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A Theoretical Review on Visible Light Communication (VLC) and Li-Fi Technologies: Advancements, Applications, and Challenges

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Abstract – **Visible Light Communication (VLC) and Light Fidelity (Li-Fi) are emerging wireless communication technologies that utilize the visible light spectrum for data transmission, offering a promising alternative to traditional radio frequency-based systems like Wi-Fi. VLC leverages Light Emitting Diodes (LEDs) for communication, taking advantage of their ability to switch at high speeds, which is imperceptible to the human eye. This technology offers significant benefits, including high bandwidth, energy efficiency, security, and immunity to electromagnetic interference, making it ideal for use in environments where radio frequency communication is either impractical or undesirable. Li-Fi, an extension of VLC, provides bidirectional communication capabilities that enable high-speed internet access, secure data transmission, and efficient network management. With the increasing adoption of LED lighting systems in homes, offices, and public spaces, VLC and Li-Fi are positioned to revolutionize wireless communication by offering seamless integration with existing infrastructure. This paper reviews the development and principles of VLC and Li-Fi, highlights their potential applications, and discusses the challenges that must be addressed for their widespread implementation. Additionally, it explores the ongoing advancements in LED technology and modulation techniques that promise to enhance the performance of optical wireless communication systems.**

Keywords – **Visible Light Communication, Li-Fi, LED, Wireless Communication, Data Transmission, High-Speed Internet, Security, Optical Wireless Communication.**

I. INTRODUCTION

In the modern era, wireless communication systems are at the core of our connected world, facilitating everything from personal interactions to enterprise operations. Among the most common technologies, Wi-Fi has long been a dominant solution for providing wireless internet access. However, as data consumption continues to grow exponentially and demand for higher-speed connectivity increases, there is a pressing need for more efficient and high-capacity communication systems. A promising solution lies in the field of Visible Light Communication (VLC), which uses visible light, typically emitted by Light Emitting Diodes (LEDs), to transmit data. VLC operates in the optical spectrum, which offers several advantages over traditional radio frequency-based wireless communication technologies, such as Wi-Fi.

The principle of VLC lies in the modulation of light emitted from LEDs, which are capable of switching at speeds undetectable to the human eye. The potential of VLC is vast, spanning a range of applications from high-speed internet access to secure communications in electromagnetic-sensitive environments like hospitals and airplanes. Moreover, VLC holds the promise of transforming any LED-based light source into a communication unit, enabling ubiquitous wireless communication systems that are energy-efficient and cost-effective. This technology is gaining increasing attention as a viable alternative or complementary technology to current wireless communication standards, such as Wi-Fi and Bluetooth.

In parallel with the advancements in VLC, another cutting-edge technology, Light Fidelity (Li-Fi), has emerged as a revolutionary concept. Li-Fi extends the capabilities of VLC by enabling bidirectional communication, which is comparable to Wi-Fi, but with significantly higher speeds and more secure connections. Li-Fi leverages the visible light spectrum, ensuring that the transmitted signals remain confined to the area illuminated by the light, offering improved security by reducing the chances of unauthorized interception of data. Furthermore, unlike traditional RF-based systems, Li-Fi does not interfere with other wireless systems, making it suitable for use in environments where RF interference is a concern.

The development of VLC and Li-Fi is being propelled by innovations in LED technology, which continues to advance in both brightness and energy efficiency. These innovations are critical in supporting high-speed data transmission rates that can reach gigabit and terabit speeds in the future. As the demand for high-speed internet, particularly in indoor environments, grows, VLC and Li-Fi offer exciting new opportunities for wireless communications, potentially leading to a future where all forms of wireless connectivity, from mobile devices to home networks, are powered by light.

This paper explores the development, principles, advantages, and applications of VLC and Li-Fi, providing an overview of their potential to revolutionize wireless communication systems. In addition, it delves into the key challenges and future research directions that will shape the next generation of optical wireless technologies.

II. VISIBLE LIGHT COMMUNICATION (VLC)

VLC is a wireless optical communication technique, in which the light produced by an LED (Light Emitting Diode) in the visible spectrum is used as a data carrier through the use of Intensity Modulation (IM). It is a protocol that converts WiFi to VLC through LED light. While WiFi (Wireless Fidelity) uses the radio part of the electromagnetic spectrum (between 2.4 and 5 GHz), VLC takes advantage of the optical part of the spectrum (between 384 and 789 THz) [1]. VLC technology has the potential to transform any LED light source into a data broadcasting unit [2] [3] [4] [5] [6].

A. History of VLC Development

The history of VLC dates back to the Romans, when polished metal plates were used to reflect sunlight and transmit signals over a long distance. In 1794, Claude Chappe developed a semaphore system consisting of a series of towers equipped with mounted arms to transmit information. In the late 19th and early 20th centuries, the heliograph was used for long-distance communications. In the heliograph, sunlight is reflected using a mirror to transmit Morse code. The Australian and British armies used it until 1960. Graham Bell is best known for his invention of the modern telephone, which uses electricity to transmit voice. However, Bell described the photophone as one of his most important inventions [7]. The photophone uses voice to vibrate the mirror, which in turn is used to modulate sunlight. It was Graham Bell's idea that paved the way for fiber optic communication. The first commercial fiber optic communication system was launched in 1975 and was capable of operating at a data rate of 45 Mbps. VLC is a form of optical communication that operates in open air, at a distance of two to three meters, instead of a guided medium (optical fiber). The term VLC began to take shape in 2003 for the first time by the Nakagawa Laboratory of Keio University, Japan [5]. In 2000, this laboratory demonstrated the first VLC system using light-emitting diodes (LEDs), these LEDs are energy efficient and have quickly replaced traditional incandescent lighting.

