# Visible Light Communication: Concepts, Applications and Challenges

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**Abstract**

During the last decade, the exponential growth of mobile devices and wireless services created a huge demand for radio frequency-based technologies. Meanwhile, the lighting industry has been revolutionized due to the popularization of LED light bulbs, which are more economical and efficient. In that context, Visible Light Communication (VLC) is a disruptive technology based on LEDs that offers a free spectrum and high data rate, which can potentially serve as a complementary technology to the current radio frequency standards.

In this work, we present a comprehensive state-of-the-art survey of Visible Light Communication, as well as the main concepts and challenges related to this emergent area. We overview VLC technology, from its physical aspects and communication architecture to its main applications and research challenges. Finally, we present the main research platforms available today, along with a deep analysis of the system design and future directions in the field.

## I. INTRODUCTION

The number of mobile devices around the world has increased considerably in recent years. Smartphones, tablets, and sensors are becoming more common in people's everyday lives. These devices become increasingly powerful —in the broad sense of the word— due to users need of continuous communication/Internet access and continuous sensing.

In addition to the popularization of powerful and ever-connected mobile devices, there is the imminent approximation of the next big revolution in computing: the Internet of Things (IoT) era, when every device will have connectivity and processing. Daily devices such as TVs, microwaves, refrigerators, and vehicles will be 24x7 connected, requiring even more resources, either from the devices themselves or from the supporting network infrastructure. Considering this scenario, the increasing crowding of the electromagnetic spectrum band allocated to Wi-Fi[1] [1] is a serious problem that has drawn the attention from both, the academic community and industry.

This problem, known as "Wi-Fi Spectrum Crunch", occurs in environments where there is a large demand for wireless resources. As a consequence, the existing infrastructure cannot provide the appropriate resources for wireless communication. In fact, the expression "Wi-Fi Spectrum Crunch" has been repeated several times by the media over the last few years and has alarmed both the academic community and the industry. Consequently, new technologies —e.g., cooperation with Wi-Fi [2], [3]— has been developed in order to avoid such a situation.

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[1]Will we ever face a wireless "spectrum crunch"? - http://www.bbc.com/future/story/20131014-are-we-headed-for-wireless-chaos, 2013.

Among the new technologies to solve the problem of Wi-Fi spectrum crunch, Visible Light Communication (VLC) [4], [5] presents great potential. In fact, the interest in such form of wireless optical communication has grown, especially given the possibility of cooperation with radio frequency systems [6]. Another factor that attracts researchers to this new research field is the possibility of working with frequencies much higher than those used in WiFi devices. The use of these frequencies allows wireless communications at very high speeds (theoretically in the order of terabytes/s).

In addition to that, new light-emitting technologies, such as LEDs, become more popular and accessible, enabling new perspectives for optical wireless communication [7], [8]. Finally, the increasing interest and exploration of the visible light spectrum have brought a number of innovations that are already present in the market, such as Li-Fi technology [9], presented in 2011 and already marketed by companies specializing in VLC.

In this work, we present a comprehensive survey of Visible Light Communication. In order to accomplish that, we analyze the main concepts and challenges related to this promising area. This includes the recent applications of Visible Light Communication in emerging areas and discussion of the open questions that may foster new research. We also point to future directions considering recent work found in the literature. To summarize, we provide the following contributions related to the VLC area:

- We explore the fundamentals of the light spectrum and provide a discussion regarding the adoption of that part of the electromagnetic spectrum to provide communication;
- We provide a comprehensive insight into how VLC became popular throughout the last 10 years, giving the main reasons behind the growing popularity of that technology.
- We give an overview of Visible Light Communication and its architecture, including transmitters, receivers and standardization efforts throughout the last decade. We also provide a detailed explanation of modulation schemes and multiple access techniques adopted in the literature.
- We delve into application and challenges of the area.
- We offer a detailed analysis of the main research platforms developed in the literature.
- We give a perspective of the future of Visible Light Communication in the wireless technology field.

Despite the novelty of VLC and the emergence of new research in the field, we already observe a number of surveys about VLC in the past couple of years, from a broader perspective to specific areas. In [10], the authors present an initial review on LED-based communication, while highlighting the main benefits of this type of communication. Following the popularization of Solid State Lighting (SSL), authors in [11] offer a review on VLC while focusing on challenges and channel modeling. In addition, authors also offer a comprehensive review of the IEEE 802.15.7 [12], which was relatively new at that time. The integration of illumination and communication has been studied carefully in [13]. The authors adopt the idea of Smart Lighting and Mobile Optical Wireless Networks (LightNets) and focus their survey on the integration of VLC in the mobile communication field. The idea of using VLC as a complementary technology to radiofrequency was further explored in [14], where authors explore the possibility of using Visible Light Communication as part of the 5G wireless communication system. The main focus of this work is to compare VLC with RF-based communication and offer a review on mobile and

fixed VLC researches. In [15] and [16], a comprehensive review of LED-based VLC is offered. Both works adopt a broader review perspective, passing through several aspects of the area, and authors in [15] also target indoor applications challenges. In [17], authors discuss the benefits that VLC systems may offer to the current issues in wireless communication networks. In [18], authors explore the state-of-the-art on multi-user VLC systems, exploring new concepts in literature such as NOMA-VLC, also explored in this survey. Al *et al.* follow the same path by exploring multi-user VLC techniques in [19] In [20], a system's perspective overview is given by the authors, with two main focuses: uplink strategies and challenges in the co-existence with RF technologies. Also, some platforms are analyzed by the authors (OpenVLC and SmartVLC). This survey differs significantly because we focus on the hardware and software characteristics of all current research platforms in VLC field. In sum, Table I summarizes the existing surveys of VLC and highlights the topics each survey address.

The present work takes a horizontal approach, in which we cover the main aspects of Visible Light Communication by offering a comprehensive discussion of the main features responsible for the popularization of VLC-based applications, such as LEDs, along with their main drawbacks and future directions. Moreover, we take an approach to Visible Light Communication from a broader perspective, offering a deep survey of the main novelties in the area considering the context of the actual Internet. Finally, we offer a deep study over the research platforms developed for VLC studies, covering hardware and software designs, main contributions to the scientific area and evaluation within the future paradigm of the **Internet of Light**.

| Content explored | | Pathak et al. [21] | Karunatilaka et al. [15] | Kumar et al. [10] | Medina et al. [16] | Saadi et al. [11] | Wu et al. [14] | Sevincer et al. [13] | Khan et al. [17] | Obeed | Al | Rehman | This survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Optical Communication | History perspective | | ✓ | | ✓ | | | ✓ | | | | ✓ | ✓ |
| | Classification of types | | | | | | | | | | | | ✓ |
| | Comparison to VLC | | | | | | | | | | | | ✓ |
| | Channel Modelling | ✓ | ✓ | ✓ | | | | ✓ | | | ✓ | | |
| LED | LED theory | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | ✓ |
| | LED types | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ |
| | Properties as photosensors | | | | | | | | | | | | ✓ |
| Integration with the Internet | | | | | | | | | | | | | ✓ |
| Communication Architecture | Transmitters properties | ✓ | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | ✓ |
| | Receiver properties | ✓ | ✓ | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | Standardization | | ✓ | | ✓ | ✓ | | | | | | ✓ | ✓ |
| Physical Layer | Channel characteristics | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ |
| | Modulation schemes | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ |
| Multiple Access | Orthogonal Multiple Access | ✓ | ✓ | | | | ✓ | | | ✓ | ✓ | | ✓ |
| | Non-Orthogonal Multiple Access | | | | | | | | | ✓ | ✓ | | ✓ |
| MIMO | | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ |
| Applications | Indoor Communication | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| | Vehicular Communication | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | ✓ | ✓ |
| | Underwater Communication | | ✓ | | ✓ | | | | | | | | ✓ |
| | Localization | ✓ | ✓ | | ✓ | | | ✓ | | | | | ✓ |
| Challenges | Flickering | | | | | | | | | | | | ✓ |
| | Dimming | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | | ✓ |
| | LOS | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| | Noise and interference | | ✓ | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ |
| | Mobility | ✓ | | | ✓ | | | ✓ | | | ✓ | | ✓ |
| | Uplink | ✓ | ✓ | | ✓ | | | | | | | ✓ | ✓ |
| Research Platforms | Software Overview | | | | | | | | | | | | ✓ |
| | Hardware Overview | | | | | | | | | | | | ✓ |
| Multi-hop | | | | | | | | | ✓ | | | | ✓ |
| Perspective of VLC in the future | | | ✓ | | | | | | | | ✓ | ✓ | ✓ |
| Market and commercialization | | | ✓ | | ✓ | | | | | | | | ✓ |
| Energy Harvesting in VLC | | | | | | | | | | | ✓ | | |

Table I: Surveys on Visible Light Communication

The remainder of this paper is organized as follows: initially, we offer a fundamental introduction to the area along with a brief background and motivation. Then, in Section II, we overview Visible Light Communication. In Section III, we present components of a VLC system. In Section IV, we discuss technical details of modulation methods and MAC layer protocols. Section V introduces a series of applications found in the literature where VLC is used, and section VI presents the main challenges surrounding the area nowadays. We analyze all research platforms designed to study VLC in Section VII. In Section VIII, we give a future perspective to VLC considering the advancements in the area. Finally, in Section IX, we present the final discussions, as well as a broader perspective of the area.

