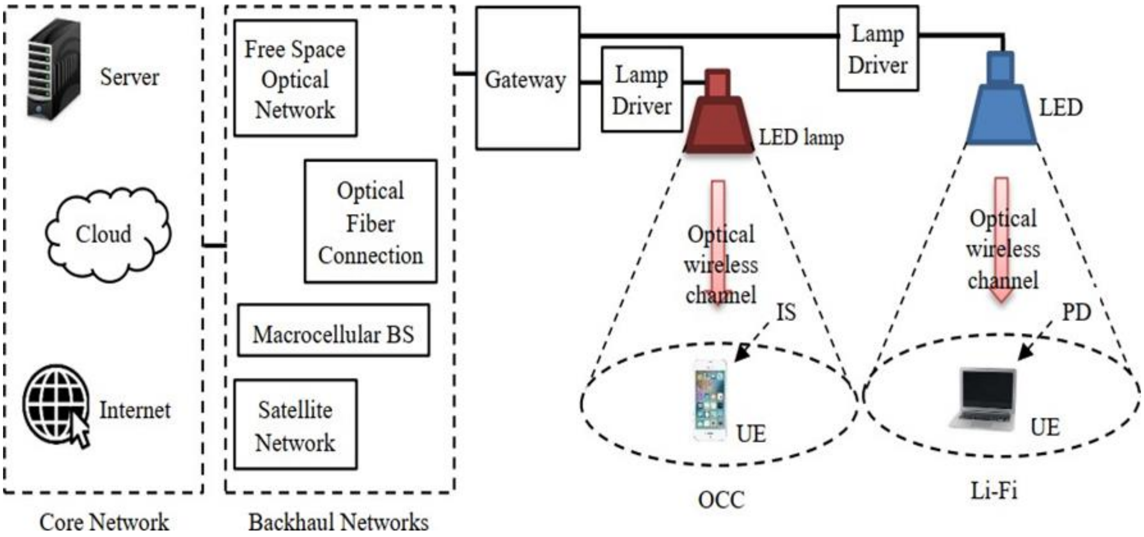


Figure 1.5. Architecture of Li-Fi networks [19].

1.10. Applications of a Li-Fi network

Li-Fi technology has many uses, including providing public Internet access using existing LED lighting and enabling communication between self-driving automobiles using their LED headlights. Li-Fi can be applied in regions where Wi-Fi is unavailable, such as aircraft, hospitals (including operation theatres), power plants, and other locations where electromagnetic (Radio) interference poses significant risks to the safety and security of equipment and individuals. Li-Fi can be safely utilized in various settings and areas because it relies solely on light. Implementing Li-Fi technology will allow street lighting to serve as data transfer stations by utilizing Li-Fi connectivity. Consequently, this will enable internet access in all public locations and streets [20]. Potential future applications of Li-Fi include:

- Applications in education: Li-Fi is the most recent technology in education systems that offers the highest speed for Internet connectivity. Li-Fi can enhance or substitute Wi-Fi in educational institutions and corporations, enabling individuals to utilize its high-speed capabilities.

- Applications in medicine: Wi-Fi is not permitted in operation theatres (or OTs) because of worries about radiation. Wi-Fi in hospitals causes interference or disruption to the monitoring equipment's signals. Improper functioning of medical equipment may have detrimental effects on the patient's health. To address this issue and enhance the technological capabilities of OT, Li-Fi can be employed to enable internet access and facilitate the control of medical equipment. This will be advantageous for doing robotic operations and other automated procedures.
- Cheap In-Flight Internet: Passengers on aircraft are provided with access to the Internet, but at a steep cost and with limited speed. Furthermore, Wi-Fi is not employed because of its potential to disrupt the pilots' navigational systems. Li-Fi can be utilized for data transfer in aircraft. Li-Fi can deliver high-speed Internet using any light source, including overhead reading bulbs, within the airplane.
- Underwater applications: Underwater ROVs, also known as Remotely Operated Vehicles, use substantial cables to provide power and receive signals from their operators above the water surface. However, the length of the rope utilized in remotely operated vehicles (or ROVs) must be increased to enable them to investigate expansive regions. If the cables were substituted with illumination emitted by an underwater, high-intensity bulb, they would have significantly greater investigative freedom. In addition, they can utilize their headlights to communicate amongst themselves, independently analyzing data and regularly transmitting their discoveries to the surface. Li-Fi can function underwater, unlike Wi-Fi, which cannot do so. This presents numerous possibilities for military operations conducted underwater.
- Disaster management: Li-Fi can serve as a potent mode of communication during catastrophic events like earthquakes or hurricanes. The general populace may need to know the protocols to follow during such calamities. Li-Fi is supported by subway stations and tunnels, typically areas where emergency communications are complex.
- Applications in areas requiring a high level of sensitivity: Power plants require efficient and interconnected data systems to monitor demand, grid integrity, and core temperature (in the case of nuclear power plants). Radio communication interference is detrimental to the vulnerable areas surrounding these power facilities. Li-Fi can provide secure and enough connectivity for all sections of these vulnerable settings.

Additionally, the power plant's reliance on its reserves for power consumption in radio communications deployments will be reduced.

- Traffic management: Li-Fi can be utilized at traffic signals to establish communication with vehicles going by, using the LED lights of the cars, among other methods. This can significantly enhance traffic management, leading to a more efficient flow of vehicles and fewer accidents. Additionally, LED car lights cancan notify drivers when there is an insufficient distance between their vehicle and other vehicles.
- Mobile connectivity allows for seamless communication and data transfer across mobile devices such as smartphones, laptops, tablets, and other smart devices. Li-Fi's
- Short-range network offers high-speed transmission rates and enhanced security.
- Alternative to existing technologies: Li-Fi operates without radio waves. Therefore, it can be conveniently employed in locations where Bluetooth, infrared, Wi-Fi, and similar technologies are prohibited.

1.11. Advantages of Li-Fi technology

In this part, we outline the inherent advantages of Li-Fi technology:

- The operation of Li-Fi is based on the use of LED bulbs, which are already extensively employed for lighting purposes, along with a receiver. This approach ensures both cost-effectiveness and simplicity.
- Performance: The advertised speeds are tenfold more significant than those of Wi-Fi. Li-Fi benefits from minimal interference with radio or electromagnetic waves, as the data is only transmitted through light fields.
- Safety: Since the data interchange is confined to the emitted light fields, the flow is manageable and does not disperse. Furthermore, it is essential to note that an opaque object, such as a wall, does not allow light transmission. Thus, exploiting the neighbor's network becomes increasingly challenging.
- Health: Light waves do not penetrate the human body like electromagnetic waves do, so they are unlikely to cause health issues [21].

1.12. Limitations of Li-Fi technology

First and foremost, the limitation of Li-Fi is directly tied to its operational mode, which requires the presence of light for communication to occur. Daylight can disrupt emissions during the daytime. Furthermore, Li-Fi remains predominantly unidirectional in the majority of current deployments. This implies that you can only passively receive data from the light source, and it is only feasible to actively transmit data to it if it is combined with another technology, such as CPL or Wi-Fi. Li-fi is limited to local usage since the transmission of light signals cannot penetrate opaque materials [21].

1.13. Uses of Li-Fi technology

Considering these particular details, Li-Fi presently has a restricted use, typically serving as a supplement to existing network infrastructures [21]:

- On a local scale, it could be advantageous to use Li-Fi technology to alleviate the load on a Wi-Fi or wired network in the reception area.
- A person's or terminal's location inside a tourist destination or hypermarket could be accurately determined using a unique identifier.
- The user did not provide any text. Li-Fi could be employed in environments prone to electromagnetic interference, such as airplanes or hospitals.
- The user did not provide any text. Given the excellent propagation of light in water, implementing this communication technology could significantly enhance the marine environment.
- This list is not comprehensive, but it encompasses ideas that are currently being developed or are yet to be explored.

1.14. Comparison between Wi-Fi and Li-Fi

Li-Fi refers to the use of high-speed wireless connectivity. The name of this technology is derived from its similarity to Wi-Fi, which uses light instead of radio waves. Wi-Fi technology is well-suited for providing wireless coverage across large areas in buildings. At the same time, Li-Fi is ideal for delivering high-density wireless data coverage in limited regions and mitigating issues related to radio interference. Thus, the two technologies are mutually supportive. Li-Fi offers several benefits regarding wireless system capacity, energy efficiency, and security. Although they have several notable benefits compared to Wi-Fi, they are a supplementary technology. The following Table 1.1 concisely overviews the distinctions between Li-Fi and Wi-Fi [22].

Features	Li-Fi	Wi-Fi
IEEE Standard	802.15.7	802.11
Operations	LiFi is a technology that utilizes LED lights to transmit data via light.	Wi-Fi utilizes radio waves to convey data facilitated by a Wi-Fi router.
Interferences	There are no interference problems like those caused by radio frequency waves.	Could experience interference due to neighboring access points (routers).
Applications	Employed in aviation, deep-sea expeditions, surgical suites in medical facilities, and business and residential settings to transmit data and access the Internet.	Employed for web browsing through the assistance of Wi-Fi kiosks or hotspots.
Privacy	The walls act as a barrier, preventing light from passing through and enhancing data transit security.	Regarding RF signals, dry walls are transparent, meaning extraordinary measures must be used to ensure secure data flow.
Data transfer speed	Approximately 1 Gbps.	WLAN-11n provides a speed of 150 Mbps, whereas WiGig/Giga-IR can achieve speeds of approximately 1-2 Gbps.
Frequency of operation	10,000 times frequency spectrum of the radio (In the THz range).	2.4 GHz and 5 GHz.
Data density	Operates effectively in a highly concentrated setting.	Operates more effectively in environments with lower density due to complications caused by interference.
Coverage distance	Approximately 10 metres.	The WLAN 802.11b/11g range might vary depending on factors such as broadcast power and antenna type. However, it is typically around 32 meters.
System components	The LiFi system will have a light driver, an LED bulb (lamp), and a photodetector.	Installing routers is necessary, and the devices subscribers use, such as laptops, PDAs, and desktops, are called stations.
Security	LED lighting is safer due to the inability of light waves to penetrate walls and be detected by anybody outside the area illuminated by the LEDs.	Due to the significant dispersion force of radio waves, they can be intercepted by anyone on the road.

Table 1.1. An analysis of the differences between Wi-Fi and Li-Fi.

1.15. Safety of a Li-Fi system

Ensuring the safety of a visible light transmission system is now a significant concern. The primary objective is to safeguard the confidentiality of information, limiting access to only authorized individuals. Additionally, it is crucial to safeguard information during transmission over the network, including protecting files, passwords, and access to computer systems and applications. To address this issue, a potential solution would involve requiring users to utilize keys to access their workstations, safeguard important documents by employing a password, and authenticate their emails with digital signatures. The second security problem pertains to preserving infrastructure. The primary goals are to safeguard against attacks on the configuration of network devices, the pilferage of network resources, and subsequent malevolent interference of nodes or connections with counterfeit data that obstruct the transit of authentic messages [23].

1.16. Conclusion

VLC originated and evolved due to an increasing need for wireless communication technology. Advancements in the SSL sector, which have consistently enhanced the efficiency of LEDs, have facilitated its swift development.

This chapter provided an overview of VLC, explaining the fundamental principles and illustrating the structure of a VLC system. The primary uses of VLC have been showcased. Also, it has demonstrated the evolution of VLC technology and the performance achieved over that period. One significant use of VLC is to establish high-speed indoor connections for quick internet access or rapid data streaming. The scientific community in this field has made substantial endeavors, resulting in remarkable achievements for VLC.

Throughout this chapter, we have provided a Definition of Li-Fi technology. Li-Fi is a novel technology that offers a compelling and dependable alternative to the challenges associated with Wi-Fi. We additionally showcased the benefits of Li-Fi and its diverse applications across multiple domains. Nevertheless, the current absence of appropriate consumer devices indicates that Li-Fi technology is now more suitable for professional applications.

CHAPTER 2

Components of a Li-Fi communication network

2.1. Introduction

Light-Emitting Diodes (or LEDs) form the foundation of Visible Light Communication (or VLC) technology, which offers optical wireless communication (OWC). VLCs modulate the visible light spectrum [380–750 nm], which LED lighting and light intensity use, to transmit information in a way that is invisible to the human eye. Experiments and analytical studies have demonstrated VLC's ability to perform fast-speed data communication. This chapter covers the VLC as well as its capabilities. More specifically, we describe the characteristics of the LED as a transmitter and the photodiode as a receiver, along with a list of frequently used modulation techniques.

2.2. General digital transmission links

Digital transmission systems use electromagnetic waves, cables, optical fibers, and other media to transfer data between the transmitter and the receiver. For Li-Fi connectivity, the light serves as the transmission channel. Figure 2.1 outlines a simple digital transmission system. However, the transmitter source creates the data for Li-Fi technology, codes it, and modulates it to ensure channel transmission. The receiving end then demodulates and decodes this signal to ensure its understanding (see Figure 2.1) [24].

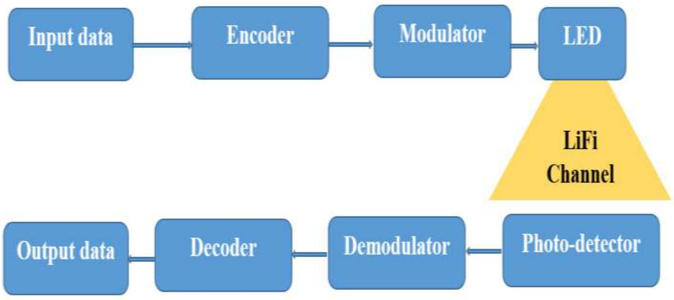


Figure 2.1. Diagram of a digital transmission system.

2.3. Presentation of a Li-Fi environment

A range of parts required for the Li-Fi communication system to function properly have been used in this study.

2.3.1. Transmitter

a. Description

A VLC transmitter is an electro-optical transduction device that uses visible light waves to transmit data over a wireless transmission channel, also known as a Li-Fi channel [8]. The information bits are modulated and converted into an analog signal by a Digital-to-Analog Converter (or DAC), and the transmitter is composed of high-speed LEDs, a TransConductance Amplifier (or TCA), and Low-Pass Filters (LPF) [9]. In terms of information processing, the LED converts the electrical signal into an optical signal, allowing for both lighting and connectivity. Prior to being transmitted as an optical signal, the data is processed and adjusted in real-time by the DAC, which alters the amplitude or other characteristics of the LED light [10].

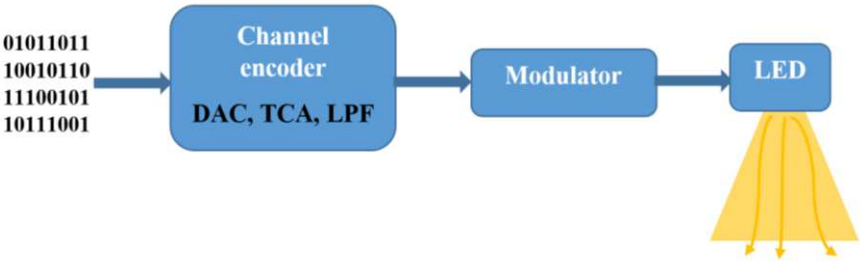


Figure 2.2. Transmitter component of a Li-Fi system.

b. Optical source

A primary light source is an object that produces light by converting another form of energy into light. The Sun serves as an exemplary instance: the energy generated by nuclear fusion is turned into electricity to create luminescent light. This principle is applicable to all types of artificial light sources [25].