The 2014 Nobel Prize was awarded to three scientists, Hiroshi Amano, Isamu Akasaki, and Shuji Nakamura, for their invention of efficient blue LEDs in the 1980s and 1990s. The invention of blue LEDs not only enabled the production of bright and energy-efficient white light sources, but also paved the way for the idea of using LEDs for data transmission. In 2009, the University of Oxford successfully demonstrated a 100 Mbps VLC transmission link using on-off keying (OOK) modulation [8]. Meanwhile, VLC using orthogonal frequency division multiplexing (OFDM) modulation has also attracted attention. The authors of [9] invented a low-power optical OFDM modulation that was later considered for VLC and fiber optic systems. In 2008, the OMEGA (Home Gigabit Access Network) project [10] was established in Europe, and aimed to achieve gigabit data rates for home users, using both VLC and RF communications. In 2010, the OMEGA project successfully demonstrated a 513 Mbps VLC transmission link using OFDM modulation [11]. In 2011, the term "LiFi" was first introduced by Professor Harald Haas, at a TED Global conference and attracted the attention of the public and the wireless industry [12]. In the same year, the IEEE 802.15.7 standard was formalized and defined the physical (PHY) and media access (MAC) layer mechanisms for short-range optical wireless systems [13]. In recent years, the use of multiplexing techniques, such as MIMO and wavelength division multiplexing (WDM), to increase the transmission data rate has shown great promise. In 2013, the University of Oxford demonstrated a 1 Gbps VLC system using MIMO [14]. In 2015, Fudan University successfully demonstrated 8 Gbps VLC transmission using WDM with RGBY LEDs [15].

In 2016, the University of Oxford further increased this transmission rate to 10 Gbps using WDM and OFDM [16]. In 2019, the University of Edinburgh increased this rate to 15.73 Gbps using commercially available LEDs [17]. In the same year, Fudan University successfully established a 15 Gbps underwater VLC transmission link using RGBYC LEDs and WDM [18]. With various new technologies still under development, the VLC research community aims to improve the transmission rate to Tbps by using eye-safe lasers [19].

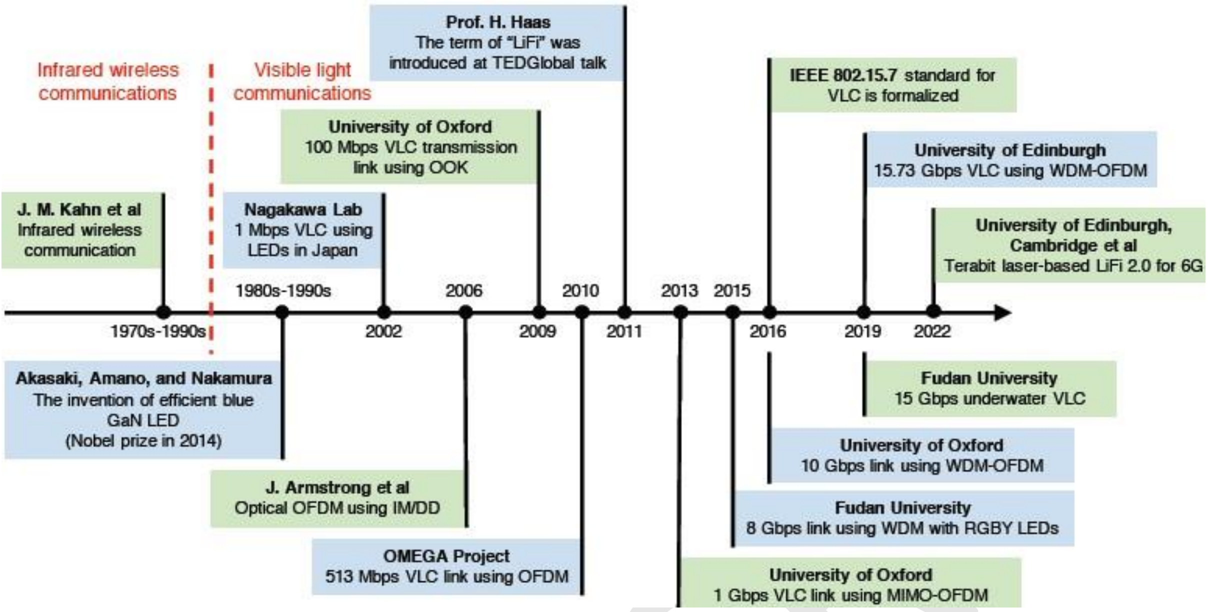

Figure 1: Some major stages of VLC research [20]

B. Principle of Operation

Knowing that LEDs are semiconductors, they are able to turn on and off with times of the order of nanoseconds. High-speed bright and dark flashing signals emitted by a fluorescent lamp, or white LEDs are used to transmit information by creating a frequency [19].

If an LED is off, it sends a bit 0, and if it is on, it sends a bit 1, see Figure 2.

The most important features that allow LEDs to support communication are their ability to switch to different light intensities with a fast speed that is imperceptible to the human eye. High electrical-optical conversion efficiency, long life, low cost and high operating speed [20].

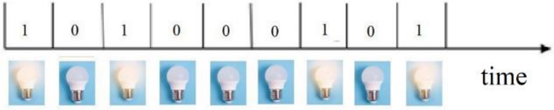

Figure 2: LED operating principle [20]

C. Advantages and Disadvantages

Advantages: Like any other communication techniques, VLC wireless communication has many interesting advantages, including:

- ***High Bandwidth:*** VLC takes full advantage of the use of the visible light spectrum which is between 384 and 789 THz, which adds 400 THz to the bandwidth available for wireless communications.
- ***Health Safety:*** The use of visible light as a data carrier allows VLC to be completely safe for human health. RF electromagnetic waves are currently classified as a possible cause of cancer in humans according to the World Health Organization. Human body safety can be one of the major advantages of VLC to be safe for human health.