## A. What is VLC?

Visible Light Communication is the name given to the type of communication in which data is sent through the modulation of light waves from the visible spectrum, ranging from 380 nm to 750 nm wavelengths. In general, any system in which information can be transmitted using some kind of light visible to human eyes can be named as Visible Light Communication. However, the idea of this type of communication is to transfer data in an imperceptible way to human vision, so that what is seen is only the regular environment illumination, without any noticeable change. There are several other nomenclatures created over the years for similar technologies, such as OWC (Optical Wireless Communication) and Li-Fi(Light Fidelity), for example, which will be discussed in Section II.

Note that radio waves have been studied by various works since the beginning of the nineteenth century [22]. This has led to a number of discoveries about the properties of this type of wave, bringing several new technologies to the daily lives of people around the world, from military resources to medical applications. The efficiency of radio communications has improved greatly due to advances in research. Although, visible light as a form of communication medium has attracted the attention from academic institutions and industry only over the past decade [23], it is still underexplored when compared to the radio frequency spectrum of the electromagnetic spectrum.
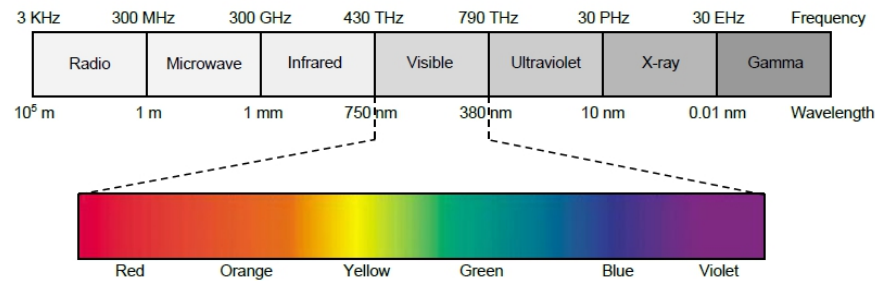


Figure 1: Electromagnetic Spectrum [21].

Figure 1 shows the range of the electromagnetic spectrum from low frequencies, where radio waves are located, to higher frequencies where the gamma radiation is located. As we previously pointed, the visible spectrum of light ranges from 380 nm to 750 nm. Any information that is transferred by modulating the light waves in this range can be considered a type of Visible Light Communication. It is important to observe that the radio waves, which includes the Wi-Fi technology, covers frequencies ranging from 3 KHz to 300 GHz. On the other hand, visible light frequencies vary from 430 THz to 770 THz, which is 10,000 times larger than the entire radiofrequency spectrum [3].

It is worth noting that Visible Light Communication is a very promising technology once the implementation of VLC systems is closely linked to the rapid and increasing adoption of LEDs around the world, as well as the imminent approximation of the smart lighting paradigm [13]. Presumably, the industry has reacted positively to these novelties in lighting technologies. For example, Philips HUE[2] is a LED light bulb that can be controlled by

[2]Your personal Wireless lighting system -www2.meethue.com/en-us/about-hue/, 2017.

the Smartphone, creating ambiances for specific purposes, such as work or study. In this way, it is likely that, in the future, LED light bulbs will play two different roles: lighting and communication.

### B. A Brief History of VLC

Despite the recent interest in VLC, studies involving light-based communications systems can be found over the past centuries. Light has always been among the elements used by humans to communicate with each other. Since the earliest times, the use of light as a means of communication was already seen in many cultures around the world, whether in the use of smoke signals or torches, for example. In this sense, a great example of a functional Visible Light Communication system was registered centuries ago, in Ancient Greece. Historian Polybius developed a communication system in which torches were used in order to exchange information. This was done by establishing an agreement between emitter and receiver, and the alphabet was represented by a set of 5 torches [24].

By the end of the eighteenth century, in Napoleonic France, engineer Charles Chappe invented the optical telegraph [25]. This mechanism consisted of two lateral bars, called indicators, attached to a long bar, called the regulator. Through the rotation of the lateral stems, it was possible to create a series of different symbols. Optical telegraphs were placed in towers, at a distance of 10 to 15 kilometers. Using this structure and efficient coding, it was possible to create up to 98 different combinations, which could be seen from miles away. In a few decades, France was already equipped with hundreds of telegraphs, forming a large communication network, which served French interests for more than 50 years and was later replaced by the electric telegraph system.

Later, by the end of the nineteenth century, Alexander Graham Bell and his assistant Charles Tainter established communication at a distance of 213 meters using the Photophone [26]. This device, created by Graham Bell itself, was formed by a transmitter and a receiver, as can be seen in Figure 2. Briefly, the system worked as follows: the sunlight was reflected in a mirror, reaching a thin surface of a glass, which vibrated according to the person's voice. Thereafter, the light was transported through a second lens to the receiver, where a parabolic mirror reflected the light in a selenium cell, whose resistance varied according to the intensity of light received. Despite the popularity of the telephone, another device patented by Graham Bell, the scientist has always considered the photophone his greatest invention.
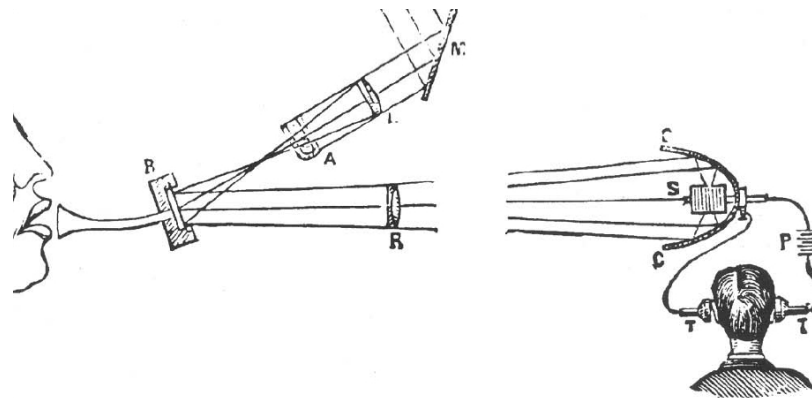


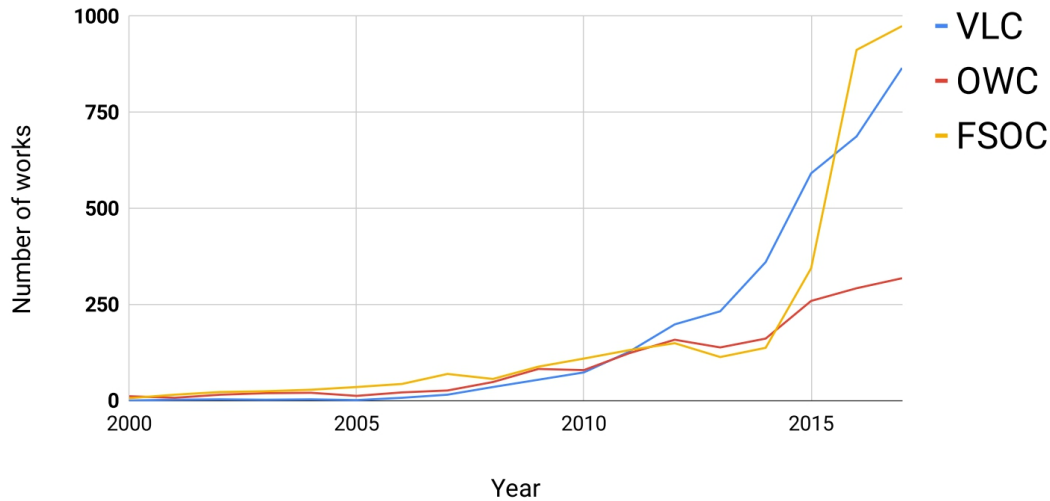Figure 2: The photophone, created by Alexander Graham Bell [26].