A secondary light source is one that has the ability to reflect a portion of the light it receives. The moon, the blue sky, and the ceiling of our apartment reflect a portion of the sunlight they receive back into our eyes. This principle also holds true for the majority of common objects. We can classify light sources as either point sources or extended sources. If the largest dimension of the source is smaller than the distance between the source and an observer, the source seems to be stretched out and regarded as a flat surface. On the other hand, observers perceive the source as elongated and a flat area [25].

c. Optical transmitter parameters

The light emitter [26] is defined by the following parameters:

- The emission area refers to the specific region of the emission window, measured in square meters.
- The term "transmitting power" describes the power that the surface responsible for transmission transmits. It is often measured in units of [dBm] or [mW]. Conduct the

power measurement in an unobstructed environment, away from the optical transmission system, and as close as feasible to the system's emission window.

- Beam divergence angle refers to the largest possible angle between the beam's line of symmetry, which represents the highest power density, and the direction, which represents power densities lower than -3 [dB]. Divergence is measured in milliradians [mrad].
- Wavelength, denoted as λ, is defined by the center wavelength and spectral spacing. For this, the nanometer is the unit of measurement [26].

d. Light-emitting diodes

When activated, the light-emitting diode transforms an electric current into light of a specific wavelength, which determines its color (red, green, yellow, or blue). The diode deactivates when it is in a locked state [14]. Table 2.1 presents a brief summary of the electrical properties of LEDs, as documented in reference [14].

A Li-Fi network employs LED light as a means of transmitting information. Shuji Nakamura and Takashi Mukai from Nichia achieved the functionality and economic viability of this idea during the 1990s. Currently, there is a significant increase in consumption and a wide range of applications, such as enhancing the lighting of various types of devices (smartphones, TVs, etc.). LED lamps are increasingly supplanting traditional incandescent light halogen, or fluorescent lighting. Throughout the past decade, their performance has consistently undergone improvements, addressing the numerous small weaknesses they previously exhibited. For instance, the color rendering index, previously around 80 %, has now reached nearly 100% [14].

Color	Wavelength [nm]	Threshold voltage [V]	Semi-conductor
Infrared	$\lambda > 760$	$\Delta V < 1.63$	AlGaAs
Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	AlGaAs, GaAsP
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	GaAsP
Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	GaAsP
Green	$500 < \lambda < 570$	$2.18 < \Delta V < 2.48$	GaN, GaP
Bleu	$450 < \lambda < 500$	$2.48 < \Delta V < 2.76$	ZnSe, InGaN, SiC
Ultra-Violet	$\lambda < 400$	$\Delta V > 3.1$	C, AlN, AlGaN

Table 2.1. LED characteristics.

Several factors, such as spectrum, number of chips, shape, power, and size, can categorize LEDs. Based on these factors, there are:

- SMD (Surface Mounting Device) LEDs: LEDs that require low current (20–30 mA);
- White LEDs: LEDs that emit white light;
- Colored LEDs: LEDs that emit light in various colors;
- UV LEDs: LEDs that emit ultraviolet light;
- High Power LEDs: LEDs that have high power output;
- Organic LEDs (OLED): LEDs made from organic materials;
- Multicolor LEDs: LEDs that can emit light in several colors.

Table 2.2 shows various LED types categorized by their power.

Power [W]	**Power driver [W]**	**Total power [W]**	**Light Flow [lm]**	**Light Efficiency [lm/w]**	**IRC**	**Color Temperature [°K]**	**Lifetime [h]**
3	0,6	3.6	136	45	80-90	2 700-3000	15000-30000
5	0.9	5.9	250	50			
8	1.6	9.6	470	59			
10	2	12	650	65			
12	2.4	14.4	810	68			
14.5	5.9	20.4	1055	73			

Table 2.2. Comparative table of LEDs by power rating.

2.3.2. Receiver

a. Description

The receiver consists of two components: the Photo-Diode (or PD) and the light collection lens. The PD selection [14] determines the lens design. Figure 2.3 shows the Li-Fi receiver system's principle.

A photodetector, also known as a photosensitive detector, optical detector, or light detector, is a device that transforms absorbed light into a quantifiable entity, typically an electric current or voltage [24]. Photodiodes are the most commonly used photodetectors to capture light.

The photodiode transforms the optical power it receives into an electrical signal. This signal is subsequently demodulated, amplified, and decoded by a TransImpedance Amplifier (or TIA) and a Low-Pass Filter (or LPF). An Analog-to-Digital Converter (or ADC) is used to convert a physical current signal into a digital signal for the purpose of extracting the bits of the user's message.

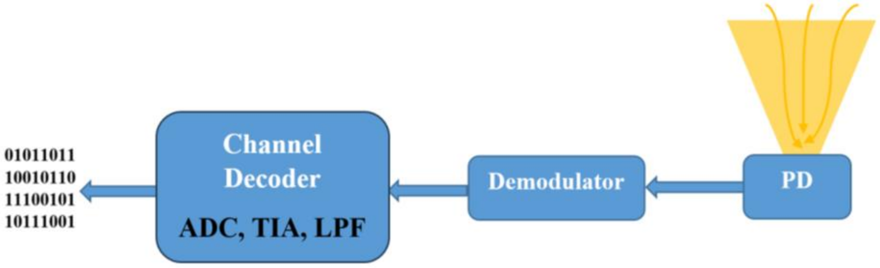


Figure 2.3. Receiver component of a Li-Fi system.

There are various types of photodetectors, each with unique features. These include photomultipliers, photoconductors, phototransistors, and photodiodes. Photo-Diodes (or PD) are widely employed as photodetectors due to their small size, exceptional sensitivity, and rapid reaction. The primary photodiode types exploited as photodetectors are P-I-N (Positive Intrinsic Negative Diode) and APD (Avalanche Photodiode) [11]. Due to the avalanche effect, an avalanche photodiode has a high gain but is also highly susceptible to quantum noise. PIN photodiodes are more affordable and stable at high temperatures and in extreme light conditions. A PD PIN is an excellent option for low-speed applications, while an avalanche PD is preferred for broadband applications. The capacity of a PD is related to its response time: the smaller the detection area, the lower the capacity and the faster the response. The light flow, on the other hand, is less crucial and, therefore, captures a weaker signal. Lenses can enhance signal reception by allowing sensors to improve light transmission, resulting in increased flow rate and extended signal range. The shape of the lenses must be considered during development. For example, due to its size and volume, a hemispherical lens is unsuitable for integration into mobile communication devices. The emitting source's overall target and enlarged image must be considered.

The following will discuss the most important characteristics to consider when choosing a photodetector:

Photodiode response time: The response delay is the time required for the photodiode to reach 90% of the final current. This time is determined by:

$$Reponse\ Time = \sqrt{(t_t)^2 + (t_d)^2 + (t_\tau)^2} \tag{2.1}$$

Where, t_t refer to the carriers' travel time within the space charge zone, t_d is the travel time of carriers in neutral regions and t_τ is the time constant of the equivalent scheme (resistance $R_s + R_c$ and capacity $C_j + C_y$ such as $t_\tau = (R_s + R_c) \cdot (C_j + C_y)$).

Photo-detection noise: The sources of noise and the frequency and distortion power of a wireless optical connection are crucial factors that determine the connection's performance. Identifying the noise source at the receiver's front end is critical for most communication systems, as the incoming signal contains the least power. The primary noise sources at the receiver's input are the discharge noise of the received photo-current and the noise from receiver electronics. Discharge noise is a significant source of interference in wireless optical connections, while thermal noise is influenced by the receptor transfer function (i.e., the topology of the preamplifier). Therefore, circuit noise is also modeled as distributed in a Gaussian manner. The various noise sources in optical communications are discussed in the section "Noise in VLC systems."

Photo-detection techniques: Photo-detection converts optical beams carrying information into corresponding electrical signals to retrieve the transmitted data. At the transmitter level, information can be encoded in the frequency, phase, or intensity of radiation from an optical source. The encoded radiation is transmitted to the receiver through either the open-space channel or the optical fiber. The receiver's frontal devices, which include a telescope and an optical filter, concentrate the filtered radiation onto the photodetector surface in the focal plane, using IM-DD and consistent patterns.IM-DD is the most common and straightforward coherent detection scheme. It provides the opportunity to retrieve complete information about the optical carriers, including the amplitude (phase component) and the phase (quadrature constituent) of the complex optical electric field, as well as the polarization state of the signal. However, these receptors are sensitive to the received optical signal's phase and polarisation state.

- Direct detection: In direct detection by intensity modulation, the intensity of light emitted by an LED is used to transmit information. No local oscillator is used in direct detection. For this type of receiver to retrieve encoded data, the information transmitted must be associated with the variation in the field intensity [14]. Therefore, this type of detection is also called envelope detection.
- Consistent detection: In consistent optical communication, the data is encoded onto the optical signal by modulating its amplitude, phase, and frequency. A local optical oscillator (LOO) is used at the receiver end, and combining the LOO with the received signal allows for heterodyne or homodyne optical detection [14]. The local oscillator frequency does not need to match the incoming information-bearing radiation frequencies.

b. Optical receiver parameters

The following are the parameters that determine the characteristics of an optical receiver:

- Receiving area refers to the overall size of the receiving window, expressed as square metres. The modulation format determines the detection technique the receiver applies. It's crucial to keep in mind that not all detection techniques are appropriate for every modulation format. Direct detectors, for example, lack the ability to detect phase and polarization information.
- Sensitivity refers to the minimal number of photons required to achieve a specific level of data transmission quality. The dBm is the designated unit of measurement.
- Saturation sensitivity is defined as the highest achievable optical level for a specific data transmission quality, both with and without controlled attenuation adjustment. The distinction between saturation and sensitivity determines the dynamic range.
- The field of view is defined as the angular range between the central axis and the direction at -3 [dB]. You can express this value either as a half-angle or as a total angle, but you must explicitly state it. We employ the milliradian [mrad] as the measurement unit [27].

2.4. Noise

Knowledge of various noise sources is necessary to evaluate the performance of indoor wireless optical communication systems. This knowledge enables you to select the optimal wavelength and modulation type. Two primary sources of noise can be identified in communication systems: ambient noise and thermal noise. We will now present the various sources of noise in the following sections [21].

2.4.1. Environmental noise

Environmental optical noise is the most significant source of interference in wireless optical communications. This noise in enclosed spaces mainly originates from sunlight, light emitted by incandescent lamps, and low- and high-frequency fluorescent lamps. Figure 2.4 illustrates the spectral power distribution of the surrounding noise sources based on the wavelength of the optical link. This figure notes that the noise power primarily depends on the wavelength, emphasizing the importance of selecting the appropriate wavelength in the design of wireless optical communication systems [21].

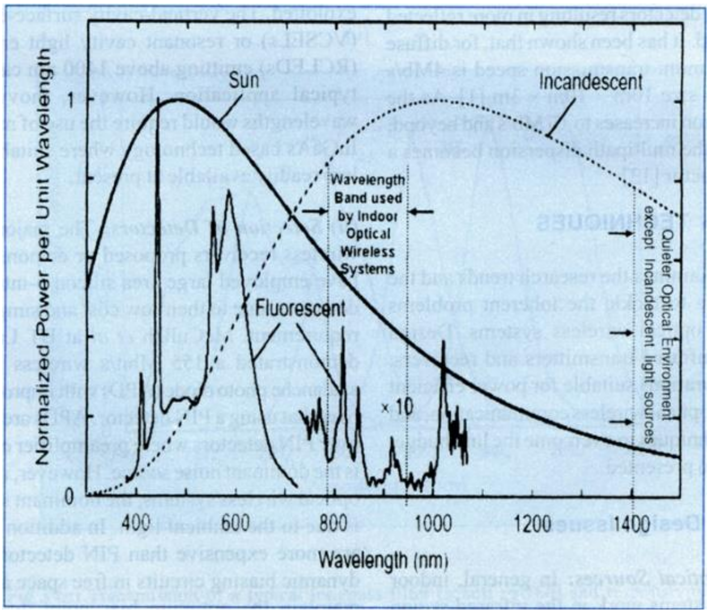


Figure 2.4. Power spectrum of various noise sources varies depending on the wavelength of the communication [28].

Sunlight is a crucial natural source of ambient light, influenced by the angle of the sun's rays on the photo-detector. Its power can saturate wireless optical connections, and most wireless optical communications systems designed for confined environments do not work outdoors. It is a continuous source of background noise that is hard to filter. Its maximum power spectrum is around 500 nm, and it can significantly interfere with infrared links ranging from 700 to 970 nm. It is important to note that the current induced in the photodetector by sunlight is not sporadic but continuous, persistently adding to the received signal. Thus, the ambient noise caused by sunlight can be represented as an additive Gaussian AWGN-type noise.

The incandescent lamps, with tungsten filaments, are a source of ambient noise that can affect wireless optical communications due to their broad spectrum with a maximum of ≈ 1000 nm. The photo-current induced by this noise source is sinusoidal at a frequency of 100 Hz with significant harmonics up to 2 KHz. It is added as RMS current to the continuous current linked to sunlight. By applying a high-pass filter, the noise associated with this current can be modeled by AWGN noise.

Low-frequency fluorescent lamps traditionally operate at the same 50Hz or 60Hz frequency as the main electricity supply. However, operating fluorescent lamps at frequencies exceeding 2000 Hz can significantly increase luminous efficacy by almost 10%, as in modern electronic ballasts. This increase in efficacy is due to the lamp emitting lighter when driven at higher frequencies, reducing the 'off' periods of the discharge and leading to a more continuous light output. The first installation of fluorescent lamps with high-frequency ballasts was on the train carriages of the London Underground, where a 400Hz mains frequency was required due to varying inductance at higher frequencies [29].

High-Frequency Fluorescent Lamps: These lamps utilize a ballast, generating a periodic signal between 20 and 40 kHz, along with significant harmonics reaching up to MHz. The use of a ballast with fluorescent lamps significantly reduces energy consumption and extends the lifetime of the lamps. It is important to maintain spectral spread, so using a high-pass electrical filter is not effective as it filters out the valuable signal.

2.4.2. Thermal noise

Thermal noise is caused by the resistance of the receiver's electronic circuit. The primary source of this type of noise is the preamp, a receiver component. The receiver often utilizes the preamp to amplify the received signal, mainly when the receiving photodiode is a PIN. The preamplifiers with field-effect transistors have low output resistance, resulting in minimum noise. With the correct choice of the receiver's electronic circuit, this type of noise can be minimized, making it negligible compared to the surrounding noise. Figure 2.5 shows the spectral density of one-sided noise power based on signal frequency (transmission rate) for ambient and thermal noise. At low speeds (less than ≈ 10 Mbps), ambient noise dominates (10 × higher), but then the receiver's thermal noise becomes predominant [21].