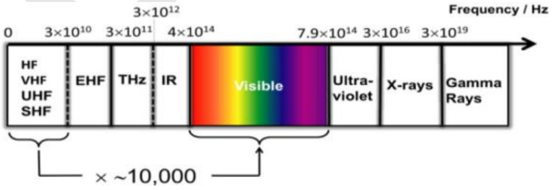

Figure 3: Electromagnetic spectrum distribution and visible spectrum [21]

- ***Unrestricted Technology:*** It does not involve any risk of electromagnetic interference, VLC is suitable for communication systems in restricted or EMI (interference immunity) environments, such as airplanes, hospitals and industrial areas, etc.
- ***Information Security:*** Security is a major concern for radio frequency communications, since radio waves can penetrate through walls and cause its information loss. Since light cannot pass through obstacles and opaque objects, VLC can be limited to enclosed indoor spaces to provide more secure communication links against eavesdropping.
- ***Low Cost Implementation:***
    - A VLC uses visible light for communication, which is in an unlicensed region of the electromagnetic spectrum. Since no licensing fees are involved, the

  - implementation cost is significantly reduced.
  - The ubiquitous nature of light helps VLC reduce the cost of implementing certain systems.
  - Reduced complexity: VLC uses LED emitters and photodiode receivers, components that are somewhat expensive.

Limitations/Disadvantages: Although this technology has all these advantages, it also has some limitations/disadvantages. Optical communication systems have direct links (LoS) that maximize energy efficiency and minimize multipath distortion. In some cases, the mandatory LoS condition can be considered as an advantage. However, there are other cases where it is considered as a major drawback, such as if an object interposed between the transmitter and receiver can block the communication unless an alternative route is available. Susceptibility to interference is another disadvantage, where VLC is likely to be affected by some lighting devices such as incandescent or fluorescent light sources and sunlight. In addition, the transmission range is also limited.

D. Application Area of VLC

The above-mentioned features enable a variety of indoor and outdoor applications of VLC. The most interesting application is indoor high-speed internet access for computers and smartphones. Generally, users spend 80% of their time at home and or office for studying, working, etc. It would be all simply more convenient to access the internet using LED lights installed on the ceiling, and 20% of the time in outdoor environments.

Due to the advantages of this technology, several applications are realized in various fields.

- ***Data Transmission:*** Li-Fi (light Fidelity) is one of the most important applications of VLC, created in 2011 by Harald Haas. It transmits data using LEDs, which have become widespread in lighting systems nowadays. Therefore, lighting systems provide a suitable infrastructure for Li-Fi systems. Thanks to the fast switching capability of LEDs and the wide spectrum of visible light, the transmission of a large amount of data is possible at high speed. Li-Fi is still an emerging technology suitable for short ranges. See Figure 4.
- ***Intelligent Transportation Systems:*** In modern life, vehicles have become a vital asset for humans. In addition to reliable and quality transportation services, humans want more ad hoc functions. The most crucial functions are in communication and safety. These include in-vehicle internet access, forward collision warning, emergency brake lights, lane departure warning, loss of control warning, intersection travel assist, and do not pass warning. It is predicted that by 2025, 90% of vehicles sold will have the ability to communicate with each other and with the infrastructure. Given these requirements and developments, vehicles will generate higher data rates due to the number of sensors they are equipped with. RF technologies will not be up to the task due to current barriers. High bandwidth and low latency are required to ensure reliable accessibility. High-speed VLC technology can be easily adapted due to the ubiquity of vehicle traffic lights and traffic light infrastructure (Figure 5).

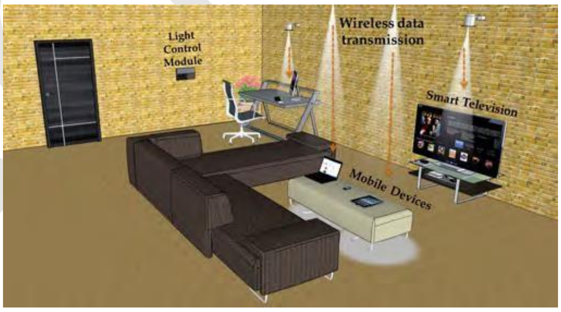

Figure 4: Smart lighting system compatible with VLC [22]

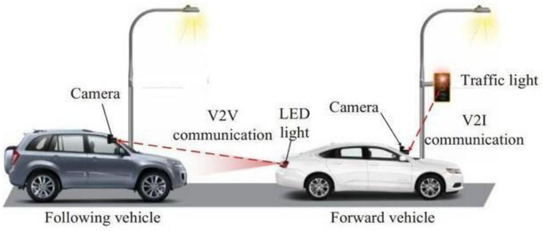

Figure 5: Vehicle-to-vehicle communication [23]

- ***Indoor Localization and Positioning:*** Global positioning system (GPS) technology does not work well in indoor environments, but an indoor positioning system (IPS) is crucial for tunnels, coal mines, supermarkets, exhibition halls, and hospitals. VLC can be used for indoor localization and navigation systems.

VLC-based positioning systems are less susceptible to multipath transmission, and the localization accuracy is much better than RF-based indoor positioning systems (Figure 6).

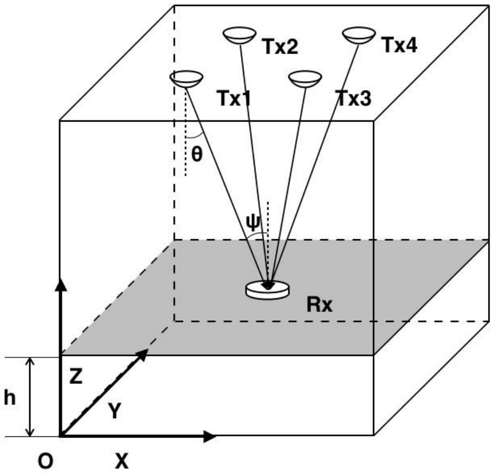

Figure 6: Prototype of a VLC-based indoor positioning system [24]

III. Li-Fi (Light Fidelity)

Li-Fi or VLC is a wireless communication technology based on the use of visible light between blue (450 nm) and red (760 nm), generated by LEDs. Unlike WiFi which uses the radio part of the electromagnetic spectrum, Li-Fi uses the optical spectrum. The Li-Fi protocol layers are governed by the international standard IEEE 802.15.7 established since 2011 by the IEEE committee.