Figure 3: Light spectrum research themes in the past decade.

Communication through optical media only gained attention in the 1970's. On that period, studies demonstrated the potential of wireless optical communication (in this case, infrared) in an internal environment where it was possible to explore bands of the Electromagnetic spectrum on a scale of THz- [27]. Such systems were able to reach up to 1 Mbps. More recently, in the late 1990's, infrared systems were able to achieve up to 50 Mbps data rate [28].

In the early of 2000's, LED bulbs were first considered for experiments involving VLC. Tanaka et al. used a white LED bulb for lighting and communication in an indoor environment, reaching up to 400 Mbps communication data rate [29]. This was the first step in a wide range of VLC works in the 21st century. After this work, other researchers came with great innovations, such as new modulation techniques and new technologies of LED bulbs.

An important milestone in the history of Visible Light Communication was achieved in 2011, when Harald Haas made the first demonstration of Li-Fi (Light Fidelity) during a TED Talk[3]. This presentation has become very popular, reaching millions of views in a few months. Clearly, the academic community reacted to the novelty and, as a consequence, the amount of research in the area increased considerably, as it can be seen in Figure 3. Notable, the number of works with the keyword *"Visible Light Communication"* on the *IEEE Xplore* platform over the years increases exponentially.

Currently, VLC is extensively studied. Major names from industry and academy, such as NASA [30], [31], Disney [32] and Philips[4] have products and research in the field.

*C. Motivation*

The interest in technologies involving VLC has increased considerably in recent years. For example, actions from the international standard body and major corporations [12] show the increasing interest in this form of

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[3]Wireless data from every light bulb -Https://www.ted.com/talks/harald_haas_wireless_data_from_every_light_bulb, 2017.

[4]Perfect light, precise location - http://www.lighting.philips.com/main/Systems/themes/led-based-indoor-positioning.html, 2016.

communication.

Moreover, the exponential increase in the number of mobile devices around the world has become a major incentive for the study of VLC as a complement to Wi-Fi [33] technologies, especially in indoor environments where light can be controlled and there is less interference from external factors. Since most people tend to stay most of the time indoors, the implementation of VLC technologies would be simpler, using a preexisting infrastructure.

While there has been an effort in the study of VLC in the last decades, one of the factors that limited research reasonably was the technology used in commercial light bulbs, mostly incandescent or fluorescent, which did not allow precise and high-speed control of illumination. The popularization of LED bulbs in the last decade offered a new opportunity for research. Currently, several devices use LEDs in addition to conventional light bulbs. TV displays, smartphones, and automobiles are among devices equipped with LEDs. With the advancement of technology and popularization of LED prices, much of the research has focused on the use of these types of a light source as transmitters, and even as receivers [9], [32], [34], as it will be discussed further on Section II.

The possibility of higher data rates provided by the frequencies, in the order of THz, is another great motivation for studies in the area. Currently, Wi-Fi technologies are struggling to reach speeds in the order of Gbps. The 802.11n Wi-Fi standard, for example, can reach up to 150 Mbps[5]. It is important to observe that many upcoming Wi-Fi standards will bring further improvements in throughput, which can lead to a future where Wi-Fi speeds are up to 6 Gbps [35]. Systems using Optical Wireless Communication have already achieved rates of up to 42.8 Gbps[6].

Visible light spectrum brings a number of opportunities for studies involving VLC. In contrast to the radio frequency, the visible light spectrum is not licensed, therefore devices can transmit at any frequency [36]. Whereas in the spectrum of radio waves the frequency varies from KHz to GHz, in the visible spectrum the frequency is in the order of THz, that is, $1,000$ times greater. Furthermore, unlike infrared and ultraviolet, which may be harmful to human health, visible light spectrum presents no danger. Finally, radio waves can traverse obstacles like walls, so that a conventional wireless network can be intercepted by intruders at any time. In VLC systems, typically what you see is what is transmitted. In other words, due to the properties of light, an indoor VLC system becomes much safer [37].

In general, the current VLC scenario is very rich and broad, with opportunities in the most diverse areas, from applications such as LightId[7] to the exploration of different modulation methods considering particular properties of light [38].

## II. VISIBLE LIGHT COMMUNICATION OVERVIEW

This section provides an overview of Visible Light Communication. Initially, we will discuss the main technologies that relate to VLC in some way, among them Light Fidelity (Li-Fi), Optical Wireless Communication and Free Space Optical Communication. It is important to highlight the similarities and differences between these types of

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[5]Examining the Adoption Rate of Gigabit Wi-Fi - https://yourdailytech.com/networking/examining-the-adoption-rate-of-gigabit-wifi/, 2017.

[6]Wi-fi on rays of light - https://www.tue.nl/en/university/news-and-press/news/17-03-2017-wi-fi-on-rays-of-light-100-times-faster-and-never-overloaded/#top, 2017.

[7]Light ID Technology - http://www.panasonic.com/global/Corporate/technology-design/technology/lightid.html, 2016.

communication. After that, we will present the main works responsible for leveraging the studies in the area [21], [32], [39], [40] and boosting the interests for the commercialization of this technology in different sectors [9], [41], [42]. We also discuss the relationship of increasing interest in the area of VLC and the popularization of LEDs (Light Emitting Diodes). In this sense, the main types of LEDs will be presented, along with their importance for the area. After this, we point out a series of advantages and disadvantages that VLC systems have when compared to Wi-Fi systems. Finally, the main academic and commercial trends will be addressed.

## A. VLC and other nomenclatures

There are a number of nomenclatures given to the different technologies involving light as a form of communication. Some of the main nomenclatures are:

**Optical Wireless Communications (OWC):** Optical Wireless Communication involves any type of data transfer in which the medium used is the optical medium. In other words, the entire spectrum of light can be used as a form of communication, be it infrared, visible or ultraviolet [43].

**Free-Space Optical Communication:** Despite having a similar concept to OWC, this nomenclature has been widely used for large-scale transmissions, such as communications between satellites and towers on Earth [44]. Communication in free space involves data transmission in a media without barriers, such as air, atmosphere, and space. Applications using such nomenclature tend to be very complex, dealing with atmospheric turbulences [45], [46] and high-cost equipment [47].

**Visible Light Communication (VLC):** The use of wireless optical communication has become very popular in recent years. In particular, studies involving the visible light spectrum are increasingly common, since this area has a great academic and commercial potential [33]. Visible Light Communication includes all the frequencies of the visible light spectrum, that is, waves ranging from 430 THz to 790 THz [21].

**Light Fidelity (Li-Fi):** The term Li-Fi was coined in 2011 during a TED Talk, as discussed earlier, where Professor Harald Haas gave a practical demonstration of the potential of the technology. One can say that Li-Fi is a type of VLC [9]. However, the creator of the term published a paper in 2015, highlighting the main differences between VLC and Li-Fi [48]. Among the differences between the two technologies, two-way multi-user communication and high speed, aspects present in the concept of Li-Fi, can be highlighted.

## B. LEDs: a great opportunity for VLC

Several factors contributed to the growing interest in VLC. Among all, what stands out most is the use of LED for manipulation of light waves. Due to its characteristics such as price, LED light bulbs have become the main medium used for Visible Light Communication. In addition, LED light bulbs became increasingly popular, integrating various environments where it would be advantageous to use light as a form of communication. Therefore, it is common to choose this type of light bulb in VLC [15] systems.

The LED (Light Emitting Diode) is a device which uses **electroluminescence** and **semiconductors** in order to generate light. More specifically, LEDs are made of materials that are partly capable of conducting current. Additionally, light is emitted when the electric current passes through the material, a phenomenon known as

| Semiconductor Material | Wavelength | Color |
|---|---|---|
| GaAs - Gallium Arsenide | 850-940nm | Infra-Red |
| GaAsP - Gallium Arsenic Phosphide | 630-660nm | Red |
| GaAsP - Gallium Arsenic Phosphide | 605-620nm | Amber |
| GaP - Gallium Phosphide | 585-595nm | Yellow |
| InGaAIP - Indium Gallium Aluminum Phosphide | 550-570nm | Green |
| SiC - Silicon Carbide | 430-505nm | Blue |
| GaN - Gallium Nitride | 450nm | White |

Table II: LEDs and colors

**electroluminescence**. This happens due to the existence of electron holes (when an atom lacks electrons) between two semiconductors. Therefore, when electrons flow through it, they fill the **electron holes**, and consequently, they emit photons. The light is emitted in the visible spectrum, which varies from low to high-frequency waves, corresponding to a specific color. Red LEDs, for example, are commonly made of gallium arsenide phosphide (GaAsP), and their wavelength varies from 630 nm to 660 nm. Table II presents some colors and its respective semiconductor material, as well as the wavelength of the emitted light.