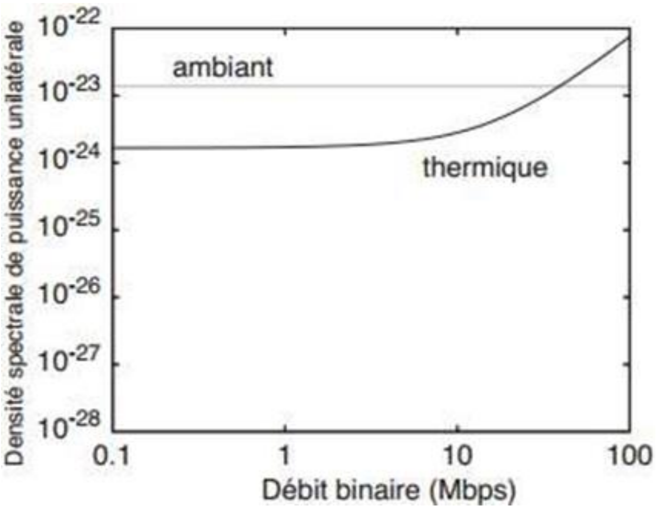


Figure 2.5. Spectral density of one-sided noise power depends on the frequency of the optical signal.

2.5. Transmission channel capacity

For VLC systems using direct intensity modulation detection (IM/DD), the classic Shannon channel capacity formula is applied (see Figure 2.6).

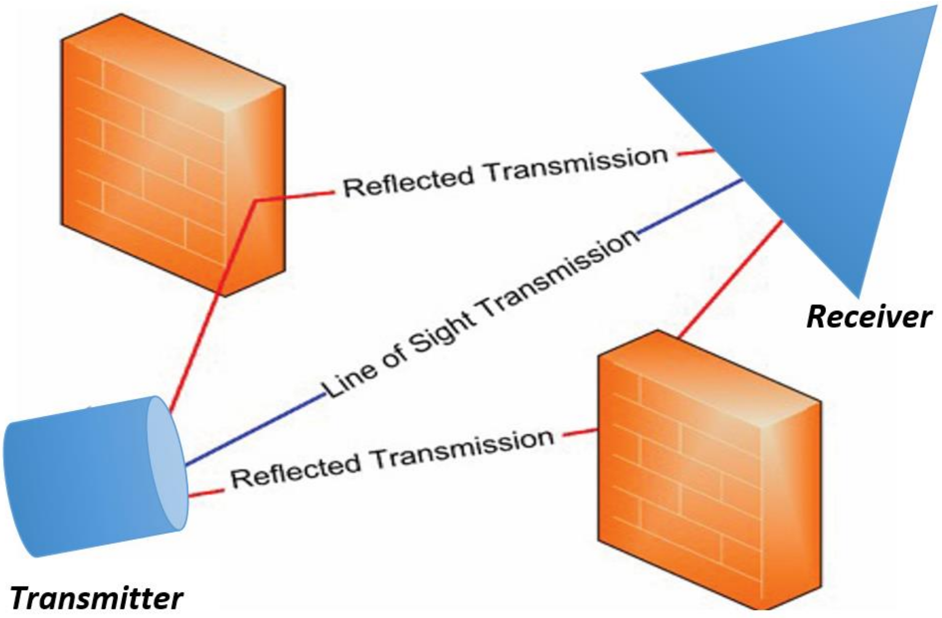


Figure 2.6. Canal de transmission Li-Fi [14,30].

However, this formula may not be suitable for actual wireless optical channels due to the following reasons:

- In VLC systems based on intensity modulation with direct detection (IM/DD), the amplitude determines the voltage applied to the LEDs and the emitted optical power. Therefore, the signal must be non-negative and real-valued. In addition, LEDs have a maximum permissible direct current, resulting in a limited maximum signal amplitude value. Therefore, the transmitted signal must be unipolar and limited in amplitude.
- If the electrical power of the signal is limited, the signal following a Gaussian distribution would traditionally approach the capacity of the Shannon channel. Nevertheless, since LEDs are mainly used for lighting, the signal is subject to average optical power, not electrical power. If the electrical power strain does not apply, the distribution of the input signal to approach the capacity of the Shannon channel in the wireless optical channels does not necessarily track the Gaussian distribution [14].

2.6. Transmission channel modeling

Wireless optical channels are categorized into three types: open space optical intensity channel, discreet-time fish channel, and enhanced open space intensity canal.

- The open space optical intensity channel is commonly utilized in optical communications, where noise exhibits white and Gaussian characteristics and is independent of the signal [9, 31].
- The Discrete Time Fish Channel is another widely studied channel model in VLC systems [9], which considers the discrete nature of photons. The transmission signal is modeled as a fish-counting process, where the amount of incoming photons remains statistically constant for an extended period but varies over a short period.
- The open-space optical intensity channel is analyzed in [32]. Signaling follows a normal distribution, but its variance depends on the signal. In this model, quantum, background, and thermal noise are considered and assumed to be Gaussian.

2.7. Modulations related to VLC

Optical wireless communications employ a variety of modulation techniques. The selection of a particular modulation in the context of VLC is founded on two criteria:

Lighting requirements vary for different activities; for example, 30–100 lux is recommended for normal visual activities in public places. There is a non-linear relationship between the measured light and the perceived light, described by equation (2.2):

$$Perceived\ Light\ (\%) \ = 100\sqrt{\frac{measured\ light(\%)}{100}} \tag{2.2}$$

Adaptation to the scintillation effect should ensure that changes in the brightness of the modulated light are invisible to humans. According to IEEE 802.15.7, switching must occur at a rate faster than 200 Hz to avoid harmful effects [2].

The first IEEE 802.15.7 standard proposes various modulations: On-Off Keying (OOK), Variable Pulse Position Modulation (VPPM), and CSK (Color Shift Keying) modulation. Many studies have demonstrated the effectiveness of multi-portable modulations, such as Orthogonal Frequency Division Multiplexing (OFDM) modulation. The IEEE 802.15.7 standard's physical layer (PHY) includes the first three modulations. PHY I and II are designed for a single light source, enabling OOK and VPPM technologies. At the same time, PHY III uses different optical sources at numerous frequencies (colors) via CSK modulation. All three systems can coexist, offering flicker reduction and dimming support and the ability to arbitrate between data rates and dimming ranges [33].

2.7.1. OOK modulation

In Figure 2.7, OOK is shown as a simple modulation technique. In this technique, the numerical "1" represents the presence of the signal, corresponding to the "ON" state, while the "0" defines the absence of the signal or the "OFF" state. "ON" and "OFF" denote two separate amplitude levels essential for communication and do not necessarily indicate that the light source is completely switched off. IEEE 802.15.7 specifies using the Manchester code for OOK to ensure the exact duration of positive and negative pulses. However, this doubles the required bandwidth for OOK transmission [7]. Five different speeds are used: 11.67 kbps, 24.44 kbps, 48.89 kbps, 73.3 kbps, and 100 kbps [7]. Higher binary flows use a more spectrally efficient encoding known as Run Length Limited (RLL). Grading is facilitated by introducing an OOK extension that adjusts the combined output to the accurate level [34].

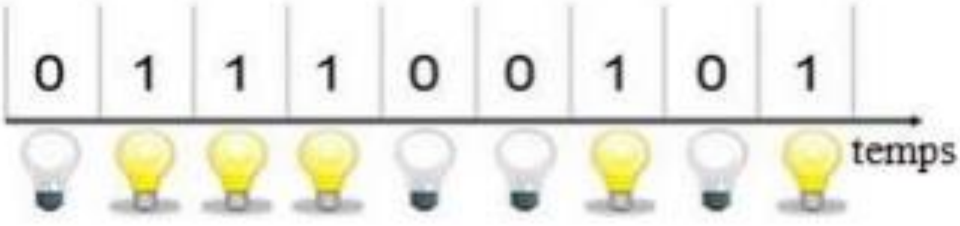


Figure 2.7. OOK modulation scheme [35].

2.7.2. VPPM modulation

VPPM modulation is a variant of Pulse Position Modulation (PPM) specifically developed for VLC communications. In PPM modulation, information is conveyed by the timing of the pulses. Depending on the light intensity level, the VPPM variant also incorporates Pulse Width Modulation (PWM) variation, which applies a variable cyclic ratio to Manchester OOK modulation. VPPM modulation stops scintillation issues by removing long sequences of "0", while PWM technology enables the control of light intensity (refer to Figure 2.8) [36].

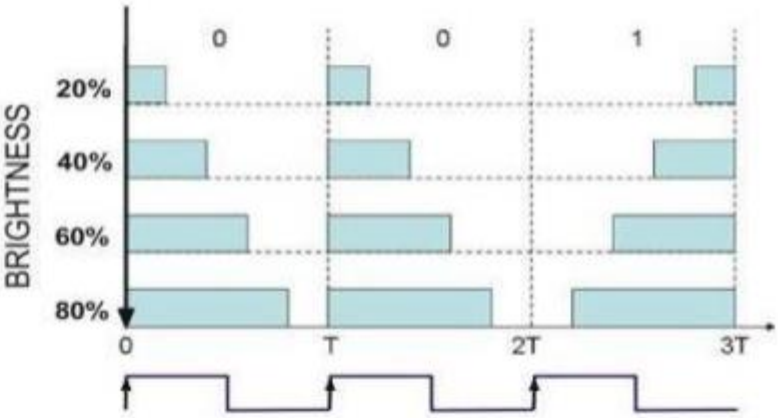
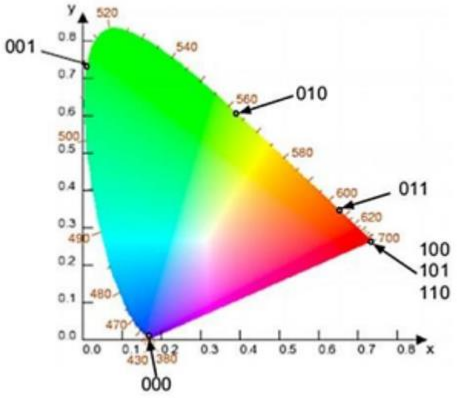
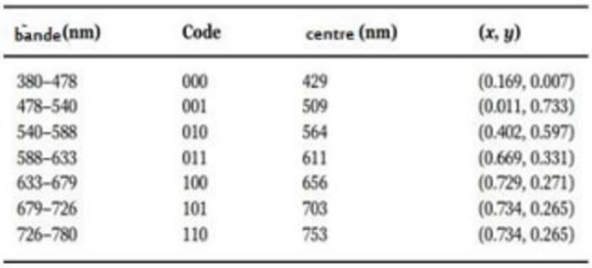


Figure 2.8. VPPM Modulation [36].

2.7.3. CSK modulation

Color-Shift Keying, like VPPM modulation, is specific to Visible Light Communications (VLCs). It was proposed in IEEE 802.15.7 to improve low data throughput in other modulation types. The use of yellow phosphorus and blue LEDs to produce white light can slow down the switching capacity. Another way to produce white light is by using three distinct LEDs: green, blue, and red. It is achieved by controlling the intensity of the three colors of an RGB LED source (Red, Green, and Blue). The CSK modulation relies on the color space chromaticity diagram. Unlike other modulations, the symbols are chosen to maintain constant light emission while the different chromatic components associated with each color vary. This modulation represents all perceptible colors using two chromaticity parameters: x and y. Figure 2.9 displays the seven visible wavelength bands and their centers on the diagram [2, 36].





bande(nm)	Code	centre (nm)	(x, y)
380–478	000	429	(0.169, 0.007)
478–540	001	509	(0.011, 0.733)
540–588	010	564	(0.402, 0.597)
588–633	011	611	(0.669, 0.331)
633–679	100	656	(0.729, 0.271)
679–726	101	703	(0.734, 0.265)
726–780	110	753	(0.734, 0.265)

Figure 2.9. CSK modulation [2].

2.7.4. OFDM modulation

For high-speed applications, bandwidth limitations and IES (Interference between Symbols) pose significant challenges. To best address these issues, one can employ OFDM-type modulation (Orthogonal Frequency Division Multiplexing). The modulation principle involves transmitting data across multiple parallel channels using different subcarriers. Thus, the time for each symbol conforming to each support is much more significant than its equivalent for a single port, significantly reducing the impact of the IES while optimizing the bandwidth. The use of a guard interval also stops interference between sub-carriers. The primary advantage is achieving a very simple equalization in reception [36]. This technique stops sparkling problems. Additionally, the constant emitted light flow keeps the control current constant, thus significantly reducing stress on the sources. The complexity of this modulation poses a limitation, as reception must be capable of receiving each color [37].

2.8. Types of encoding

2.8.1. NRZ (Non-Return-to-Zero)

The binary data "1" corresponds to an optical pulse with a duration significantly equal to the symbolic time (inverse of the flow rate), while the data "0" represents the absence of a signal. In practical terms, there is never a complete absence of signal because the extinction rate is never infinite. NRZ encoding (refer to Figure 2.10) is utilized for speeds lower than 10 Gbps, commonly used in many WDM systems at 2.5 Gbps, and necessitates an external modulator [10].

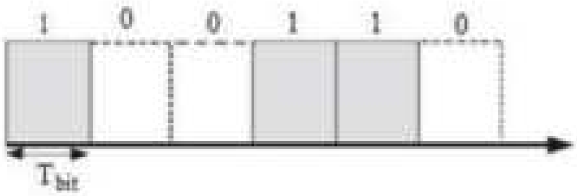


Figure 2.10. Format NRZ [10].

2.8.2. Manchester

The Manchester encoding, or two-phase coding, involves introducing a transition in the middle of each interval. This means that the data "1" will be encoded by a positive transition in the middle of the clock period, and the data "0" will be encoded by a negative transition in the middle of the clock period. The data is encoded using an exclusive "Yes" (XOR) between the signal and the clock signal. This encoding eliminates the need for a separate continue component. In Figure 2.11, you can see the data (1 0 0 1 1 0) encoded in Manchester format [10].

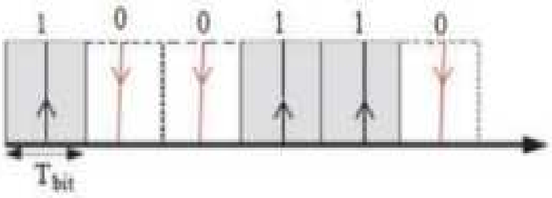


Figure 2.11. Format manchester [10].

2.9. Conclusion

This chapter has discussed the various components of a Li-Fi communication network and the characteristics of LEDs as transmitters, different types of LED lamps, and the use of PDs as receivers. The channel modeling section also discussed three wireless optical channels due to varying noise levels in various application scenarios. Finally, we have also explained modulation and encoding in the Li-Fi (or VLC) system.

CHAPTER 3

Simulation results and interpretations

3.1. Introduction

The current scope of study in new-generation communication employing LEDs is wireless optical communication, or Li-Fi, as it is more often known. Light fidelity is the name of the new technology, which implies the transfer of data into an internal channel. We examined Li-Fi's performance in an indoor channel while accounting for both Non-Line-of-Sight (NLoS) and Line-of-Sight (LoS).

This chapter uses Optisystem v.15 software to give simulation results for three different scenarios. These simulations aim to assess a Li-Fi system's performance in various scenarios. Specifically, we investigate the effects of multiple vital factors: fluctuations in the bit rate of the Li-Fi link, fluctuations in the viewing angle (or FOV) at the receiver, fluctuations in the transmission angle (or THA) at the transmitter, and the impact of ambient noise sources on this link. We can better understand the behaviour of the suggested Li-Fi system and optimize its operation if we thoroughly analyze these critical factors.