Li-Fi technology is now presented as an alternative to radio frequency (RF) technologies in different application areas and can represent an opportunity especially as the RF spectrum becomes limited in capacity.

Transmission Techniques used in Li-Fi: The system is based on the same principle of transmission in Morse code, it uses LED light to carry digital information, it operates at a speed imperceptible to the human eye, the technology transmits data by turning on and off to create a binary stream of 1 and 0, Li-Fi only works with light-emitting diode (LED) bulbs, it will be a real alternative to the electromagnetic waves of Wi-Fi since it is 80% more economical, it can reach a flow rate of 1 Gbit and can be accessed for free. The principle of Li-Fi is to send data by amplitude modulation of light sources according to a well-defined and standardized protocol. It differs from laser, fiber optic and IrDa communication by its protocol layers. The protocol layers of Li-Fi are suitable for wireless communications up to ten meters, slightly more than Bluetooth. Li-Fi communication is carried out according to the communication protocol established by the international committee IEEE 802 (local and metropolitan area networks). This standard defines the PHY layer and the MAC layer to be adopted in order to develop globally compatible solutions. The standard is capable of delivering sufficient flow rates to transmit audio, video and multimedia services. It also takes into account the mobility of optical transmission, its compatibility with artificial lighting present in the infrastructure, the deficiencies that can be caused by interference generated by ambient lighting. Finally, the standard complies with current safety regulations. The architecture of an optical link is similar to that of an RF link except that radio waves are replaced by optical waves and the antennas are replaced by optoelectronic components. The spectrum of wireless optical communications includes wavelengths ranging from infrared (IR), including visible (VLC), to ultraviolet (UV), a large part of this frequency spectrum is widely used in lighting. What allows this emerging technology to exploit the lighting network is to use it to transmit very high-speed data streams in free space. Using on off Key (OOK) or PPM (pulse position modulation) coding, the light is switched on and off to send 0s or 1s. The flashing speed is much higher than that perceptible to the human eye.

It should be noted that incandescent or halogen light bulbs are not suitable for acting as Li-Fi transmitters. Their state switching time is much too slow to allow rapid amplitude modulation and therefore to achieve a correct flow rate for transmitting information. On the other hand, LEDs, which are semiconductors, are perfectly suited since they allow very high switching frequencies: up to 1,000,000 cycles.

General Description of a Wireless Optical Communication Chain: The classic model of a wireless optical communication chain is illustrated in Figure 7 (a). The wave transmitted by the transmitter has an instantaneous optical power $X(t)$. The wave received by the receiver is translated into instantaneous current $Y(t)$.

Note that in optics, the surface of the photodetectors is equal to about a thousand times the wavelength (in general), which creates a spatial diversity that prevents multipath fading.

Optical signals can nevertheless be subject to multipath distortions when non-line-of-sight links are used, since the transmitted optical power then propagates via paths of different lengths. The system can be modeled in baseband as illustrated in Figure 7 (b) and by the relation:

$$Y(t) = S \cdot X(t) \otimes h(t) + N(t) \qquad (1)$$

The symbol $\otimes$ represents the convolution and S is the sensitivity of the detector. Even if the general form of the relationship presented is similar to that obtained for radio or electrical systems, the difference is related to the fact that $X(t)$ represents an instantaneous optical power at the channel input and is therefore always positive. The average optical power emitted P_t is given by the relationship:

$$P_t = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt \tag{2}$$

The received power required to achieve the desired performance depends on the optical power lost in free space, it is obtained by:

$$P_r = H_0 P_t \tag{3}$$

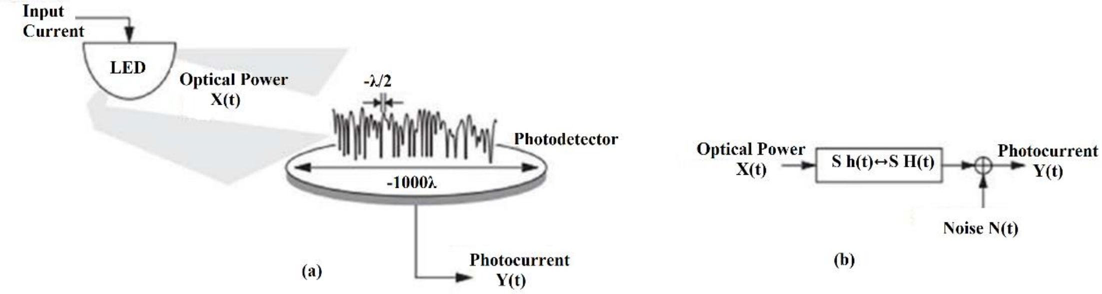

Figure 7: The wireless optical communication chain [25]

A. Li-Fi Transmitters and Receivers

1. Li-Fi Transmitters

In general, it is a diode that converts the electrical signal into optical power, the two main types of diodes used are Light Emitting Diodes (LEDs) and Laser Diodes (LDs). LEDs are commonly used in practice because of their very low costs. Most LEDs have a large emitting surface and therefore often meet the constraints related to eye safety. The disadvantage is that they have a low efficiency in terms of electrical/optical conversion. On the other hand, LDs emit very narrow beams, their electrical/optical conversion efficiency is high but their cost is higher compared to the former. To meet eye safety constraints, diffusers must be used with LDs.