There are many reasons behind the exponential growth of LEDs bulbs nowadays. Some well-known advantages of this type of light source are energy efficiency, durability, and low-cost. Residential LEDs use at least 75% less energy and can last 25 times longer than a traditional incandescent light bulb. In addition, it is possible to focus the light of an LED bulb in a single direction. Due to these advantages, LEDs bulbs are used in various devices, such as smartphones, vehicles, video screens, signs, and are present in many applications, including Visible Light Communication. The use of this technology has brought many benefits to the industry, and the future of residential lighting is firmly based on LED lights.
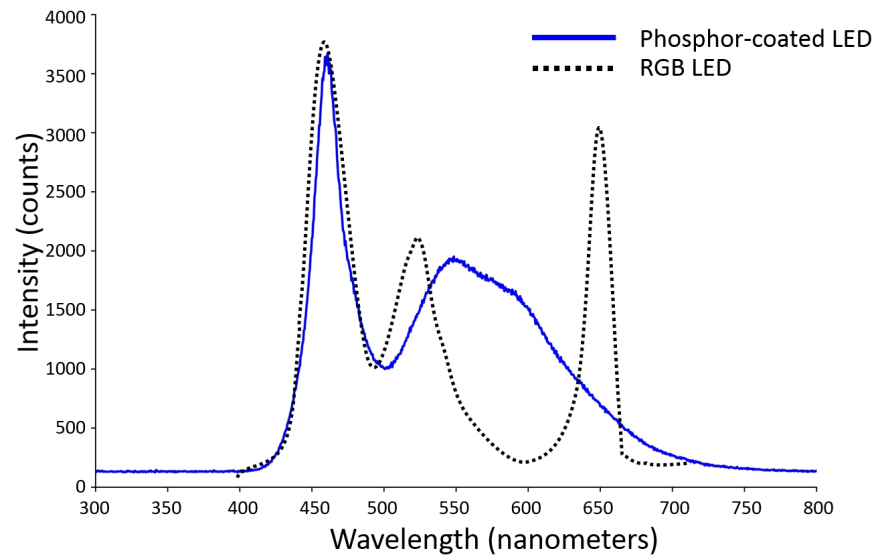


Figure 4: Comparison between the spectrum emission of yellow-phosphor LED and RGB LED

Nowadays, the most common commercial LED light bulb is the white light LED. Unlike the other colors, which

are directly related to its semiconductor materials, white LEDs are created in two conventional methods. The first method uses phosphor to produce white light. This is done by using a blue LED light bulb coated with a phosphor layer. The photons generated by the blue LED are sent through the phosphor layer, and part of them are converted into yellow. Both yellow and blue photons combine, generating white light. The spectral emissions of this method can be seen in Figure 4. The second method consists of using RGB LEDs in order to produce white light, which is done by combining red, green and blue outputs from the LEDs, producing white light. This type of white LED allows control over the emitted color. There are several differences between these two methods, and both have a set of advantages and disadvantages. In general, the phosphor method is more common between LEDs light bulbs, because it is cheaper and more efficient than the RGB method. However, in terms of Visible Light Communications, the RGB bulb tends to be more useful, because of the control it gives over light, and the IEEE standard for VLC [12] outlines a modulation method based exclusively on the intensity of the RGB LED.

It is known that an LED is a semiconductor created to perform as a light source. However, in addition, LEDs are also capable of performing optical to electric conversion. In other words, an LED can also be used as a sensor, a fact that is not widely known and is gaining popularity among VLC researches. These LEDs can act as receivers because when the light is applied to the LED, a small current is generated, which is proportional to the intensity of the light. This phenomenon is known as photocurrent [49]. While a photodiode has a broad spectral response, being able to detect ultraviolet and infrared lights, an LED can be considered a selective photodiode, due to the fact that it detects a narrower wavelength range. In general, it is said that an LED can detect the same or higher frequencies of light that it emits [50]. In other words, a red LED would be able to detect red, green and blue lights, while blue LEDs would detect only blue light. Shin *et al.* characterized 4 different types of LEDs in terms of emission and spectral response [51],shown in Figure 5. In this figure, the curve with the continuous line pattern represents each peak of emission for Blue, Green, Red, and IR, respectively. The other curves represent the spectral response of each frequency and are explained in the figure caption. However, in practical terms, this theory may not apply. The spectral response of LEDs may vary depending on the frequency it emits. Normally, in the visible spectrum, the spectral response shifts slightly towards the blue color (higher frequencies). However, the green color, for example, has a very narrow band of spectral response, different from the emitted frequency. In other words, a green LED may not detect green light. In [52], authors explore the impact of colors in LED-to-LED communication, by combining multiple colors as transmitters and receivers so the spectrum is fully covered. In addition, authors study the impact of distance in the performance of different combinations.

There are several types of LEDs, each with its own peculiarities, which makes them suitable for VLC applications. Depending on the material used in the manufacturing of the chip, light is emitted in a specific region of the visible spectrum. As a result, the photon will be emitted with a characteristic wavelength, resulting in a color. Gallium Arsenide (GaAs), Gallium Phosphide (GaP), are examples of compounds used in LEDs. The main types of LEDs are listed below, along with their details.

**Phosphor Converted LEDs (pc-LEDs):** The pc-LEDs are widely used, and present low complexity and low cost. They consist of a blue LED chip coated with a phosphor layer, whose function is to convert part of the blue light to green, yellow and red, while a fraction of the blue light is emitted, resulting in white light. This type of
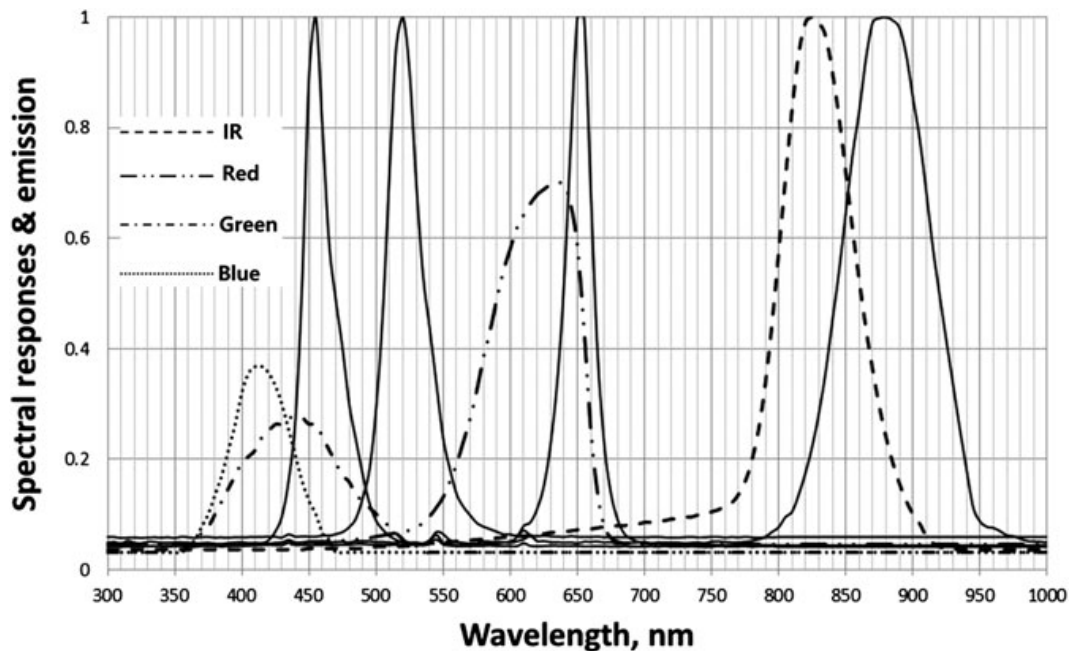
Figure 5: Spectral response of 4 different LED types [51].