3.2. Optisystem simulation tool for indoor Li-Fi system

Optisystem v.15 (see Appendix 1) is a simulation program that allows users to plan, test, and simulate optical networks in the transmission layer. The tool is based on a realistic Li-Fi communication system model. It features a robust simulation environment with a hierarchical architecture and component specification. The application offers a global view of system performance and graphically presents design alternatives and circumstances (LoS/NLoS) for Li-Fi installation. We look at the LoS and NLoS propagation models in our simulation to evaluate a Li-Fi system's performance. First, our simulation investigates a direct path with a single LED as a transmitter using the LoS propagation model. Next, we explore the NLoS propagation models in our simulation. The following subsections show our simulations using the Optisystem simulation program, which considers both LOS and NLOS propagation models.

3.2.1. LoS propagation model

Our simulation of the LoS propagation model considers a direct path from a single LED in an interior context, as shown in Figure 3.1. Figure 3.1 shows the dimensions of the inside area as 3 m high, 3 m broad, and 3 m long. At the receiving site, a single LED is the transmitter, while a photodiode is the detector. The definitions of the transmitter-receiver distance l, and the angles of irradiance θ_s , and incidence θ_d are as follows:

$$l = 3{,}1\,m,\ \ \theta_s = 14.47° \ and\ \theta_d\ = 16.26° \qquad (3.1)$$

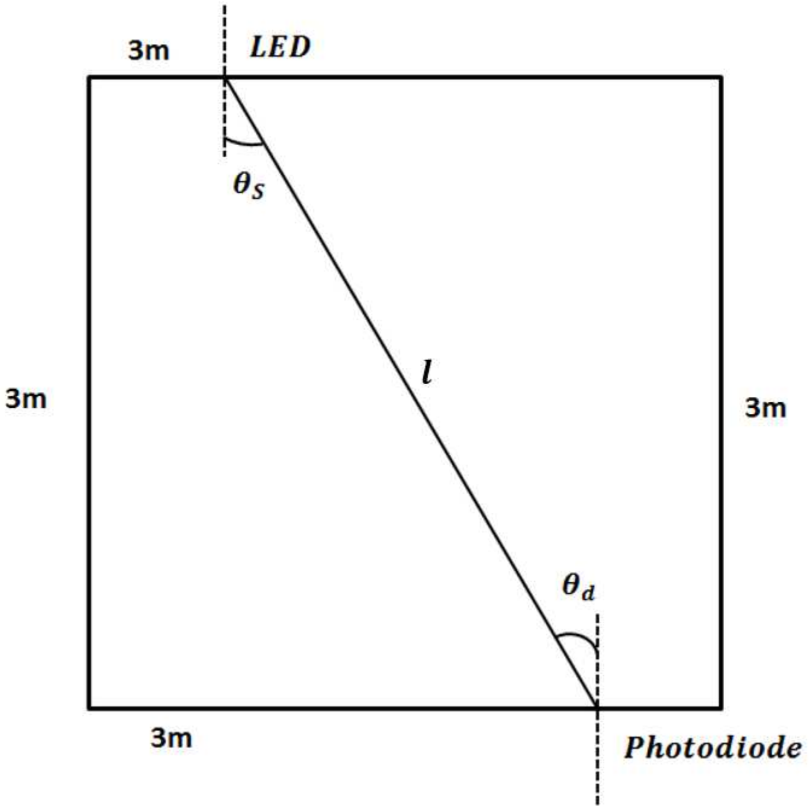
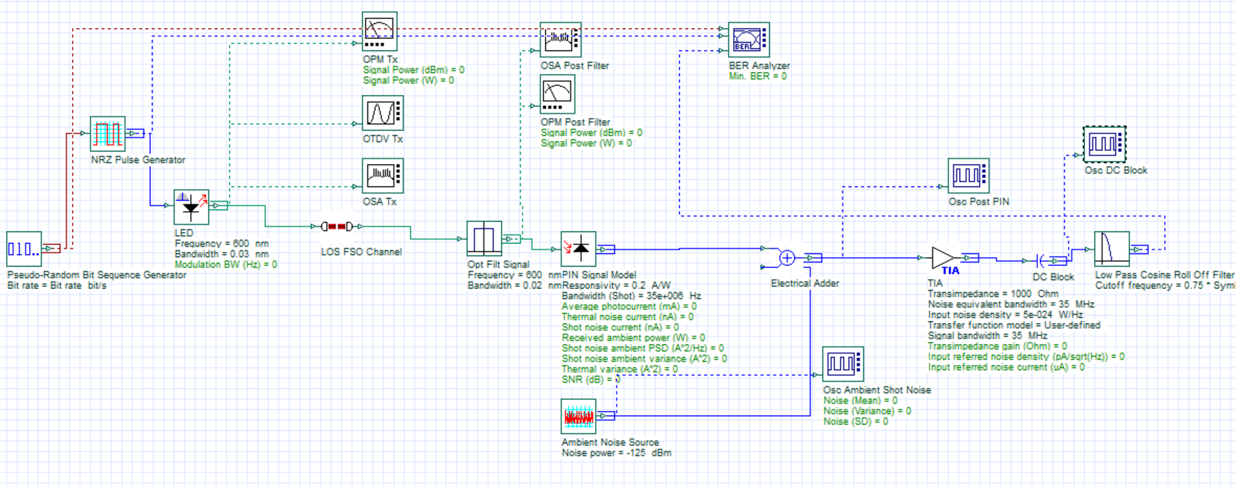


Figure 3.1. Design of experiments for the LoS propagation model: the three-meter-long experiment used a single LED and photodiode.

An Optisystem simulation of the LiFi system using a LOS propagation model is shown in Figure 3.2. The simulation model includes a pseudo-random data sequence generator with a bit rate of 10e6 [bits/s] and a symbol rate of 10e6 [symbols/s]. The produced data are transformed into NRZ electrical pulses, which are then directly exploited by the LED. Furthermore, the transmitter and receiver components are coupled via a LoS FSO channel. Before a PIN signal model serves as the detector, we filter the incoming signal at the receiving end using an optical filter. The ambient noise source then associates with the PIN photodiode's output electrical signal, amplified by the TIA component. Next, the low-pass cosine roll-off filter is used to recover the transmitted electrical signal and convert it to data bits. The DC block intercepts the DC component from the amplified signal by removing its mean value.

On the other hand, several optical and electrical visualizers examine the shape of input and output signals on the transmitter and receiver sides, while the BER analyzer assesses the bit error rate. Table 3.1 displays the specifications for the components used in the Optisystem simulation tool.



OPM Tx
Signal Power (dBm) = 0
Signal Power (W) = 0

OPM Post Filter
Signal Power (dBm) = 0
Signal Power (W) = 0

BER Analyzer
Min. BER = 0

Pseudo-Random Bit Sequence Generator
Bit rate = Bit rate bit/s

LED
Frequency = 600 nm
Bandwidth = 0.03 nm
Modulation BW (Hz) = 0

Opt Filt Signal
Frequency = 600 nm
Bandwidth = 0.02 nm

PIN Signal Model
Responsivity = 0.2 A/W
Bandwidth (Shot) = 35e+006 Hz
Average photocurrent (mA) = 0
Thermal noise current (nA) = 0
Shot noise current (nA) = 0
Received ambient power (W) = 0
Shot noise ambient PSD (A^2/Hz) = 0
Shot noise ambient variance (A^2) = 0
Thermal variance (A^2) = 0
SNR (dB) = 0

TIA
Transimpedance = 1000 Ohm
Noise equivalent bandwidth = 35 MHz
Input noise density = 5e-024 W/Hz
Transfer function model = User-defined
Signal bandwidth = 35 MHz
Transimpedance gain (Ohm) = 0
Input referred noise density (pA/sqrt(Hz)) = 0
Input referred noise current (uA) = 0

Low Pass Cosine Roll Off Filter
Cutoff frequency = 0.75 * Syml

Osc Ambient Shot Noise
Noise (Mean) = 0
Noise (Variance) = 0
Noise (SD) = 0

Ambient Noise Source
Noise power = -125 dBm

Figure 3.2. LoS propagation model simulation for Li-Fi system using Optisystem.

3.2.2. NLoS propagation Model

The NLoS propagation model considers both the direct and reflected paths of light. By changing the number of reflected light paths in the NLoS propagation model, the proposed simulation shows three possible scenarios for the Li-Fi system's propagation models. In the first situation (as described in the previous part), we have examined the behavior of a single LED using a Line of Sight (LoS) propagation model. In the second scenario, we will analyze the performance of a single LED using an NLoS propagation model with one reflected path of light. Finally, in the third scenario, we will investigate the behavior of a single LED using an NLoS propagation model with two reflected paths of light. We evaluate the performance of the Li-Fi system at the receiver side by analyzing the shape of the received signal.

a. Illustration of a single reflected path of light in an NLoS channel

In the second scenario, as stated in the preceding paragraph, we use a single LED as the transmitter while considering both the direct and reflected paths of the light. Figure 3.3 illustrates the propagation model for this scenario. The primary distinction between this model and the LoS propagation model is that it includes both a direct and a reflected light path rather than solely considering a direct path. The equations in each circumstance determine the distance between the transmitter and receiver and the incidence and irradiance angles:

$$l_1 = 3.1\ m, \theta_{1S} = 14.47° \ and \ \theta_{1d} = 16.26° \tag{3.2}$$

$$l'_2 = 2.8\ m, \theta'_{2S} = 45.23° \ and \ \theta'_{2d} = 44.76° \tag{3.3}$$

$$l''_2 = 1.6\ m, \theta''_{2S} = 47.15° \ and \ \theta''_{2d} = 42.84° \tag{3.4}$$

LED	**Specification**
Frequency	600 nm
Electron life time	0 s
RC constant	8×10^{-9}s
Slope efficiency	0.5 W/A
Quantum efficiency	0.65
Spectral line profile	Gaussian
Bandwidth	0.03 nm
Bit Sequence Generator	**Specification**
Bit rate	10 Mbps
Symbol rate	10 Msym/s
NRZ Pulse generator	**Specification**
Rectangle shape	Exponential
Format for pulse range	Min (1) / Max (0)
LoS FSO Channel	**Specification**
Detection surface area	1 cm^2
Optical concentration factor	Variable
Index concentration factor	1.5
Propagation delay	0 ps/m
Low Pass Bessel Filtre	**Specification**
Cutoff frequency	0.75 × symbol rate
Roll-off factor	0.75
PIN Signal Model	**Specification**
Responsivity type	Constant
Responsivity	0.2 A/W
Dark current	10 nA
Thermal power density	100×10^{-24} W/Hz
Absolute temperature	298 K
Load resistance	50 ohm
Shot noise distribution	Gaussian
Junction capacitance	3 pF
Modulation bandwidth	2 GHz
Center frequency	600 nm
Bandwidth (Shot)	35×10^6 Hz
Opt Filt Signal	**Specification**
Frequency	600 nm
Bandwidth	0.02 nm
TIA	**Specification**
Transimpedance	1000 Ohm
Noise equivalent bandwidth	35 MHz
Input noise density	5×10^{-24} W/Hz
Transfer function model	User-defined
Signal bandwidth	35 MHz
Ambient Noise Source	**Specification**
Noise power	Variable

Table 3.1. Components specification used in the Optisystem simulation tool.

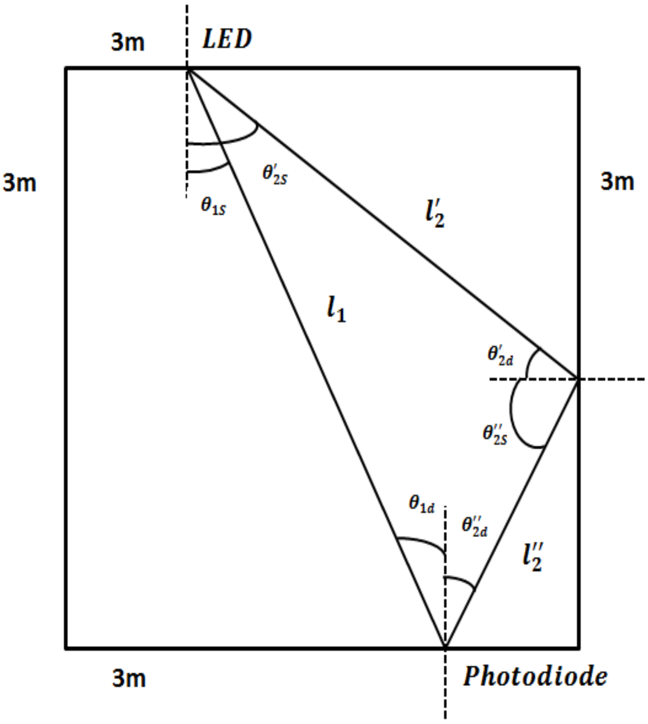
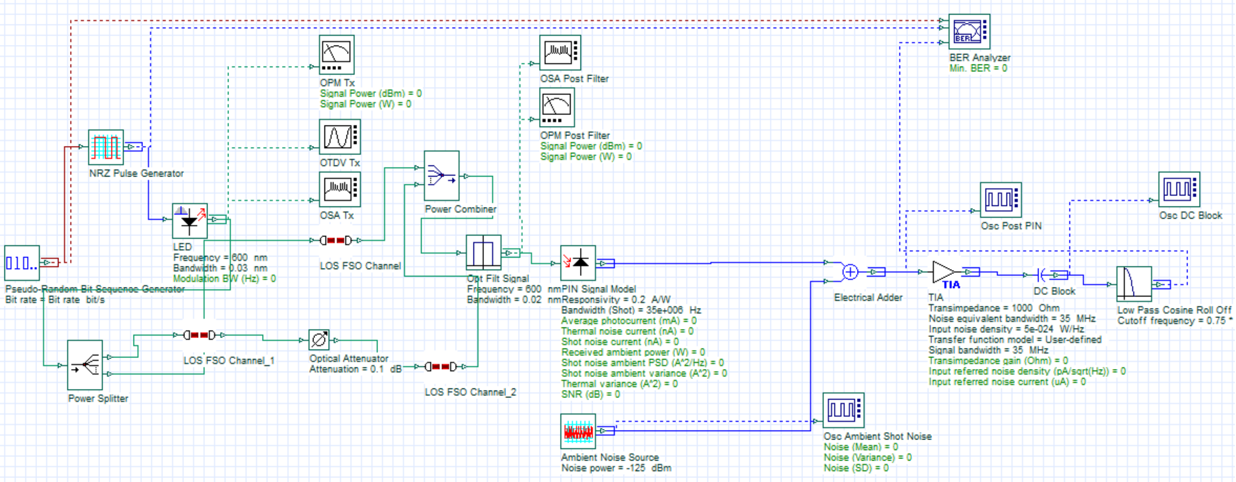


Figure 3.3. Experimental design for the second scenario: the experiment involved using a single LED and a photodiode with a single point of reflection.

Figure 3.4 illustrates an Optisystem simulation model of the experiment, which includes a single LED and a photodiode with only one point of reflection for Li-Fi system.