The optical radiation of most optical transmitters can be modeled by a generalized Lambertian model. An emitter with generalized Lambertian radiation of order "m" has a radiation pattern expressed by the following relation:

$$R_0(\phi) = \frac{(m+1)}{2\pi} \times \cos^m(\phi) \tag{4}$$

The radiated intensity for an optical power P_t is then written:

$$I_s = P_t R_0(\phi) \qquad (\mathrm{W/sr}) \tag{5}$$

When $m = 1$, the emitter is called "Lambertian". Figure 8 illustrates the radiation pattern for a Lambertian emitter and generalized Lambertian emitters with $m = 10$ and $m = 20$. Note that the larger m is, the more directional the radiation is. Furthermore, the maximum radiated intensity corresponding to $\phi = 0$ is all the greater as m is small. The order "m" is said to depend on the emitter's semi-power angle $\phi_{1/2}$. The latter is the angle for which the radiated intensity is equivalent to half of the maximum radiated intensity (corresponding to $\phi = 0°$).

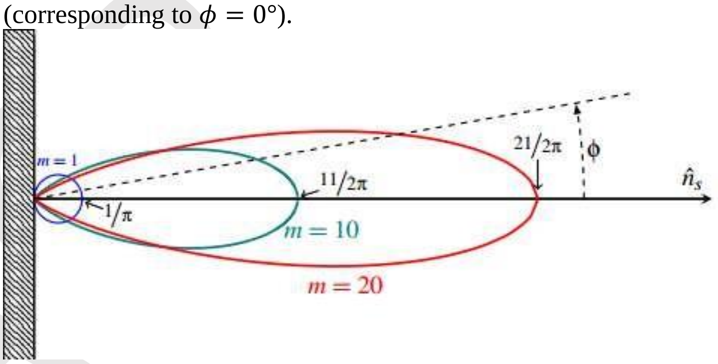

Figure 8: Radiation pattern of a Lambertian emitter ($m = 1$) and generalized Lambertian emitters with: $m = 10$ and $m = 20$ [25]

The relationship between the radiation order m and $\phi_{1/2}$ can thus be obtained via the following relationship:

$$\begin{aligned} R_0(\phi_{1/2}) &= \frac{1}{2} R_0(\phi = 0) \\ &= \frac{1}{2} \times \frac{(m+1)}{2\pi} \times \cos^m(0) \\ &= \frac{(m+1)}{2\pi} \times \cos^m(\phi_{1/2}) \end{aligned} \tag{6}$$

Simplifying the equation, we obtain:

$$\cos^m(\phi_{1/2}) = \frac{1}{2} \tag{7}$$

The solution of the equation gives the relationship between the radiation order m and $\phi_{1/2}$:

$$m = -\frac{\ln 2}{\ln(\cos\phi_{1/2})} \tag{8}$$

From this relationship, it is possible to establish the correspondence table between the different values of m and the semi-power angles of the transmitter $\phi_{1/2}$ (Table 1).

Table 1: Correspondence between $\phi_{1/2}$ and m for a generalized Lambertian radiation

$\phi_{1/2}$	10	12	15	20	30	40	45	50	60	70	80
m	45.28	31.38	20	11.14	4.82	2.6	2	1.57	1	0.646	0.396

As can be seen in this table, a Lambertian type radiation $(m = 1)$ corresponds to $\phi_{1/2} = 60°$. On the other hand, for a smaller semi-power angle of 15° for example, we obtain $m = 20$.

2. LI-FI Receivers

The receiver is a photo-detector (photodiode) that converts optical power into an electric current by detecting the flow of incident photons on the surface of the photodiode. Generally, PIN diodes are used rather than avalanche diodes to limit the impact of noise. The disadvantage of PIN photodiodes is their detection threshold 10 to 15 dB lower than avalanche photodiodes, which limits their efficiency in terms of power detection. The detection threshold is the minimum received optical power P_r that can be detected by the photodetector and it is one of the important parameters for the design of the system. The received optical power thus depends on the effective surface of the photodetector A_{eff}. This surface itself depends on the physical surface of the receiver A_{phy} and on Ψ the angle of incidence of the received radiation with respect to the axis of the photodetector. The effective surface can be expressed by the following relation:

$$A_{eff} = \begin{cases} A_{phy}\cos\Psi & 0 \le \Psi \le \text{FOV} \\ 0 & otherwise \end{cases} \tag{9}$$

In the relation, FOV is the field of view of the photodetector, outside this field, the photodetector receives nothing. Increasing the field of view of the photodetector increases its coverage but also increases the amount of noise received. In addition, the relation expresses the surface A_{eff} without taking into account other elements that may be added to the photodetector such as filters and optical concentrators. Thus, increasing the effective surface of the photodetector is expensive, and increases the level of noise detected, but also increases the bandwidth. In the context of our thesis, we focus on simple photodetectors without filters and without optical concentrators. Another important parameter of a photodetector is the sensitivity (S); it corresponds to the ratio of the photocurrent to the received optical power, and is obtained by the following relation:

$$S(A/W) = \eta \frac{q}{hf} \approx \eta \frac{\lambda_{(\mu m)}}{1.23985(\mu m \times W/A)} \tag{10}$$

Where η is the quantum efficiency of the photodetector for a given wavelength, q is the charge of an electron, h is the Planck constant, f is the frequency of the optical signal and λ is the wavelength of the optical signal.

IV. NOISE

A knowledge of the different sources of noise is necessary to evaluate the performance of indoor wireless optical communication systems. This knowledge also allows to choose the best wavelength and the best type of modulation. In these communication systems, we can distinguish two main sources of noise: ambient noise and thermal noise. In the following we present these different sources of noise and evaluate the one-sided spectral density of noise N_0.

A. Ambient noise

Ambient optical noise is the most important noise in wireless optical communications. This type of noise in confined environments comes mainly from sunlight, light emitted by an incandescent lamp and from low and high frequency fluorescent lamps.