LED has a limited band due to the slow response of phosphorus.

**Multi-chip LEDs:** The structure of this type of LED consists of three or more chips and which emit lights of different colors. Normally, the different chips emit the RGB colors in order to produce white light. The great advantage of this type of LED is the ability to control the colors that are emitted, through the intensity of each chip. It is important to note that modulation was created especially for this type of LED, called Color-Shift Keying. The Section IV will provide more details of this type of modulation.

**Organic LEDs (OLEDs):** This type of LED consists of a series of thin organic films between two conductors. When an electric current is applied, light is emitted. They are widely used in displays of smartphones. The great advantage of this type of technology is the possibility of building transparent and flexible devices. However, in terms of frequency and durability, this type of LED is still inefficient when compared to other types [15].

**$\mu$-LEDs:** The $\mu$ - LEDs are usually coupled in displays, enabling parallel communication of high density, reaching very high speeds.

*C. VLC versus RF: advantages and disadvantages*

In the last decades, the world has made great strides in communication technologies. In terms of wireless communication, Wi-Fi has become the dominant means of access to the Internet. However, factors such as the Wi-Fi spectrum crisis and the high demand for wireless communications, drive new technologies and research. In this scenario, VLC studies focus mostly on their use as a complement to Wi-Fi, in order to meet the needs of the current demand for bandwidth in wireless networks [53]. In addition to these motivations, some authors propose the use of VLC as a means of communication with the aim of replacing Wi-Fi in some scenarios [23]. In both

cases, one should consider the advantages and disadvantages that VLC offers when compared to Wi-Fi. Table III presents a general comparison between radio frequency technologies and VLC.

A major advantage of VLC is the use of existing infrastructure also to provide communication services. LED light bulbs, widely used these days, already play the role of lighting. With VLC, these light bulbs transmit data through lighting. That is, the energy used for the communication would not increase the costs [54]. In addition, many of the research of recent years have focused on the use of low-cost devices in the implementation of VLC systems, such as Wang *et al.*, which used microcomputers (Beaglebone) and low-cost LEDs for the development of an open-source platform for studies in the area [55]. Another important example in the literature is the work of researchers at Disney Research Center, responsible for the development of a VLC system that makes use of commercial LEDs [56].

An advantage of visible light is the size of the spectrum, compared to radio frequency. The frequency allocation in the radio waves band of the electromagnetic spectrum is extremely restricted, being regulated by each country, and coordinated by international telecommunication institutions. Thus, each country has its own regulation regarding frequencies allocated for each type of use, ranging from military use to broadcasts of content on AM and FM radios. As a relatively new technology, Wi-Fi devices transmit the signal in two bands: 2.4 GHz and 5 GHz, both located in regions of the spectrum intended for unlicensed devices. However, the situation is different with light. The spectrum of visible light is totally free, generating diverse commercial and academic possibilities [54]. However, visible light is prone to interference from many other sources of light, from artificial (other LEDs, incandescent and fluorescent light bulbs) and natural (sunlight). This may offer a great challenge to the deployment of VLC systems, even though there are multiple academic efforts to mitigate this issue (further discussed in VI).

|  | Wi-Fi | NFC | Bluetooth | VLC |
|---|---|---|---|---|
| Spectrum | 2.4 GHz / 5 GHz | 13.56 MHz | 2.4 GHz | ∼ 400∼THz |
| Infrastructure | Access Point | Device | Device | Illumination |
| Ambient interference | Low | Low | Low | High |
| Security | Limited | Limited | Limited | High |
| Coverage | High | Low | Low | Limited |
| System complexity | High | High | High | Low |
| Electromagnetic interference | Yes | Yes | Yes | No |

Table III: Comparison between radio frequency technologies and VLC, adapted from [15].

Due to its propagation properties, light offers security advantages when compared to radio waves. When a Wi-Fi access point is configured, radio waves can propagate according to the antenna's broadcasting capacity, which can reach hundreds of meters. In this process, waves surpass walls and other solid surfaces and may pose a security risk, since eavesdropping and sniffing attempts may occur [54]. Light, in turn, does not follow this behavior. Its waves do not go beyond walls and other surfaces, offering a much safer environment, where basically what is being transmitted is what you see [57]. This possibility of manipulating light waves is another great advantage of this form of communication.

Finally, one of the major advantages of light as a form of communication is the high frequency of waves (in the THz magnitude), which allows for very high data rate communication. Currently, in terms of Wi-Fi, the highest data rate achieved is close to 1 Gbps, in the standard WiGig [58]. Thanks to the high frequency of light waves, VLC searches have already obtained impressive results, reaching speeds of 100 Gbps [59], [60].

### D. Internet and VLC

In recent years, most of the related work has focused on the aspects of communicating LEDs with their respective sensors. There is a standard for the Physical and MAC layers in VLC systems, the IEEE 802.15.7 [12]. Some studies already addressed an architecture in which these layers are integrated with the rest of the protocol stack in order to enable full Internet access through VLC.

Commercially, there are systems that involve access to the Internet. Eg, the Li-Fi-X device, developed by pureLiFi [8], the evolution of the former Li-Flame[9], was the first system to use Li-Fi technology, coined in 2011 by scientist Harald Haas. The Li-Fi-X system allows one to install an internet access infrastructure completely based on Li-Fi. The product provides essential aspects for wireless communications such as mobility, multiple users and security, as well as speeds of 40 Mbps, for both downlink and uplink. The system consists of Access Points and Stations. As the first solution to use Li-Fi technology, the company attracted hundreds of investors. This system provides an approach in which Infra-red communication is used to perform the uplink communication.

Other works in the area try to bring different solutions, using other technologies to complement the VLC communication, while looking for mechanisms in order to integrate the lower layers of the created systems (PHY and MAC) to the higher ones. The hybrid platform PLifi [61] was created with the purpose of joining Wi-Fi to VLC, in an internal environment. Among the challenges highlighted by the author is the connectivity of LEDs with the Internet. As can be seen in Figure 6, in the PLifi architecture, the Wi-Fi access point uses Power Line Communication (PLC) technology using an Ethernet-PLC modem. In turn, the PLC network connects to the LED light bulb through a PLC-VLC modem. In this way, the packets are routed to the LED through the Wi-Fi access point.

In the last few years, many types of research began to address VLC integrated into the stack of Internet protocols directly, that is, without any type of radio frequency technology, such as Wi-Fi. Schmid *et al.* presented, in 2015, a work in which the VLC system created used commercial LED light bulbs [62]. In the proposed architecture, a commercial LED light was modified in order to behave as a transmitter with integrated Linux and VLC. For this, the light bulb is modified to contain a System-on-a-Chip (SoC) that runs Linux and the driver VLC, responsible for the modulation of light. The VLC firmware implements the Physical and MAC layers in order to provide network creation between multiple devices. Figure 7 presents the architecture of the proposed VLC system. In this case, the light bulb elements are: SoC module with Wi-Fi enabled, the communication interface between the SoC module and the microcontroller (the connection is made through UART interface (Universal Asynchronous Receiver Transmitter), microcontroller containing the firmware, amplifiers, photodiodes and finally the LED.

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[8]Li-Fi-X - The fastest, smallest and most secure Li-Fi system - http://purelifi.com/lifi-products/lifi-x/ 2017.