Pseudo-Random Bit Sequence Generator
Bit rate = Bit rate bit/s

NRZ Pulse Generator

LED
Frequency = 600 nm
Bandwidth = 0.03 nm
Modulation BW (Hz) = 0

OPM Tx
Signal Power (dBm) = 0
Signal Power (W) = 0

OTDV Tx

OSA Tx

LOS FSO Channel

Power Splitter

LOS FSO Channel_1

Optical Attenuator
Attenuation = 0.1 dB

LOS FSO Channel_2

Power Combiner

Opt Filt Signal
Frequency = 600 nm
Bandwidth = 0.02 nm

OSA Post Filter

OPM Post Filter
Signal Power (dBm) = 0
Signal Power (W) = 0

PIN Signal Model
Responsivity = 0.2 A/W
Bandwidth (Shot) = 35e+006 Hz
Average photocurrent (mA) = 0
Thermal noise current (nA) = 0
Shot noise current (nA) = 0
Received ambient power (W) = 0
Shot noise ambient PSD (A^2/Hz) = 0
Shot noise ambient variance (A^2) = 0
Thermal variance (A^2) = 0
SNR (dB) = 0

Ambient Noise Source
Noise power = -125 dBm

Osc Ambient Shot Noise
Noise (Mean) = 0
Noise (Variance) = 0
Noise (SD) = 0

Electrical Adder

TIA
Transimpedance = 1000 Ohm
Noise equivalent bandwidth = 35 MHz
Input noise density = 5e-024 W/Hz
Transfer function model = User-defined
Signal bandwidth = 35 MHz
Transimpedance gain (Ohm) = 0
Input referred noise density (pA/sqrt(Hz)) = 0
Input referred noise current (uA) = 0

DC Block

Low Pass Cosine Roll Off
Cutoff frequency = 0.75 *

Osc Post PIN

Osc DC Block

BER Analyzer
Min. BER = 0

Figure 3.4. NLoS propagation model simulation for Li-Fi system with only one point of reflection using Optisystem.

The model depicted in Figure 3.4 is the same as the LoS propagation model, except it considers the reflection point. As shown in Figure 3.4, we implement attenuation (0.1 dB) at the reflection point. The simulation commenced with the identical configuration in the LoS propagation model, and a power splitter was employed at the transmitting end. The NLoS simulation employs the identical LoS channel in the previous system (refer to Figure 3.2), incorporating the values outlined in Table 1. However, before inputting it into the optical filter and the PIN signal model, we utilized the power combiner component on the receiver side. The simulation employs the previous system's identical low pass cosine roll-off electrical filter (refer to Figure 3.2) to filter the detected electrical signal from the PIN photodiode.

b. Illustration of two reflected paths of light in an NLoS channel

In the current scenario, we utilize a single LED as the transmitter and consider both the direct and two reflected paths of light in an NLoS channel. Figure 3.5 illustrates the propagation model for this particular event. The subsequent equations yield the distance between the transmitter and receiver, the incidence angle, and the irradiance angle:

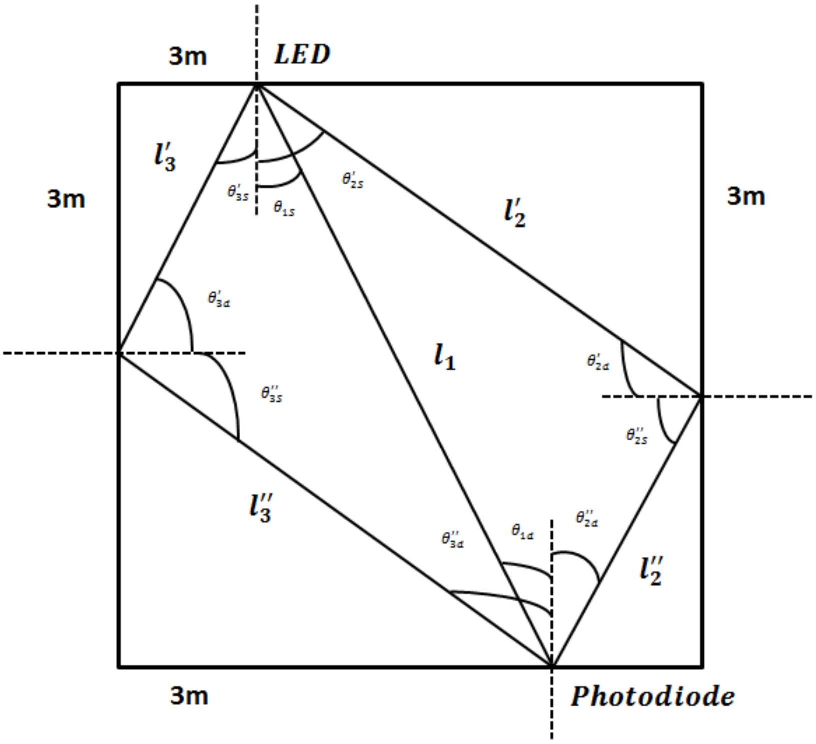


Figure 3.5. Experimental design for the third scenario: the experiment used a single LED and a photodiode with two reflection points.

$$l_1 = 3.1\ m, \theta_{1S} = 14.47° \ and\ \theta_{1d} = 16.26° \tag{3.5}$$

$$l'_2 = 2.8\ m, \theta'_{2S} = 45.23° \ and\ \theta'_{2d} = 44.76° \tag{3.6}$$

$$l''_2 = 1.6\ m, \theta''_{2S} = 47.15° \ and\ \theta''_{2d} = 42.84° \tag{3.7}$$

$$l'_3 = 1.6\ m, \theta'_{3S} = 35.90° \ and\ \theta'_{3d} = 54.09° \tag{3.8}$$

$$l_3'' = 2.8\,m, \theta_{3S}'' = 34.75° \; and \;\; \theta_{3d}'' = 55.08° \tag{3.9}$$

Figure 3.6 illustrates an Optisystem simulation model of the experiment, which includes a single LED and a photodiode with two reflection points for Li-Fi system. However, the proposed design in Figure 3.6 is exactly the same as the previous design (see Figure 3.4), except that a second reflection point with 0.1 dB attenuation is included.

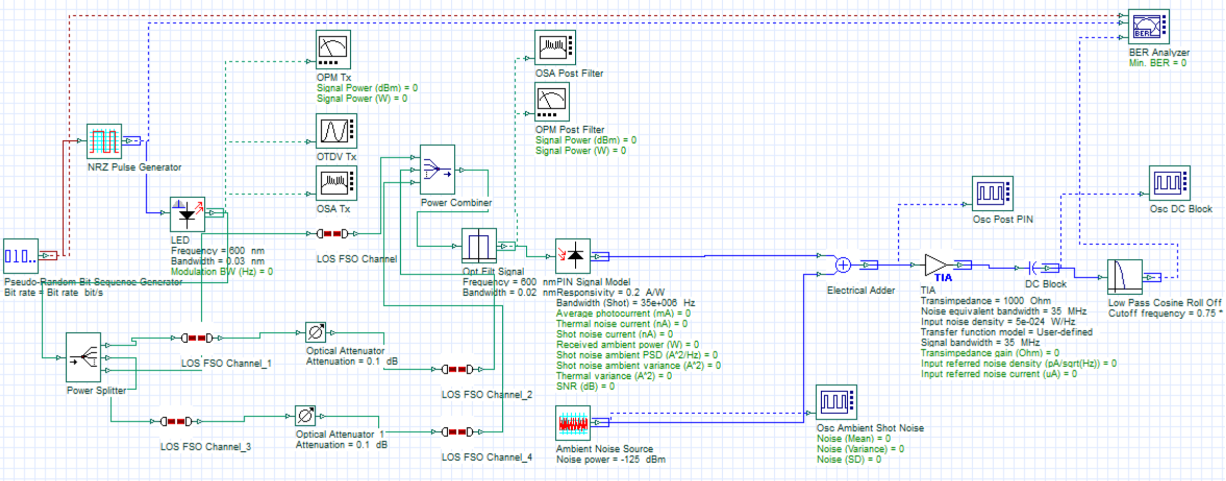


Figure 3.6. NLOS propagation model simulation for Li-Fi system with two reflection points using Optisystem.

3.3. Li-Fi channel modelling

This section explains how to represent Li-Fi sources, receivers, and channels in a multipath Li-Fi network. In addition, we explore the criteria employed to define the characteristics of a multipath channel.

3.3.1. Source modelling

In Li-Fi systems, the optical source typically consists of an LED. The LED is a generalized Lambertian source positioned at a distance $R_{k,n}$. Its orientation is determined by the unit vector q_s, perpendicular to its radiating surface and specified by the unit vector q_r.

The LED radiant intensity is defined by its radiation pattern, which exhibits uniaxial symmetry and is quantified by a radiation density as described in references [38, 39]:

$$R_0(\phi_{k,n}) = \frac{(\gamma+1)\cdot cos^{\gamma}(\phi_{k,n})}{2\pi} \tag{3.10}$$

The symbol $\phi_{k,n}$ represents the angle at which light hits the surface, while γ represents the order of Lambertian emission. The value $\phi_{1/2}$ refers to the LED semi-angle at half power, which the manufacturer gives.

The Lambertian order γ is a parameter that characterizes the radiation lobe shape and indicates the directionality of the source. It is mathematically described as:

$$\gamma = \frac{-ln\,(2)}{ln\,(cos\,(\phi_{1/2}))} \tag{3.11}$$

Figure 3.7 illustrates the radiation lobes' shapes for various values of γ. The desired radiation pattern can be achieved through the meticulous design of the lens employed at the source. It is essential to observe that regardless of the value of γ, the highest level of radiant intensity can be found at $\phi_{k,n} = 0°$.

The transmitter in Figure 3.7 emits an axially symmetric radiation pattern, meaning it has the same strength in all directions. The radiant intensity $P_t \cdot R_0(\phi_{k,n})$ defines this pattern. The irradiance $\frac{P_t \cdot R_0(\phi_{k,n})}{{R_{k,n}}^2}$ at a receiver positioned at a distance $R_{k,n}$ and an angle $\phi_{k,n}$ about the transmitter can be calculated.

Disregarding the impact of reflection losses, a detector attains an effective signal-collection area, which is expressed as:

$$A_{\text{eff}} = A \cdot cos\,(\theta_{k,n}) \tag{3.12}$$

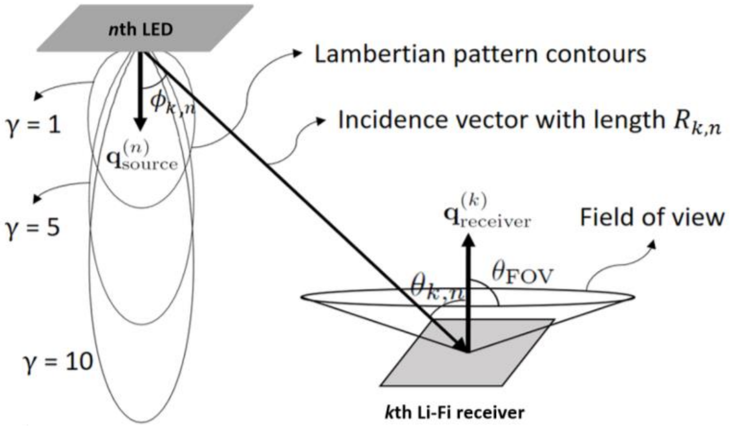


Figure 3.7. Geometry of LoS channel model.

The variable A represents the actual size of the detector, while $\theta_{k,n}$ represents the angle at which the incident light hits the receiver axis. The power received at the receiver can be determined using equations (3.10) and (3.12):

$$P_r = \frac{P_t \cdot R_0(\phi_{k,n}) \cdot A_{\text{eff}}}{{R_{k,n}}^2} \tag{3.13}$$

The channel is characterized by the DC channel gain, which may be mathematically represented as [38, 39]:

$$H = \frac{R_0(\phi_{k,n})\cdot A\cdot cos\,(\theta_{k,n})}{{R_{k,n}}^2} = \frac{(\gamma+1\,)\cdot cos^{\gamma}(\phi_{k,n})\cdot A\cdot cos\,(\theta_{k,n})}{2\pi\cdot {R_{k,n}}^2} \tag{3.14}$$

Where $\theta_{k,n}$ is the angle at which the Li-Fi receiver is inclined to the incident surface.

3.3.2. Receiver modelling

A photosensitive detector at a distance of $R_{k,n}$ is modelled as a receiving element. Its orientation is determined by the unit vector q_r, which is expected to be the photosensitive surface of area APD. The symbol for its FOV is ψ_c. The receiver does not detect the light if its angle of incidence concerning q_r is larger than ψ_c. The PD may have been manufactured or packaged incorrectly, which would account for the receiver FOV's poor value. Likewise, it can be purposefully restricted using a lens or aperture to lessen undesired reflections or to cut down on noise by blocking out too much ambient light. Furthermore, a frequent technique to boost the signal received is the use of an optical concentrator. This optical concentrator's gain is indicated as [38]:

$$G(\,\psi) = \frac{\mathrm{n}^2}{\sin^2(\psi_c)},\quad 0 \le \psi \le \psi_c \tag{3.15}$$

The refractive index of the optical concentrator is described by n.

3.3.3. LoS channel gain

A multipath Li-Fi channel model that takes into account NLoS reflection and LoS path has been employed in this thesis [40]. The Lambert radiator is a standard radiation model that can simulate the LED light source in a Li-Fi. Additionally, the reference [41] suggests that the luminous intensity pattern of the LEDs, both LoS and NLoS, can be precisely replicated using the Lambertian model. Thus, the total gain of the Li-Fi channel is the product of the LoS path, which is the direct way between the LED and the Li-Fi user, and the NLoS path, which is the path reflected by the walls. In the direct path, the channel DC gain is provided:

$${H_{LoS}}^{LED} = \left\{ \frac{(\gamma+1)\cdot A_{PD}}{2\pi\cdot {R_{k,n}}^2}\; cos^{\gamma}\big(\phi_{k,n}\big)\cdot T_s(\psi)\cdot G(\psi)\cdot \cos(\theta_{k,n}),\;\; 0 \le \psi \le \psi_c \right. \tag{3.16}$$

Here, the physical area of the PD is denoted by A_{PD}, the angle of incidence to the PD from the LED is $\theta_{k,n}$, the angle of irradiance from the LED is $\phi_{k,n}$, and the gain of the optical filter is $T_s(\psi)$.

3.3.4. NLoS channel gain

Following wall reflections, the LED's NLoS channel gain is determined by (see Figure 3.8):

$$H_{NLoS}{}^{wall} = \begin{cases} \frac{\rho_{wall}\cdot(\gamma+1)\cdot A_{PD}}{2\pi\cdot {d_1}^2\cdot {d_2}^2} \; cos^{\gamma}(\phi_1)\cdot T_s(\psi)\cdot G(\psi)\cdot \cos(\varphi_1)\cdot\cos(\phi_2), & 0\le\psi\le\psi_c \end{cases} \quad (3.17)$$

The NLoS link made with the reflecting surface (wall) has a reflection coefficient ρ_{wall}, and the incidence and reflectance angles are φ_1 and ϕ_2, respectively. As seen in Figure 3.8, d_1 and d_2 represent the distances the NLoS link transited to reach the Li-Fi user from the wall.