Sunlight: This is one of the important natural sources of ambient light. It depends in particular on the angle of incidence of the sun's rays relative to the photodetector. Its power can saturate wireless optical links and, moreover, most wireless optical communication systems designed for confined environments do not work outdoors. It is an unmodulated source of ambient noise that is difficult to filter and its power spectrum has a maximum around 500 nm and can significantly disrupt infrared links with wavelengths between 700 and 970 nm. It can be shown that the current induced in the photodetector by sunlight is a direct current that is added to $Y(t)$. Thus, the ambient noise due to sunlight can be modeled by an additive Gaussian noise of the AWGN type.

Incandescent Lamps: These classic lamps (with tungsten filament) constitute an artificial source of ambient noise that can impact wireless optical communications. The previous figure shows the spectral distribution of noise power for these lamps. The spectrum is wide and has a maximum at ≈ 1000 nm. The photocurrent induced by this noise source is sinusoidal at a frequency of 100 Hz with considerable harmonics up to 2 KHz. It is added in the form of RMS current to the direct current linked to sunlight. By applying a high-pass filter, the noise linked to this current can be modeled by an AWGN noise.

Low-Frequency Fluorescent Lamps: They represent another artificial source of ambient noise. It can be noted that the spectrum is spread up to the wavelength of 1100 nm. To reduce the impact of this type of noise it is possible to use optical and electrical high-pass filters. The current induced by this type of source is almost sinusoidal at a frequency of 100 Hz. Compared to incandescent lamps, the harmonics are more significant and the

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frequency spectrum contains significant harmonics up to 20 Hz. A combination of optical filter and high-pass filter is necessary to attenuate this noise.

High-Frequency Fluorescent Lamps: These lamps use a ballast. The latter generates a periodic signal with a frequency between 20 and 40 KHz having significant harmonics that can go up to MHz. The reason for using a ballast compared to conventional fluorescent lamps is that it allows to considerably reduce energy consumption and increases the life of these lamps. Since the spectral spread is significant, the use of a high-pass electrical filter is not effective since it also filters the useful signal.

B. Thermal Noise

Thermal noise is the noise created by the resistive elements of the receiver electronic circuit. The preamplifier is the component of the receiver that is the main source of this type of noise. The preamplifier is often used in the receiver to amplify the received signal especially when the receiving photodiode is a PIN photodiode. Among the different preamplifiers, the Trans impedance preamplifiers with a low output resistance and with field effect transistors are the preamplifiers that induce the minimum noise. With a correct choice of the receiver electronic circuit, it is possible to minimize this type of noise and thus make it negligible compared to the ambient noise. Figure 9 represents the one-sided power spectral density of noise as a function of the signal frequency (transmission rate) for ambient noise and thermal noise. It can be seen that for low bit rates (less than≈10 Mbps) ambient noise is the dominant noise (10×higher), but then the thermal noise of the receiver becomes predominant.

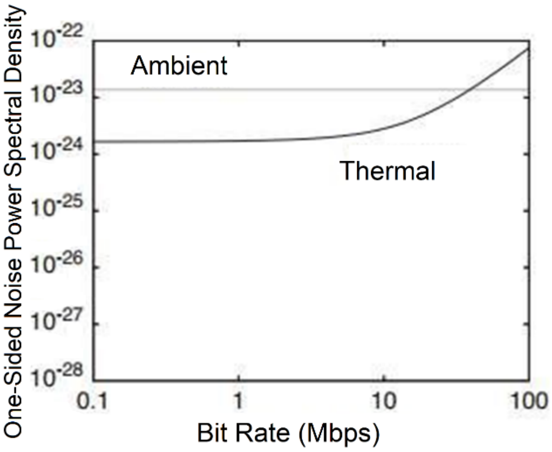


Figure 9: One-sided noise power spectral density as a function of optical signal frequency [25]

V. DIFFERENT PROPAGATION MECHANISMS IN CONFINED SPACES

In order to evaluate the performance and optimize the deployment of wireless optical communication systems in confined spaces, a good knowledge of the different propagation mechanisms is necessary. We can thus distinguish two main propagation mechanisms: direct visibility links between transmitter and receiver and non-direct visibility links. In the case of the first type, the optical radiation leaves directly from the transmitter to the receiver. In the second case, the radiation leaving the transmitter meets a reflective surface and the reflected rays arrive at the receiver.

In the following passages, we present the main mechanisms of direct visibility and non-direct visibility links. Then for each mechanism, the static gain of the H_0 channel is calculated analytically. The latter is the most important parameter that characterizes a channel, it depends on the transmitted power and the received power.

A. Direct Visibility Links

In direct visibility (LOS) links, the receiver directly receives the radiation emitted from the transmitter. Thus, it is necessary that the transmitter and receiver are in line of sight. However, since the beam emitted by the transmitter is slightly divergent, the receiving cell will only capture part of the emitted power. In general, in this type of link, only the direct path is considered and therefore it is assumed that the link is not disturbed by the presence of multiple paths. The disadvantage related to the directivity of the beam is that it can easily be subject to cuts or masking due to obstacles between the transmitter and the receiver. A general line-of-sight wireless optical communication link is shown in Figure 10.