[9]Li-Flame - http://purelifi.com/lifi-products/li-flame/, 2017.
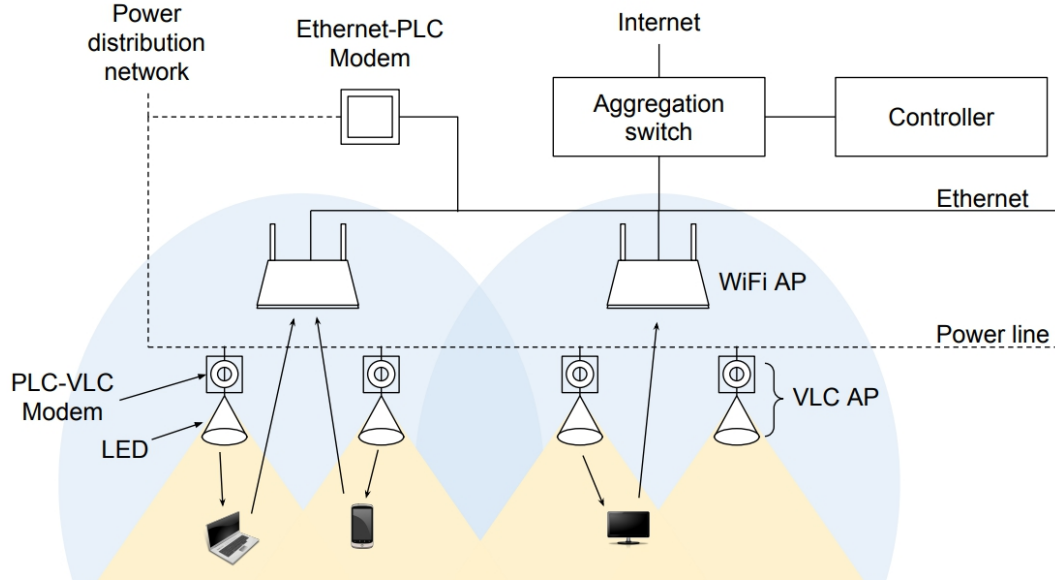
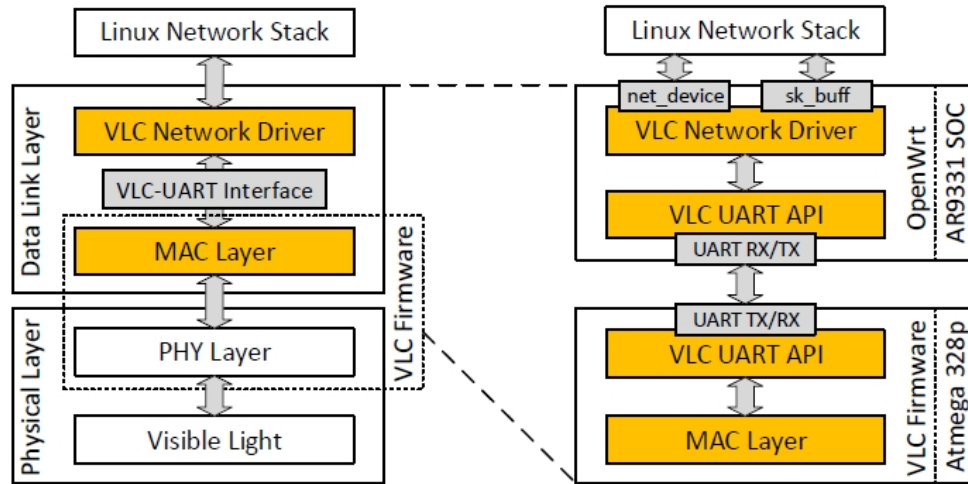Figure 6: PLiFi architecture [61].



Figure 7: System architecture [62].

Another work that stands out by presenting an integrated system to the Internet was developed by Wang *et al.*. The authors present the OpenVLC platform [63] which, unlike Schmid's work, does not use commercial LED light bulbs to implement VLC. OpenVLC is a platform developed to be a peripheral of the well-known BeagleBone Board, known as "cape". The cape can be inserted into the Beaglebone, and the entire implementation of the lower layers is done in the BeagleBone itself, whose operating system is Debian.

*E. Recent achievements*

With the growing interest in VLC systems, new opportunities and technologies have emerged in recent years. Parallel to this new trend, there are many studies that seek to increase the performance of Wi-Fi in wireless networks present today, such as WLANs and 4G. In this way, the trends and future of the area are promising, contemplating works that deal with VLC individually, and those that integrate this technology with other existing ones, such as Wi-Fi.

Many recent works focus on the development of hybrid systems, in which the network architecture integrates both Wi-Fi and VLC. In this context, works like PLi-Fi have arisen and have received attention from the academic community [61]. PLi-Fi is a hybrid system where the architecture combines Wi-Fi and VLC technologies through the use of PLC (Power Line Communication). The connection between LED bulbs and the Internet is made at high speed using accessible tools. This paper offers a new solution, whose purpose is to mitigate some challenges known in the field, such as uplink and mobility.

In addition, there are discussions about the implementation of VLC in future wireless technologies, especially in the context of 5G. Increasing use of smartphones, tablets and IoT devices raises a number of questions regarding the future demands of wireless devices, requiring today's technology to evolve and adapt to meet current and future applications. To this end, research in recent years points to the use of integrated VLCs in 5G [14], [53]. In their premise, these works find that most of the current demand on the Internet belongs to indoor scenarios, where there is the possibility of using a pre-existing infrastructure to implement VLC systems.

Smartphones have become increasingly indispensable in the lives of much of the world's population. Thus, there is an effort by some researches to integrate Visible Light Communication with Smartphones, using components such as the camera and external LEDs [64]. Since smartphones are already equipped with the camera, the challenge is to adapt the devices without any modification in hardware, in order to integrate them into Visible Light Communication systems [65].

VLC also excels at large projects, such as the Lunar Laser Communication Demonstration. In 2013, NASA launched a spacecraft in the LADEE (Lunar Atmosphere and Dust Environment Explorer) mission to collect data from the moon. Coupled to the spacecraft, was the LLST (Lunar Lasercom Space Terminal), a terminal responsible for sending data collected to Earth via Wireless Optical Communication [30]. Transfer rates of 622 Mbps were achieved, 6 times higher when compared to the radio technologies used until then[10].

## III. COMMUNICATION ARCHITECTURE

The main components that integrate VLC systems –a transmitter and a receiver– generally customize three layers of the protocol stack [66]. In fact, researchers discuss mostly physical, link, and application layers when they describe the architecture of VLC systems [32]. In this section, we first overview these three layers. Second, we discuss the supported network topologies and the challenges, such as mobility [66]. Moreover, we will discuss the different devices described in the literature, and how they are customized for specific purposes, such as a network topology created in an indoor environment, where an infrastructure next to Wi-Fi [67] is sought.

[10]NASA | LLCD: Proving Laser Communication Possible - https://www.youtube.com/watch?v=wJMPd2FJp5g, 2017.

### A. Overview

Visible Light Communication uses light to transmit information. In addition, the idea behind VLC applications is to provide lighting and communication at the same time. Thus, VLC systems will always have components to transmit and receive light. In the vast majority of work available in the literature, LEDs are used as transmitters. These LEDs are used to modulate the intensity of light in order to send data. On the receiver side, photosensors are responsible for capturing this light directly (Direct Detection), converting it into data stream [16]. In VLC, it is important that lighting illumination brightness is not affected by the manipulation of light while transmitting information, hence the type of LED has an impact on the performance of a VLC system.
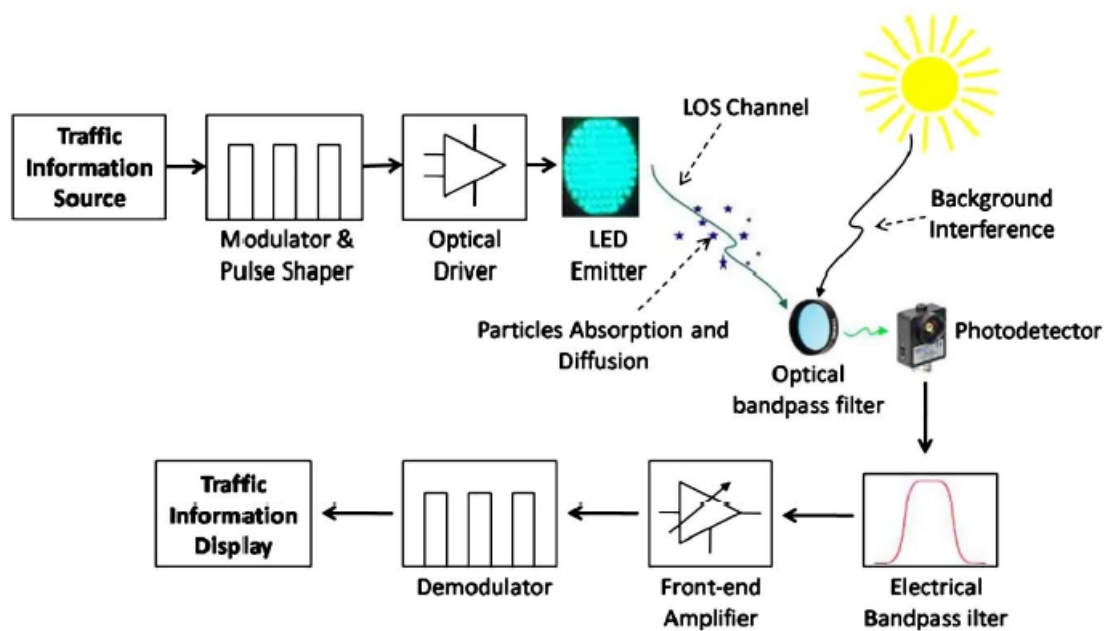


Figure 8: VLC System Architecture, adapted from [68]

Figure 8 gives an overview of the architecture of a VLC system. LEDs transmit data through Intensity Modulation. The receiver must be in the line of sight of the LED so that it receives the light beams containing the information. In fact, during light transmission, there will be a loss in light signal quality due to particles diffusion and the inherent interference of ambient light. To reduce interference, filters may be used. At the receiver node, light is incident on the photosensor, directly altering the current. The use of amplifiers turns the signals less prone to interference and noise [56]. Finally, the signal is demodulated to retrieve the original information. In what follows, we detail each component of a VLC system.