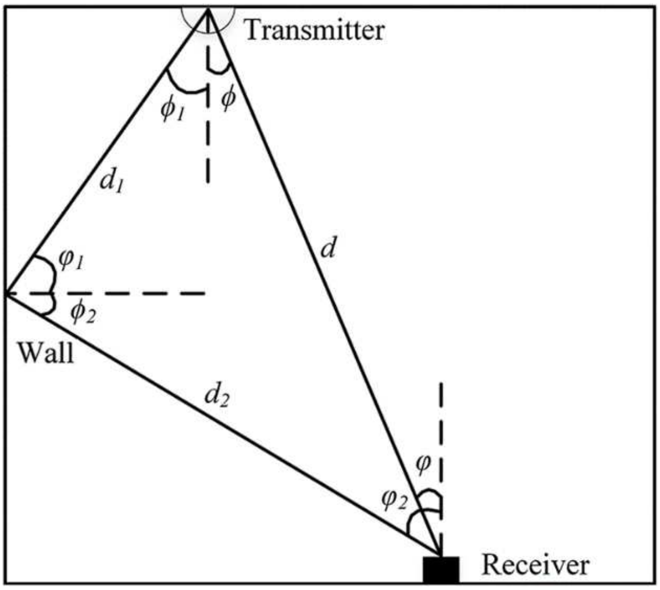


Figure 3.8. Geometry of NLoS channel model [42].

For a given transmission power P_t, the total received power at j_{th} receiver site from many i_{th} LEDs, including both LoS and NLoS channels via the walls, can be represented as follows:

$$P_r = \sum_{i=1}^{N}[P_t\cdot H_{LoS(i,j)}{}^{LED} + \sum_{k=1}^{K}[P_t\cdot H_{NLoS(i,j)}{}^{wall}] \quad (3.18)$$

The total received power is calculated by adding the LoS and NLoS link from the walls across the room, where N and K represent the total number of transmitting LEDs and reflective spots on the wall, respectively.

3.4. Simulation results

The three situations are represented by the following simulation results in this section: scenario A (see Figures 3.1 and 3.2), scenario B (see Figures 3.3 and 3.4), and scenario C (see Figures 3.5 and 3.6). However, we have examined and assessed the performance of the suggested Li-Fi system in these conditions, with the following results:

- Impact of the FOV's value variation at the recipient's end;
- Impact of the THA's value variation at the transmitter end;
- How a Li-Fi link's bit rate varies;

- The impact of varying ambient noise sources on a Li-Fi link.

3.4.1. Impact of the FOV's value variation at the recipient's end

his section presents a set of simulations performed using Optisystem v. 15. With the set noise power of the ambient source or -125 dBm, at a frequency of 600 nm, Figure 3.9 shows variations of the error rate bit, or BER, as a function of different values of the optical concentration de factor, or FOV, in the range [11.25° to 90°]. At the suggested Li-Fi system level, we assume that in the three situations (A, B, and C), the half-angle transmitter (or THA) is fixed at 60°.

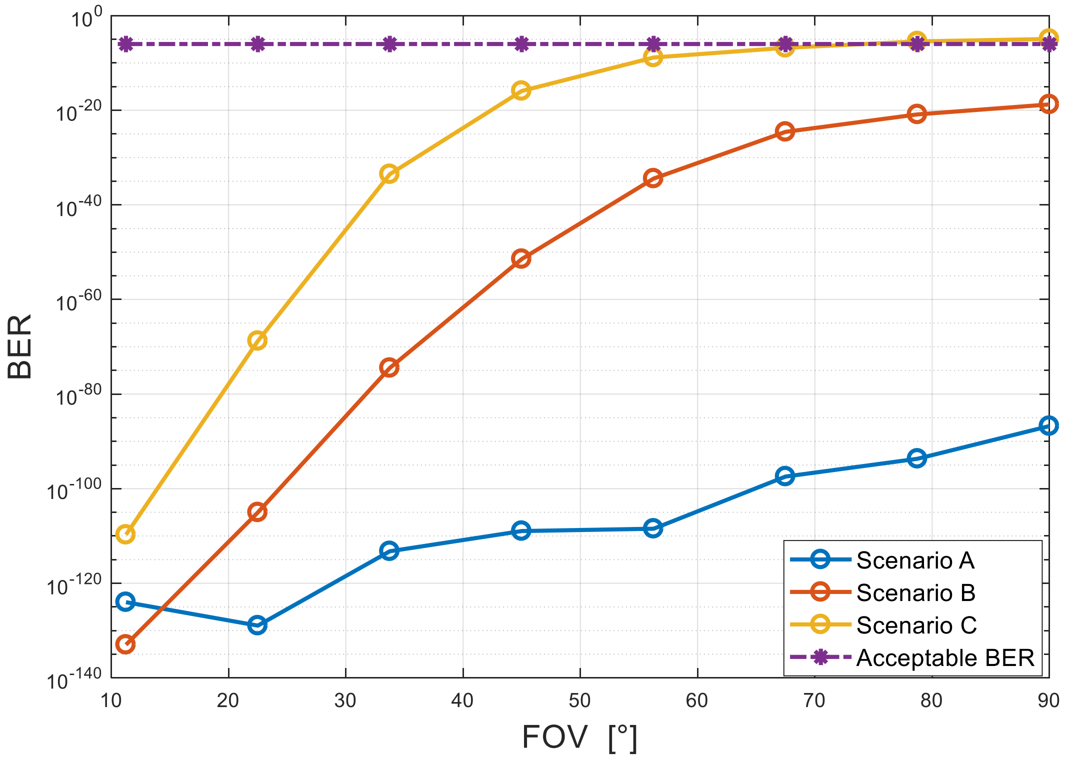


Figure 3.9. BER Vs. FOV [°].

However, increasing the FOV clearly impacts the transmission quality of the Li-Fi system at 10 Mbps. The more significant the FOV, the greater the increase in BER, and these situations are not advantageous for the proposed Li-Fi system, whatever the type of scenarios proposed. Regarding the work's objective, in the realistic scenario C, an acceptable BER of 1e-6 is attained when the FOV value equals 74.17°.

Additionally, as the BER increases, the received SNR degrades; in realistic scenario C (see Figure 3.10), the SNR decreases as the FOV increases, from [23.02 dB to -2.45 dB] as a function of the various FOV values in the interval [11.25° to 90°]. As a result, the received SNR value equals -1.884 dB, equivalent to the FOV value of 74.17°, under the acceptable conditions in realistic scenario C.

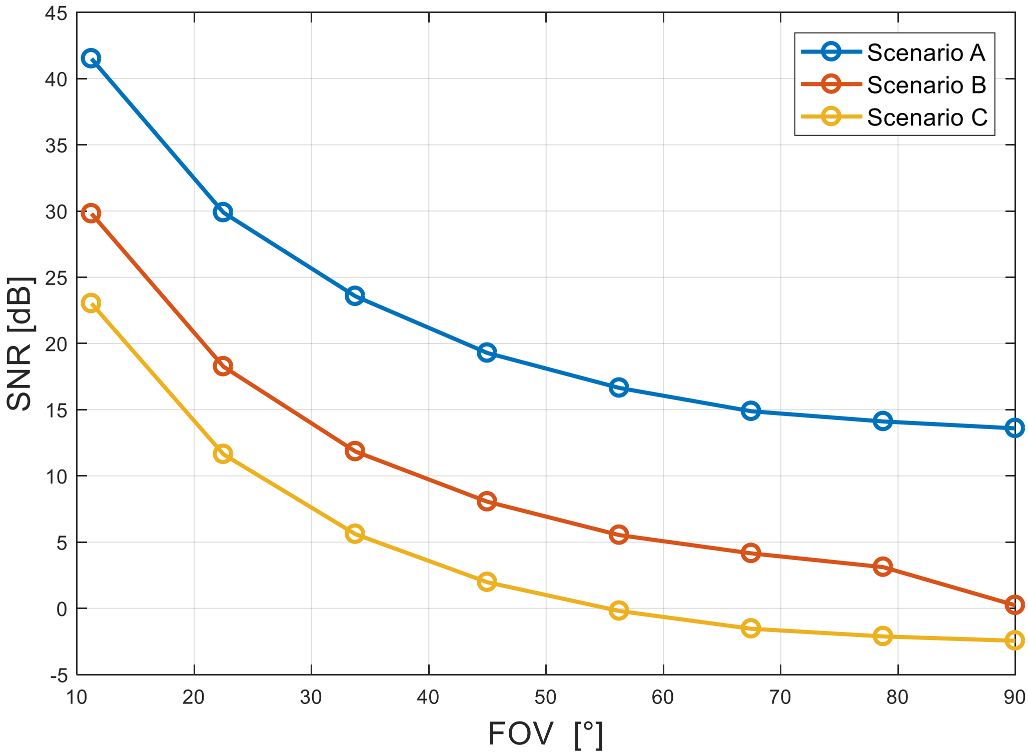


Figure 3.10. SNR [dB] Vs. FOV [°].

3.4.2. Impact of the THA's value variation at the transmitter end

Figures 3.11 and 3.12 depict how the transmitter half angle values (or THA) at the transmitter side vary over a range of 11.25° to 90°, which corresponds to a frequency of 600 nm at the Li-Fi system suggested in the three scenarios (A, B, and C). These variations affect the received SNR and BER. Assuming that each scenario delivers data at a speed of 10 Mbps across the Li-Fi system link and that the Li-Fi user's receiving side has a FOV of 90°.

Nevertheless, based on the outcomes displayed in Figures 3.11 and 3.12. The BER and received SNR values for the three scenarios (A, B, and C) at THA of 11.25°, for instance, are 1.15e-135, 3.78e-111, 2.83e-59, 28.54 dB, 16.68 dB, and 10.17 dB, respectively. For THA of 90°, on the other hand, the BER and received SNR values for the three scenarios (A, B, and C) are 0.88e-57, 45.63-9, 1e0, 8.41 dB, -1.46 dB, and -5.80 dB, respectively.

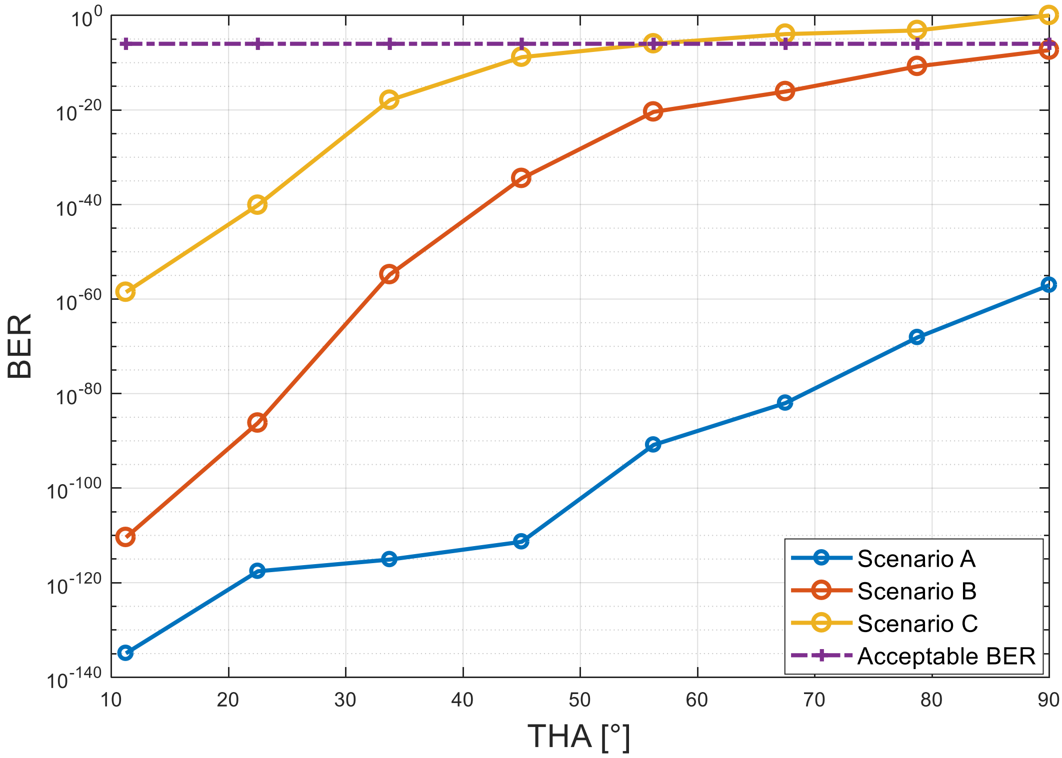


Figure 3.11. BER Vs. THA [°].

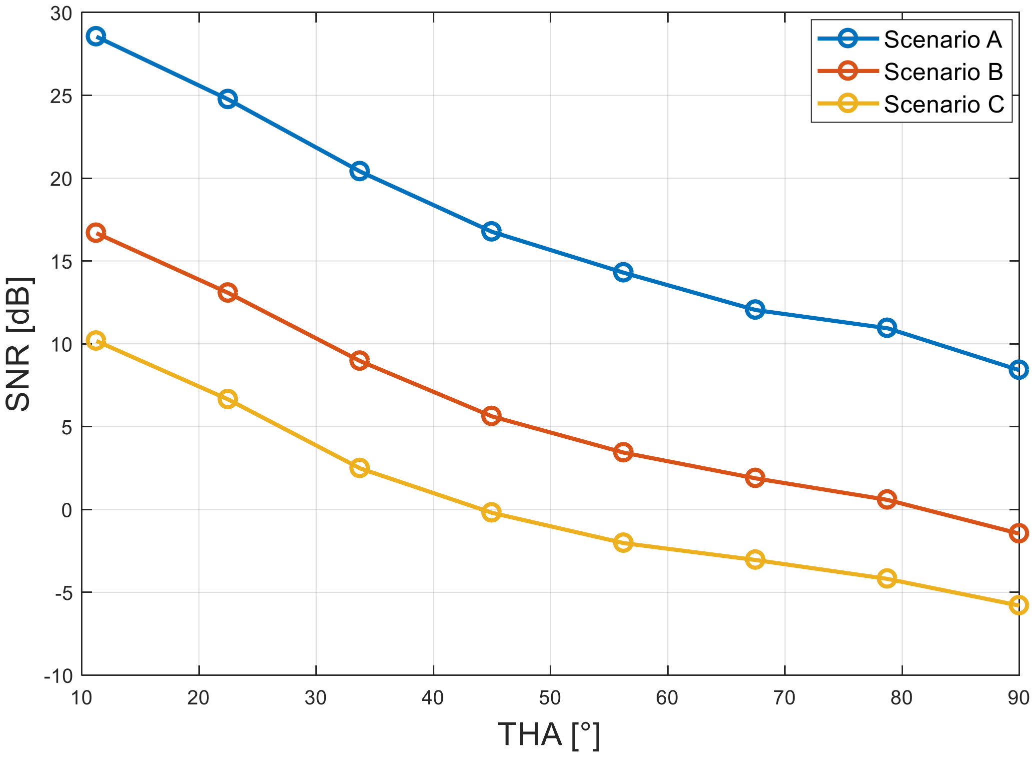


Figure 3.12. SNR [dB] Vs. THA [°].

In conclusion, we have noted that the three scenarios (A, B, and C) involve a significant increase in BER and a sharp decline in received SNR as a result of an increase in THA on the transmitter side, representing how the performance of the proposed Li-Fi system progresses. In summary, for the realistic situation C, we have found that, for an acceptable BER value of 1e-6, the permissible THA value at the transmitter side equals 56.18°, and the received SNR value equals -2.019 dB.