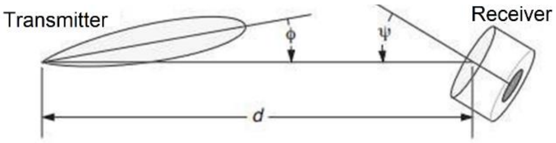


Figure 10: Line-of-sight links [25]

The emitter is assumed to have a radiation intensity $P_t R_0(\phi)$ (W/sr). At a distance d and an angle ϕ relative to the emitter normal, the irradiance is:

$$I_r(d,\phi) = \frac{P_t R_0(\phi)}{d^2} \tag{1.11}$$

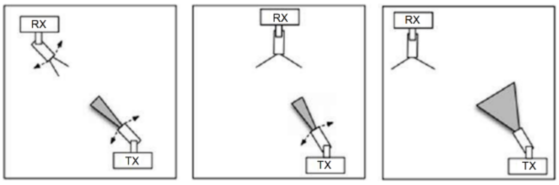
The received power P_r is thus:

$$P_r = I_r(d,\phi) A_{eff}(\Psi) \tag{1.12}$$

The static gain of the H_0 channel can be obtained by the following expression:

$$H_0 = \begin{cases} \dfrac{A_{phy}}{d^2} \times \dfrac{(m+1)}{2\pi} \cos^m \phi \cdot \cos \Psi & 0 \le \Psi \le FOV \\ 0 & Otherwise \end{cases} \tag{1.13}$$

There are generally three main types of line-of-sight links defined as illustrated in Figure 11; fully tracked links, semi-tracked links, and non-tracked links.



(a) Full Tracking (b) Semi-Tracked by the transmitter (c) Non-Tracked

Figure 11: The three main types of line-of-sight links [25]

Line-of-sight links with a full tracking system use a mechanical or electronic system that tracks the beam from the transmitter to the receiver and vice versa. Thus, perfect alignment between the transmitter and the receiver is maintained at all times. The advantage of this type of link is related to the use of transmitters with narrow beams (small $\phi_{1/2}$) generally at low power. In addition, the receivers also have a small aperture (small FOV) which allows to reject a large part of the ambient light from the environment and thus contributes to physically reducing the received noise. The disadvantage is the complexity of the deployment related to the implementation of the tracking system on both the transmitter and the receiver.

In the case of non-tracked line-of-sight links, there is no tracking system to maintain the alignment between the transmitter and the receiver. Thus, the transmitter and the receiver must have larger apertures in order to be in line-of-sight. So the required transmission power is greater compared to the two previous types of mechanisms.

In addition, misalignments between the transmitter and the receiver can cause high losses on the communications link or even completely interrupt the link. The main advantage of this type of link is in the ease of deployment.

B. Non-Line-of-Sight Links

A reflection occurs when the optical wave encounters a surface whose dimensions are large compared to the wavelength (floor, wall, ceiling, furniture, etc.). The reflection characteristics of a surface depend on several factors: the surface of the material (smooth or rough), the wavelength of the incident radiation and the angle of incidence.

VI. Li-Fi Technologies and Protocol

In a Li-Fi communication, the transmitting antenna is the LED. There are essentially two types of white LEDs: phosphor LEDs and RGB (or Red-Green-Blue) LEDs.

A phosphor LED consists of a blue LED on which a phosphor layer is deposited. This phosphor layer absorbs the blue light which will then emit on a visible spectrum centered on yellow. The combination of blue and this spectrum makes it possible to generate white light. The modulation frequencies allowed by the phosphor layer are lower (1 to 2 Mbit/s) than those allowed by the bare blue diode (100 Mbit/s). On the other hand, with an RGB LED and information multiplexing techniques, it is possible to reach speeds of 150 Mbit/s quite easily. The second important part in a Li-Fi communication device is the receiving antenna consisting of a photodiode and its associated electronics: optimized optical filter, photo detector, optical concentrator, and amplification electronics consisting of several stages. The 800 Mbit/s Li-Fi optical link was made in broadcast mode with DMT (Discrete Multi-Tone) modulation associated with wavelength division multiplexing (WDM) with a single RGB LED over a distance of 10 cm. The error rate obtained (Bit Error Ratio or BER) is still high, 2 10-13, but there is room for improvement. Line-of-sight propagation improves LED communication, but Li-Fi communication does not necessarily require a line-of-sight.

Depending on the desired application, a compromise must be made between the robustness of the communication (strong line-of-sight) and the mobility of the user (large broadcast area). Unlike radio waves, light waves do not penetrate walls. This is a disadvantage but it can also be an advantage for ultra-secure communication applications. But above all, as the lighting units of each house, each office, each public building and streets are gradually becoming LED lighting units, Li Fi bidirectional communications are designed with asymmetrical rates: a downstream rate of 150 Mbit/s or more and an upstream rate of a few Mbit/s. This is due in particular to the fact that the power consumption of the mobile terminal must be moderate so as not to dissuade the user from its use.

An obstacle to overcome lies in the directivity of the upstream path. In order to ensure a certain mobility for the user, it is necessary to work on the greatest possible directivity on the upstream path by increasing, among other things, the size of the communication reception area. It is not obvious that the MAC layer of the IEEE 802.11 p Wi-Fi protocol is applicable as it is. From a standardization point of view, a working group led by Intel has established the IEEE 802.15.7 standard. This standard is considered complete and unchangeable until 2015 by the IEEE committee in order to allow the development of products on this basis. The document is available on the IEEE organization website and covers the specifications of the physical layer (PHY).

The next generations of vehicles will be fully automated. Many laboratories and players in the automotive industry are working on this issue of autonomous vehicles. The virtual coupling of vehicles is a perfect example. The possible contribution of Li-Fi in this area, with the increasing presence of LED headlights on vehicles, Li-Fi can provide technical solutions due to its ease of implementation, its low cost and its performance. Several studies have been conducted to achieve Li-Fi communications, as a substitute or in addition to radiofrequency technologies, between vehicles and traffic lights or between vehicles themselves. One of the challenges is to be able to offer communications with high bandwidths in order to reduce the duration of the perception phase. Recent normative efforts with the IEEE 802.11p standard and the IEEE 802.15.7 standard are proof of the challenge of this technology in the field of ITS.