**Transmitters:** In general, LEDs are used as transmitters in VLC systems. Most commercially available light bulbs contain several LEDs. These light bulbs contain a driver responsible for controlling the current passing through the LEDs, directly influencing the intensity of the illumination. In other words, the current arriving at the LED is controlled by transistors, which manipulate the light signals that the LED emits at high frequency, and thus makes the communication imperceptible to human eyes [21].

**Receivers:** Receivers are responsible for capturing light and converting it into electrical current. Normally, photodiodes are used as receivers in Visible Light Communication systems [56]. However, photodiodes are extremely sensitive, and capture waves beyond the spectrum of visible light, such as ultraviolet and infrared [55]. They also saturate easily, in an external environment and exposed to sunlight, for example, and the photodiode would fail to receive data due to high interference. For this reason, other components can be used to capture light. One of them is the smartphone camera itself, which allows any cell phone to receive data sent by a VLC transmitter, as discussed in Section II. In addition to these devices, LEDs themselves can be used as receivers because they feature photo-sensing characteristics[11] [63].

Unlike photodiodes, LEDs have properties that make them efficient in certain situations. An LED detects a reduced frequency range when compared to photodiodes, reducing the presence of noise and interference. In addition, the sensitivity of LEDs is stable over time. The main advantage is the fact that LEDs can function as both transmitters and receivers, which makes it possible to create a system with only one LED at each point.[12], besides being very accessible and popular components, making VLC applications even easier to use.

*B. VLC Standards*

The first effort to standardize Visible Light Communication happened in 2003, followed by the creation of the Visible Light Communication Consortium (VLCC) in Japan. At that time, some work explored VLC around the world. However, applications such as VLC-based positioning were already being researched in Japan. A few years later, in 2007, two standards were included in JEITA (Japan Electronics and Information Technology Industries Association): the JEITA CP-1221, which covers the basics of VLC systems, and JEITA CP-1222, a standard for Visible Light ID Systems [69].

Due to the growing interest in VLC systems by the universities and industry, there was a need to standardize certain aspects of this type of communication. To this end, in 2011, the IEEE 802.15.7 Visible Light Communication Task Group developed the first draft of the official **IEEE 802.15.7** standard, in which the Physical and MAC layers for Short-Range Wireless Optical Communication Using Visible Light [12] are defined. The standard covers aspects necessary to ensure the delivery of data at rates sufficient to support services such as multimedia and audio, as well as ensuring compatibility with the visible light infrastructure. In addition, the standard covers effects of VLC on health and the environment. In general, the standard addresses issues such as network topologies, devices considered for VLC, communication architecture, physical layer characteristics, and MAC with dimming and flickering support, as well as security specifications. Details of these aspects are presented below.

Initially, the document addresses the types of devices in VLC systems, including infrastructure, mobile, and vehicles, each with its own features, as it can be seen in Table IV. The standard also specifies topologies and modulation mechanisms for VLC systems.

Much of the IEEE 802.15.7 standard is focused on physical and MAC layer characteristics (details in Section IV). In general, the IEEE standard divides the physical layer into three modes of operation: PHY I, PHY II and PHY

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[11](LED Sensing - www.thebox.myzen.co.uk/Workshop/LED_Sensing.html, 2017.

[12]How to Use LEDs to Detect Light - http://makezine.com/Projects/make-36-boards/how-to-use-leds-to-detect-light/, 2013.

|  | Infrastructure | Mobile | Vehicle |
|---|---|---|---|
| Fixed coordinator | Yes | No | No |
| Energy source | Broad | Limited | Moderate |
| Light source | Intense | Weak | Intense |
| Mobility | No | Yes | Yes |
| Range | Short/Long | Short | Long |
| Data rate | High/low | High | Low |

Table IV: Structures presented in IEEE 802.15.7, adapted from [12]

III. Any IEEE 802.15.7 compliant system must implement at least the PHY I or PHY II modes. The system that implements the PHY III mode, must also implement the PHY II.

The PHY I mode of operation is designed for external applications with short frames. PHY II and PHY III modes support only one type of encoding. PHY I mode data rates range from 11 kbps to 266 Kbps, while PHY II mode data rates range from 1.25 Mbps to 96 Mbps. The PHY III mode of operation contemplates data rates from 12 Mbps up to 96 Mbps. PHY III operating mode has a modulation scheme developed for multi-chip LEDs. Tables V, VI, and VII provide details of each mode of operation as well as modulations and encodings supported by them.

| Modulation | RLL code | Optical clock rate | FEC | | Data Rate |
|---|---|---|---|---|---|
|  |  |  | Outer code (RS) | Inner code (CC) |  |
| OOK | Manchester | 200 kHz | (15,7) | 1/4 | 11.67 |
|  |  |  | (15,11) | 1/3 | 24.44 |
|  |  |  | (15,11) | 2/3 | 48.89 |
|  |  |  | (15,11) | none | 73.3 |
|  |  |  | none | none | 100 |
| VPPM | 4B6B | 400 kHz | (15,2) | none | 35.56 |
|  |  |  | (15,4) | none | 71.11 |
|  |  |  | (15,7) | none | 124.4 |
|  |  |  | none | none | 266.6 |

Table V: PHY I in IEEE 802.15.7 Standard [12]

In addition, important concepts such as dimming and flickering are covered in detail in the standard, since a VLC system must allow manipulation of the light intensity in a way that does not influence the communication itself.

The standard also addresses security issues in VLC. In this sense, light has different properties than the radio waves, allowing new guidelines when dealing with the safety of VLC systems. As the light wave is directed and visible, an unauthorized interception of the signal can be easily detected. Even so, the proposed cryptographic mechanism is based on symmetric keys, generated by the upper layers. Among the security services offered by the encryption mechanism are confidentiality, authenticity and replay protection.

*C. Network topologies*

In a computer network, the network topology defines how devices are organized and distributed, and how information will be shared between them [70]. This is done from both a logical and a physical point of view.

| Modulation | RLL code | Optical clock rate | FEC | Data Rate |
|---|---|---|---|---|
| VPPM | 4B6B | 3.75 MHz | RS(64,32) | 1.25 Mb/s |
| | | | RS(160,128) | 2 Mb/s |
| | | 7.5 MHz | RS(64,32) | 2.5 Mb/s |
| | | | RS(160,128) | 4 Mb/s |
| | | | none | 5 Mb/s |
| OOK | 8B10B | 15 MHz | RS(64,32) | 6 Mb/s |
| | | | RS(160,128) | 9.6Mb/s |
| | | 30 MHz | RS(64,32) | 12 Mb/s |
| | | | RS(160,128) | 19.2 Mb/s |
| | | 60 MHz | RS(64,32) | 24 Mb/s |
| | | | RS(160,128) | 38.4 Mb/s |
| | | 120 MHz | RS(64,32) | 48 Mb/s |
| | | | RS(160,128) | 76.8 Mb/s |
| | | | none | 96 Mb/s |

Table VI: PHY II in IEEE 802.15.7 Standard [12]

| Modulation | Optical clock rate | FEC | Data Rate |
|---|---|---|---|
| 4-CSK | 12 MHz | RS(64,32) | 12 Mb/s |
| 8-CSK | | RS(64,32) | 18 Mb/s |
| 4-CSK | 24 MHz | RS(64,32) | 24 Mb/s |
| 8-CSK | | RS(64,32) | 36 Mb/s |
| 16-CSK | | RS(64,32) | 48 Mb/s |
| 8-CSK | | none | 72 Mb/s |
| 16-CSK | | none | 96 Mb/s |

Table VII: PHY III in IEEE 802.15.7 Standard [12]

Topologies such as Peer-to-Peer, Bus, and Ring are well-known in academia and widely used in computer networking systems.