3.4.3. How a Li-Fi link's bit rate varies

The suggested system's BER fluctuation about the Li-Fi link bit rate for each of the three situations (A, B, and C) is depicted in Figure 3.13. For this analysis, we will assume that each scenario sends data at a rate of [10 Mbps to 30 Mbps] and that the ambient noise source has a fixed noise strength of -125 dBm at a frequency of 600 nm. Additionally, based on the earlier sub-sections in Figures 3.9 and 3.11, we have determined that the appropriate values for FOV and THA, which are utilized in this section, are 74.17° and 56.18°.

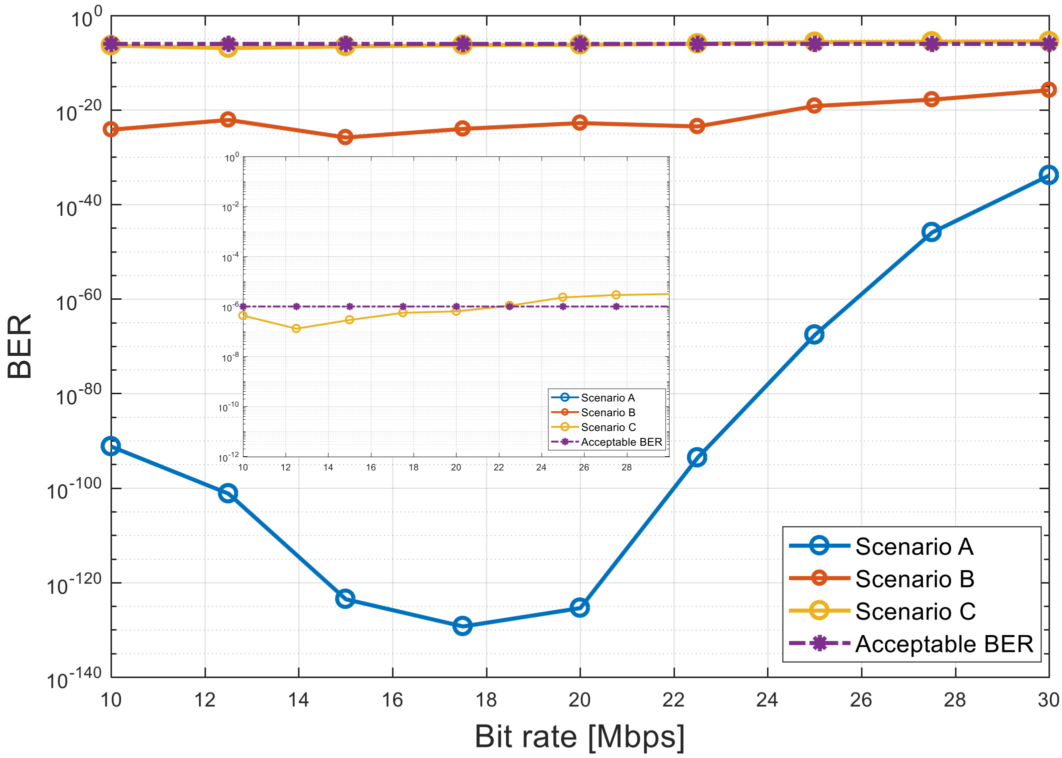


Figure 3.13. BER vs. Bit rates [Mbps].

Concerning the obtained results, we have found the following conclusions: When the bit rate increases in all proposed scenarios (A, B, and C), the BER increases, and consequently, the received SNR decreases at Li-Fi users, see Figure 3.14.

Except that in scenario A, there's a special case: a decrease in BER followed by an increase, but this scenario isn't objective for us. The most realistic case is scenario C, for which we need to know the bit rate obtained under acceptable conditions according to the BER value of 1e-6. After an estimation, the bit rate value is 22.13 Mbps with a received SNR of -1.537 dB.

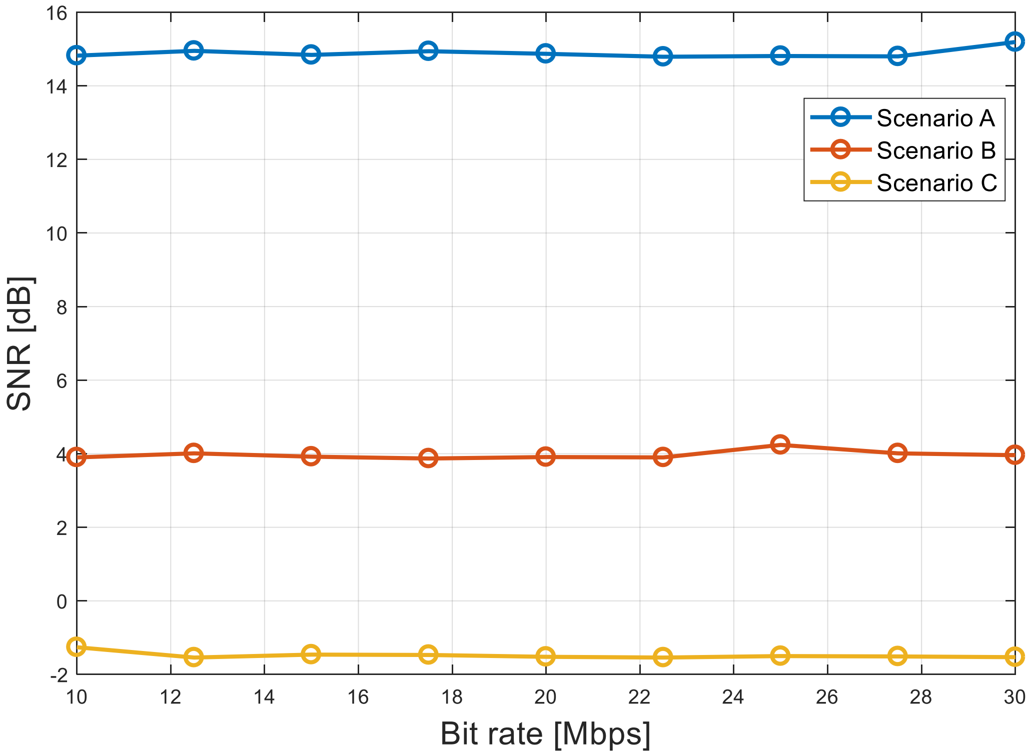


Figure 3.14. SNR [dB] Vs. Bit rates [Mbps].

3.4.4. The impact of varying ambient noise sources on a Li-Fi link

The same settings as in the previous paragraph are used in this one, but this time, we look at how different ambient noise sources affect the suggested Li-Fi link—realistic scenario C. To estimate the BER performance and the received SNR at the Li-Fi user as a function of data rate, we have varied the noise power using the following range values: -145 dBm, -135 dBm, and -125 dBm. The results from Figures 3.15 and 3.16 show that when the ambient noise power source is increased, the BER performance and the received SNR at the Li-Fi user can decline, and vice versa. For each value of noise power, for instance, the BER value and the received SNR value are approximated at about the acceptable BER of 1e-6: (5.671e-100, -1.303 dB) for -145 dBm, (2.155e-41, -1.46 dB) for -135 dBm, and (1e-6, -1.537 dB) for -125 dBm. Note that the bit rate in these acquired results equals 22.13 Mbps.

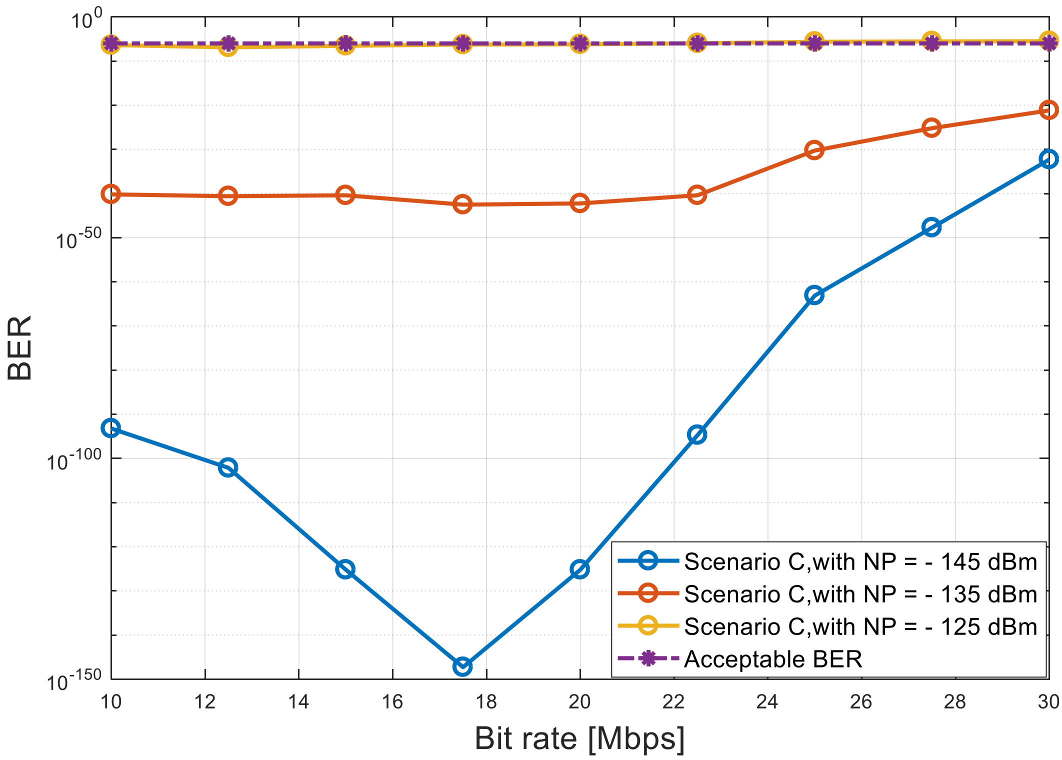


Figure 3.15. BER vs. Bit rates [Mbps], with different values of NP.

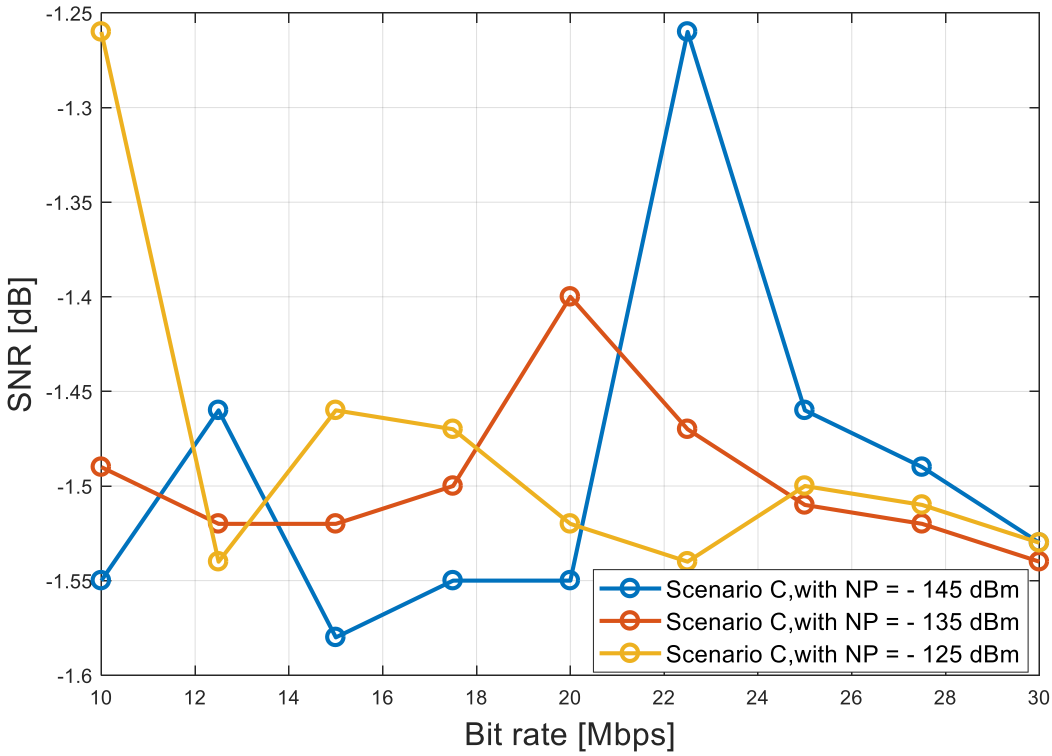


Figure 3.16. SNR [dB] Vs. Bit rates [Mbps], with different values of NP.

3.5. Conclusion

The simulation findings used in this chapter to examine how well a Li-Fi system performs regarding bit error rate (or BER) and received signal-to-noise ratio (or SNR) were conducted using Optisystem version 15. The study focuses on the effects of different parameters on BER and received SNR values, including field-of-view (or FOV) angle, transmitter semi-angle angle (or THA), and ambient noise power. The optimal FOV and THA values in a practical scenario (scenario C) are 74.17° and 56.18°, respectively, for achieving an acceptable BER of 1e-6. The highest data rate achieved with these parameters is about 22.13 Mbps, correlated with a received SNR of -1.537 dB. However, boosting ambient noise levels weakens the system's performance, which lowers received SNR and BER.

General conclusion

This project's experiment demonstrated that Visible Light Communications (or VLC) are a compelling solution to address the limited availability of the RF spectrum. This technology utilizes the visible spectrum, offering an alternative spectrum for communication purposes. Illumination as a means of communication can become the future of the Internet.

Indoor VLC systems offer a compelling alternative to address the increasing need for faster data rates and to overcome the constraints of conventional wireless technologies, such as Wi-Fi, in indoor settings.

Li-Fi transmission, a progressive form of communication via light, is a VLC technology that competes with Wi-Fi. It ingeniously employs LEDs for transmission and photodetectors for reception. The initial challenge was to establish highly efficient Li-Fi transmission, with the aim of creating a high-performance Li-Fi communication system. Once the milestone of Li-Fi transmission was reached, the focus shifted to enhancing the security of transmitted data, marking a significant step in the evolution of Li-Fi technology.

The current study commenced by providing an overview and outlining the distinctive features of visible light communications technologies, including their underlying concepts and essential structures. Subsequently, it delved into the specifics of one such application, Li-Fi, elucidating its benefits as well as the limitations of the Li-Fi network. The utilization of these technologies is still in its nascent stage and undergoing comprehensive advancement. In addition, we have directed our attention to the various elements of a communication network and the specific attributes of the LED and photodetector. We have taken into account the factors of presence noise and channel modeling. We have also showcased many modulations and their corresponding encoding methods.

However, evaluating an indoor optical wireless communication system (also known as indoor Li-Fi) that utilizes visible light involves assessing its design and performance based on two metrics: the performance BER and the received SNR at the user. The results demonstrate the efficacy of the suggested Li-Fi system.

To summarize, VLC shows excellent potential as a technology for indoor optical communications, such as Li-Fi systems. Thorough system design and precise performance measurement are crucial to guarantee reliable and effective real-time functioning. Future research will prioritize enhancing data transfer rate, minimizing susceptibility to noise, and advancing communication methods that are more resilient for various indoor applications.

APPENDIX 1

Description of the software Optisystem

4.1. Optisystem: a complete software for optical simulation

The modeling and simulation of optical telecommunications systems are pretty sophisticated. The design and analysis of these systems involve nonlinear components and non-Gaussian noise sources, which make the designer's task more challenging [43].