A. The use of Li-Fi

The use of Li-Fi could revolutionize the use of the Internet, or at least improve it significantly, particularly from a security point of view. Take for example the case of the Internet in companies, whose offices are very often equipped with Wi-Fi Internet, there is the problem of securing networks. Because for a somewhat experienced person, it is easy to penetrate the Wi-Fi network, and thus to enter the different systems (servers, private computers, etc.). Whereas with Li-Fi, only people in the company's light spectrum will have access to the network. Ideally, it would be enough to equip office lighting with Li-Fi. In this way, we control Internet access and networks by geographical area. For example, the network intended for management would only be available in the management premises, etc. The same goes for private Internet connections. In urban housing, we all have in our Wi-Fi internet connection interface, an exhaustive list of several neighbors' internet "boxes". But beyond purely security considerations, Li-Fi allows for significant possibilities in marketing, particularly at sales points, trade fairs, etc. For example, in the context of events, a stand equipped with Li-Fi would offer an excellent quality internet connection, only within its perimeter. Therefore, it could advance its advertising or create traffic flow within its perimeter, distinguishing itself from the Wi-Fi networks of trade fairs, which are often random and overloaded. Or, Li-Fi could find a use in road safety in the future, where future vehicles could exchange information with each other on the road via headlights. Finally, although for the moment there are no clear opinions on the subject, Li-Fi would not be subject to the problems of Wi-Fi and its waves, impacting the health of certain people sensitive to this. Therefore, Li-Fi, although still too recent to allow for mass democratization, seems to be positioned as the next vector of the internet.

Taking these specificities into account, Li-Fi currently has limited use, often complementary to current network infrastructures:

- Locally, it could be interesting to use Li-Fi to relieve congestion on a WiFi network, or even a wired network, in reception.
- With a unique identifier, the position of a person or terminal could be precisely determined indoors (for example in a tourist location or a hypermarket).
- Li-Fi could be used in places at risk of electromagnetic disturbance, such as airplanes or hospitals.
- Since light propagates very well underwater, the marine environment could benefit from this communication technology.

B. Advantages

- Profitability and simplicity: Li-Fi works using LED lamps, which are already widely used today for lighting, and a receiver.
- Performance: the advertised speeds are 10 times higher than those of WiFi. Li-Fi benefits from the absence of interference with radio or electromagnetic waves, and the data is only "contained" in the light fields
- Security: since the data exchange field is limited to the emitted light fields, the flow is much more controllable and does not scatter. In addition, light cannot pass through an opaque element, such as a wall, for example. It therefore becomes more difficult to take advantage of your neighbor's network.
- Health: Unlike electromagnetic waves, light waves do not pass through the human body, and are therefore not likely to cause health problems.

C. Limitations

Firstly, the limitation of Li-Fi is linked to its operating mode: communication is only possible if the light is on. During the day, daylight can interfere with emissions. Secondly, Li-Fi is still unidirectional in most installations. This means that we can only receive data, it is impossible to transmit towards the light source except by coupling it with another technology (PLC, WiFi, etc.). Finally, the use of Li-Fi can only be local, as light does not pass through opaque materials.

D. Comparison between Li-Fi and Wi-Fi

Li-Fi is a technical term used for high-speed wireless communication in visible light communication technology. It gets its name from its similarity to Wi-Fi, which uses only light wave instead of radio waves. Wi-Fi technology is suitable for wide wireless coverage in buildings. While Li-Fi technology is ideal for small environments to provide high-density wireless data coverage and minimize radio interference. Therefore, these two technologies are complementary. Li-Fi has several advantages, including wireless system security, safety, capacity, and energy efficiency. They offer a significant number of advantages over Wi-Fi, however, it is mainly a complementary technology. The characteristics of comparison between LIFI and WIFI are summarized in Table 2 [26].

Table 2: Comparison between Li-Fi and Wi-Fi

Properties	**Li-Fi (Light Fidelity)**	**Wi-Fi (Wireless Fidelity)**
Standard	IEEE 802.15.xx	IEEE 802.11.xx
Spectrum	Visible Light	Radio Frequency
Interference	Low	High
Topology	Point-to-point.	Point-to-multipoint
Bandwidth	Unlimited	Limited
Operations	Li-Fi transmits data through the light of LED lamps.	Wi-Fi transmits data by radio waves through a Wi-Fi router
Data Density	Works in a very dense environment.	Works in a less dense location
Coverage	Around 10 meters.	Around 32 meters (WLAN 802.11b/11g)
System components	The Lamp driver, LED bulb and photodetector.	Requires installation of routers, user devices (laptops, etc.)
Applications	Hospitals, airplanes, museums, offices.	Surf the Internet using Wi-Fi hotspots
Cost	Low	Higher
Modulation	ACO/DCO-OFDM	OFDM, Direct Sequence Spread Spectrum (DSSS)
Data Rate	> 10Gbps	<1Gbps
Energy consumption	Low	High

VII. CONCLUSION

In conclusion, Visible Light Communication (VLC) and Light Fidelity (Li-Fi) represent groundbreaking advancements in wireless communication technologies. VLC offers the unique advantage of utilizing the vast bandwidth of the visible light spectrum, ensuring high-speed data transmission with minimal interference. Li-Fi, as a next-generation extension of VLC, provides secure and reliable wireless communication with greater data rates, making it an ideal alternative to traditional Wi-Fi in various applications, particularly in areas sensitive to electromagnetic interference such as hospitals, airplanes, and military environments. Although the full potential of VLC and Li-Fi is yet to be realized, ongoing research and technological developments are rapidly addressing key challenges, including signal propagation, indoor localization, and data security. The widespread deployment of LED lighting infrastructure, coupled with advances in modulation techniques and photodetector technology, is expected to facilitate the growth of these technologies in both residential and commercial settings. As the demand for high-speed wireless communication continues to surge, VLC and Li-Fi stand at the forefront of next-generation wireless networks. Their ability to provide secure, high-bandwidth solutions without the limitations of radio-frequency-based systems positions them as critical technologies in shaping the future of wireless communication. Continued innovation and standardization will likely enable VLC and Li-Fi to complement existing Wi-Fi systems and contribute to the development of fully integrated, high-speed communication networks in the near future.

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