The Optisystem program effectively addresses these design challenges due to its user-friendly interface and extensive collection of components in its library. This software is designed to simulate optical communications in simulation mode (see Figure 4.1). This cutting-edge software enables designers to realistically create, analyze, and enhance optical connections of various kinds [43].

The Optisystem program allows users to manipulate the graphical user interface regardless of the arrangement of the optical components and the netlist. Furthermore, it encompasses many dynamic and static elements with adjustable physical configurations.

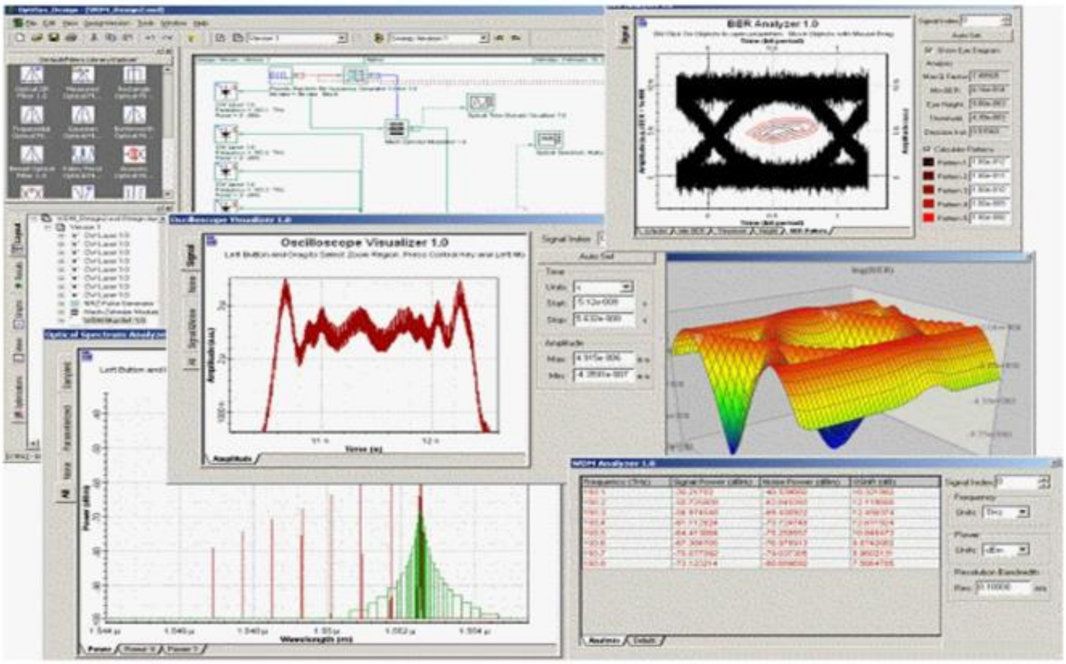


Figure 4.1. Graphical user interface, component library, and visualization tools.

4.2. Main advantages

The Optisystem software is a pervasive application for simulating and testing optical assemblies. Its diverse components library includes customizable fibers and measuring devices, see Figure 4.2 [43].

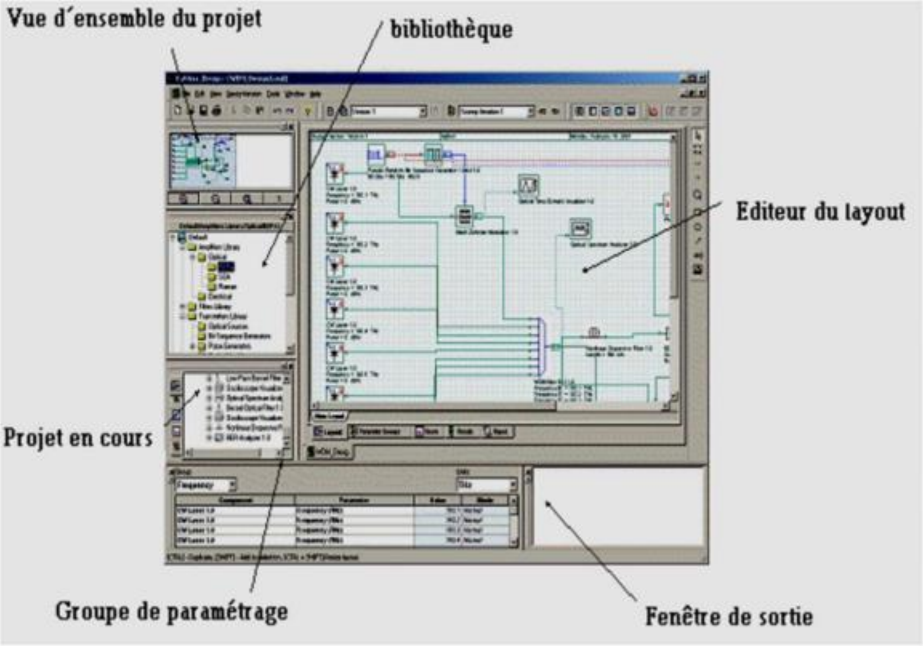


Figure 4.2. Optisystem sub-windows.

The Optisystem program operates within the Xwindows environment and comprises a primary window separated into multiple sections:

- Project Overview: Provides a concise preview of the layout that is being altered.
- Library: a repository of diverse pre-existing components.
- Layout Editor: the layout editor provides the capability to modify and customize the design layout.
- Current project: Presentation of the several files and components associated with the ongoing project.
- Parameterization: this window facilitates the universal parameterization of the current project and simulation.
- The output window provides a visual display of the various simulation stages and any error messages that may occur [43].

4.3. Editing and simulation

To create a layout, drag the library component onto the design to position it. Furthermore, Optisystem allows for parameterizing every component specified in the layout. Indeed, when a component is double-clicked, its parameters are displayed, see Figure 4.3 [43].

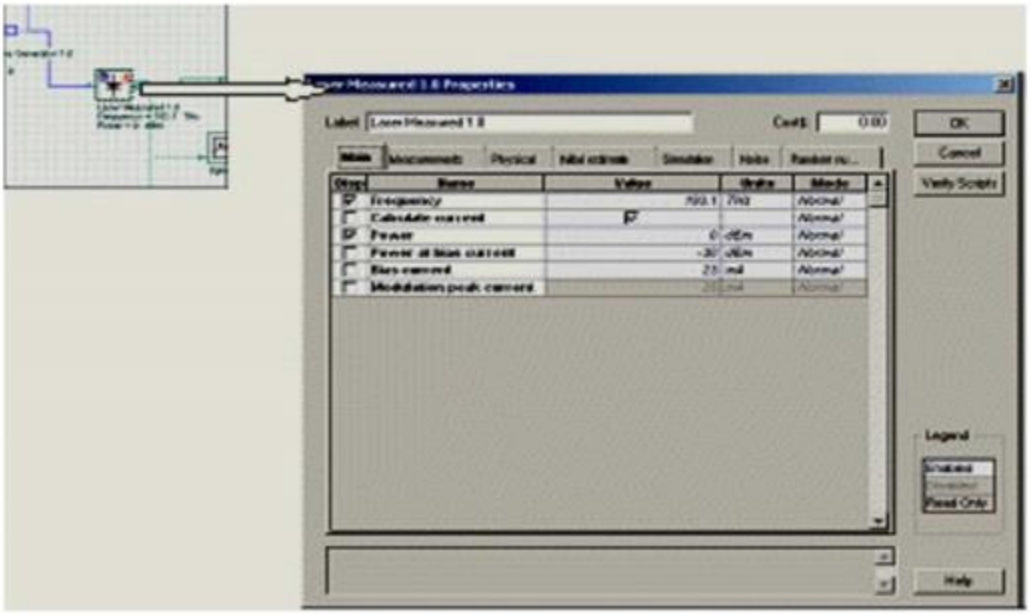


Figure 4.3. Parameterization of a component.

The model provides access to the parameters that can be adjusted by double-clicking on them prior to launching the simulation, see Figure 4.4 [43].

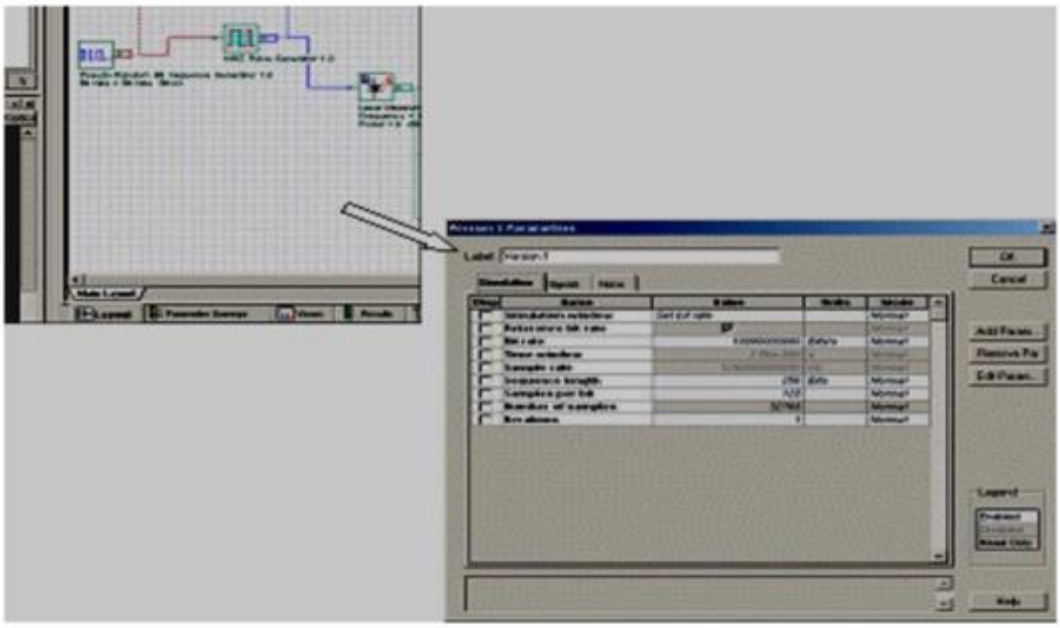


Figure 4.4. Modification of the global layout parameters.

To initiate a simulation (see Figure 4.5), you need to either press Ctrl+F5 or navigate to the File menu and select the compute option [43].

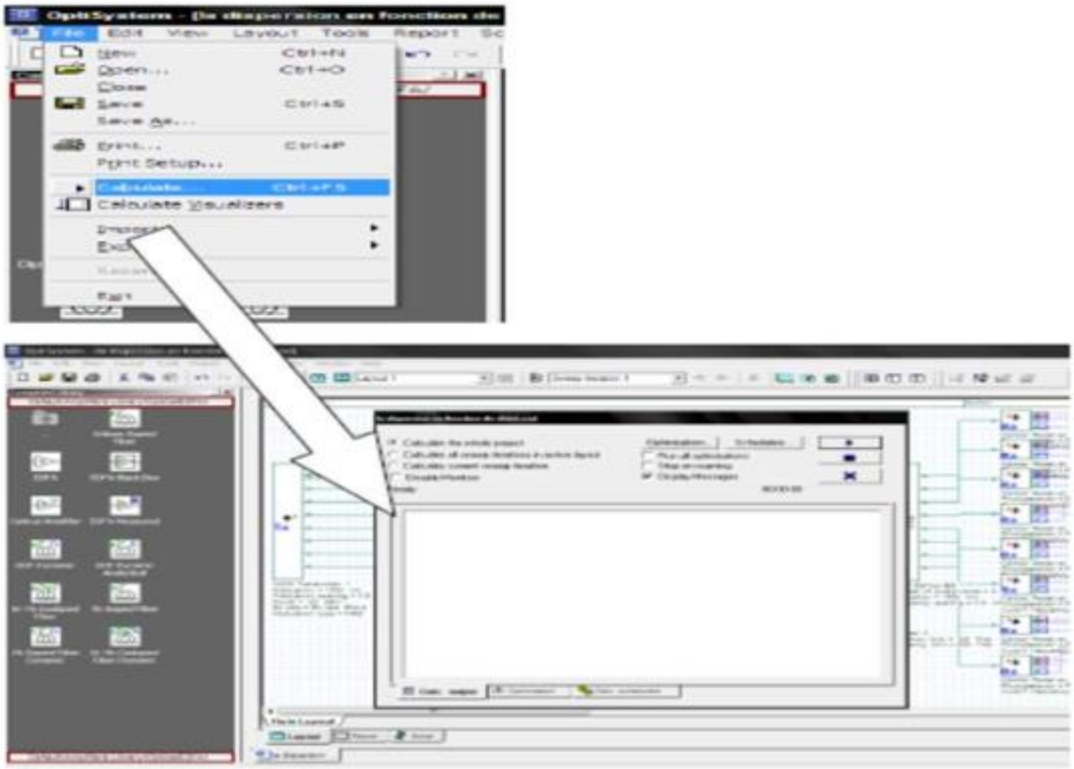


Figure 4.5. Starting the simulation.

Ultimately, to facilitate the visualization of various analyses, a simple double-click on the measuring instrument allows for the display of the simulation in either a 2D or 3D format, see Figure 4.6 [43].

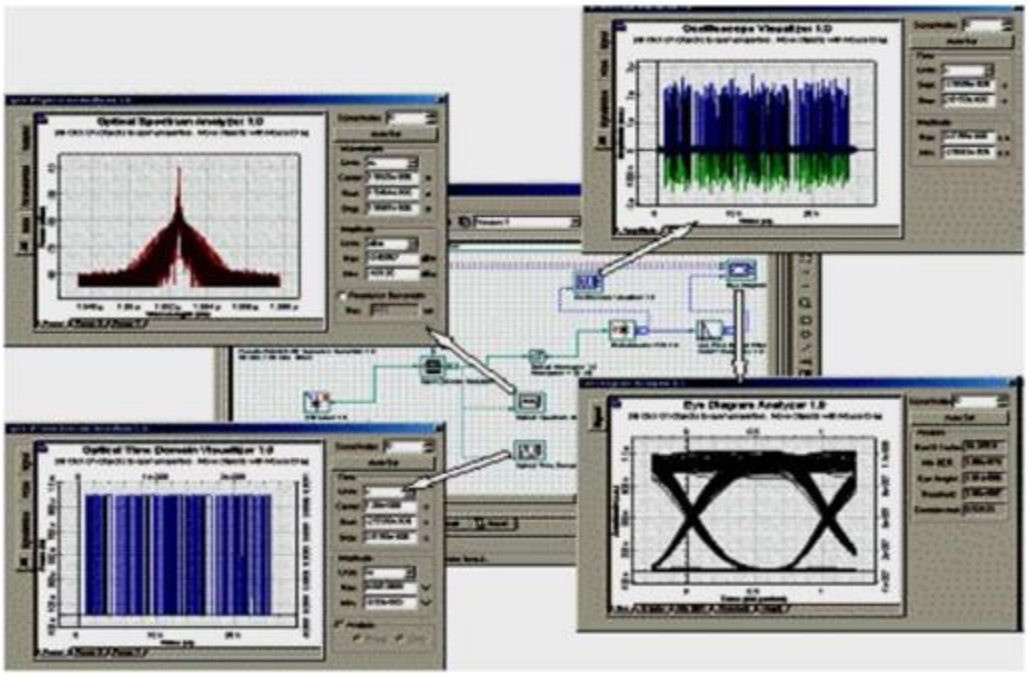


Figure 4.6. Display of the simulation results.

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