The idea is analogous to VLC systems. According to the official VLC standard [12], there are three classes of devices considered for VLC systems: infrastructure, mobile, and vehicles (Table IV). In this way, IEEE 802.15.7 defines the applications in three topologies: peer-to-peer, star and broadcast, as shown in Figure 9.

**Peer-to-Peer:** In a peer-to-peer topology, a device can communicate with any other in its coverage area. Besides that, one of the connected devices must assume the role of coordinator. The coordinator role can be assigned to the first device to communicate in a channel, for example.

**Star:** In a star topology, there is a central controller, called coordinator, and communication is established between the coordinator and each device in the network. Every network in the star topology works independently of other networks in operation because there is an identifier associated with a single star network.

**Broadcast:** In this topology, one device can send information to others without a network being formed. The communication, in this case, is unidirectional.

Based on the above-described topologies, IEEE 802.15.7 presents a series of modulation techniques at the physical layer, as well as specific protocols at the link layer, which will be discussed in detail in Section IV.
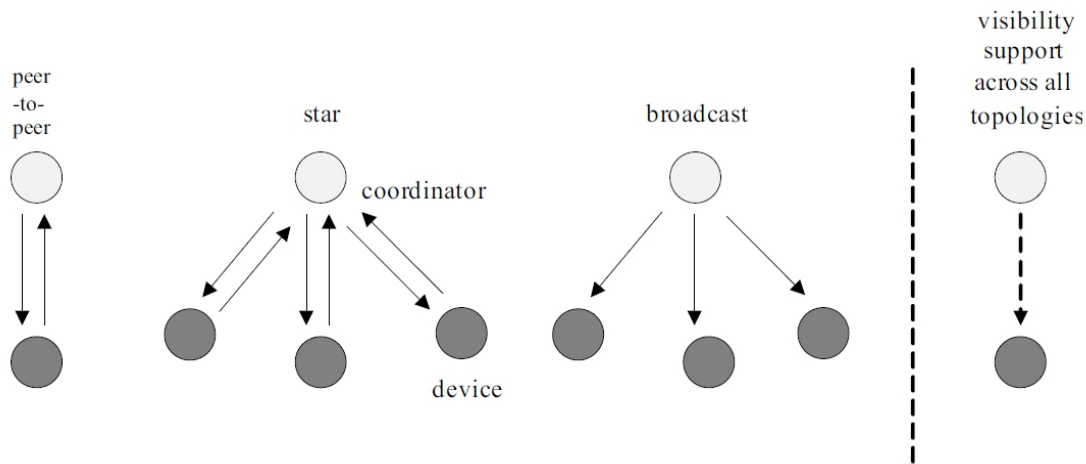
Figure 9: Supported MAC topologies [12].

## IV. PHYSICAL AND MAC LAYERS

In this section, we describe the physical and link layers in VLC systems. Visible Light Communication integrated with the Internet has already been studied by several works. Therefore, we will discuss the main techniques used for light coding/decoding and modulation/demodulation such as CSK (Color Shift Keying), OOK (On-Off Keying and OFDM (Orthogonal Frequency Division Multiplexing), implemented in the physical layer, as well as the multiple access protocols as CSMA/CA, CSMA/CD, CSMA/CD-HA, implemented in the Link layer. We also delve into novel and promising approaches for wireless technologies, such as MIMO-NOMA,

### A. Physical Layer

The Physical layer is responsible for transmitting data (bits) through a communication channel, such as a twisted pair or radio waves. The issues that need to be addressed in the physical layer of a system involve aspects such as the representation of signals, how these signals will be sent, the establishment of communication, involving elements of the electronic interface and synchronization [70]. Physical layer performs similar function also in VLC, but in this particular case, light is used as the transmission medium. In what follows, we present a number of aspects that influence decisions regarding the implementation of the physical layer in VLC systems.

**Path Loss**: A physical layer design in VLC needs to consider the fact that LED light bulbs present two main functions: **illumination and communication**. Therefore, it is necessary to understand the requirements in terms of brightness for communication to occur in a satisfactory manner. The photometric parameters determine a series of characteristics of light, such as brightness, color, among others, from a human vision perspective. On the other hand, the radiometric parameters measure the energy of the electromagnetic radiation of light. Through these parameters, we can calculate the luminous flux, which represents the quantity of the energy of the light emitted. Based on the luminous flux, it is possible to calculate an important value for the physical layer: the path loss [71].

**Propagation:** Lightwave propagation is also a property that is important to consider to develop VLC Physical layer. In indoor environments, usually, there are multiple transmitters, such as LED light bulbs and surfaces that may reflect light. Therefore, it is important to understand the impact of reflected light on VLC systems.

**Noise:** In a VLC system, noise is an important factor to consider for communication performance. During the day, in an outdoor environment, for example, sunlight can either cause VLC to fail or degrade significantly due to light interference. In this case, filters can be used to prevent photo sensor saturation. Some work uses LEDs as receivers since they are considered "selective photodiodes", to address this issue partially.

Light modulation is another essential point of the VLC Physical layer. In VLC, some aspects of light, for example, intensity, must be converted to digital signals to represent the bits. Unlike other types of communications, light modulation must seek a high rate of data while not interfering with the light perceived by humans [33]. One of these requirements is *dimming*. Light bulbs from various residential and corporate locations are equipped with dimmer circuits so that light intensity can be controlled, provide adequate and comfortable light in an environment. In this sense, according to the IEEE 802.15.7 standard, Visible Light Communication must still be possible at reasonable performance even with light bulbs that support this dimming feature. The second requirement concerns oscillation of light, also known as *flickering*. The applied modulation technique cannot cause any kind of oscillation perceptible by human vision [72]. In what follows, we present the main modulation techniques for Visible Light Communication found in the literature.

**On-Off Keying (OOK):** OOK is a simple type of Amplitude Shift Keying (ASK) modulation, in which the digital data is represented by the presence or absence of the source signal. In other words, bits 0 and 1 are directly related to the amplitude of the source signal. The concept of OOK is very adaptable to the idea of VLC, because in order to perform communication, light must be modulated. A simple and easy way to modulate the light consists in turning the LED on and off, which in turn will be received and demodulated as 1 and 0, respectively. This approach has been broadly used by works in the literature [62], [63], and is detailed in the IEEE 802.15.7 standard. Some of the drawbacks of OOK are related to the flickering and limited data rate.

**Variable Pulse Position Modulation (VPPM):** Another technique widely used in VLC systems is VPPM. This method uses two different modulation types: Pulse Position Modulation (PPM) and Pulse Width Modulation (PWM). In Pulse Position Modulation, the width and amplitude of the pulse are constant. However, the digital value of the signal is given by the position in which the pulse is located, according to the time [73]. One of the advantages of PPM is the ease of implementation. However, only one pulse is emitted for each symbol, which causes the data rate to be limited. Pulse Width Modulation works based on the length of the signal, which determines the width according to time. In Pulse Width Modulation, the length of the pulse determines its value, given a time period. Variable Pulse Position Modulation was first presented in the IEEE 802.15.7 standard [12] and uses PPM to provide communication and PWM to support dimming control. Figure 10a presents some examples of VPPM modulation based on dimming configuration. As seen in the figure, the position of the pulse determines its value, while its length determines the brightness.

**Color Shift Keying (CSK):** In CSK, the signal is modulated according to the intensity of the three colors that make up a type of LED known as multi-chip. This LED is composed of three or more LED chips, usually red,
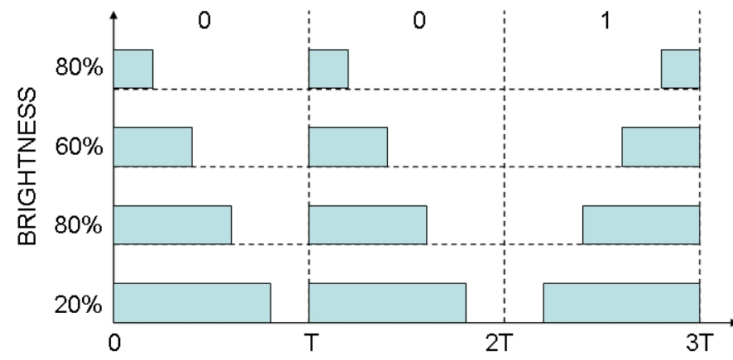
(a) Variable Pulse Position Modulation [12]
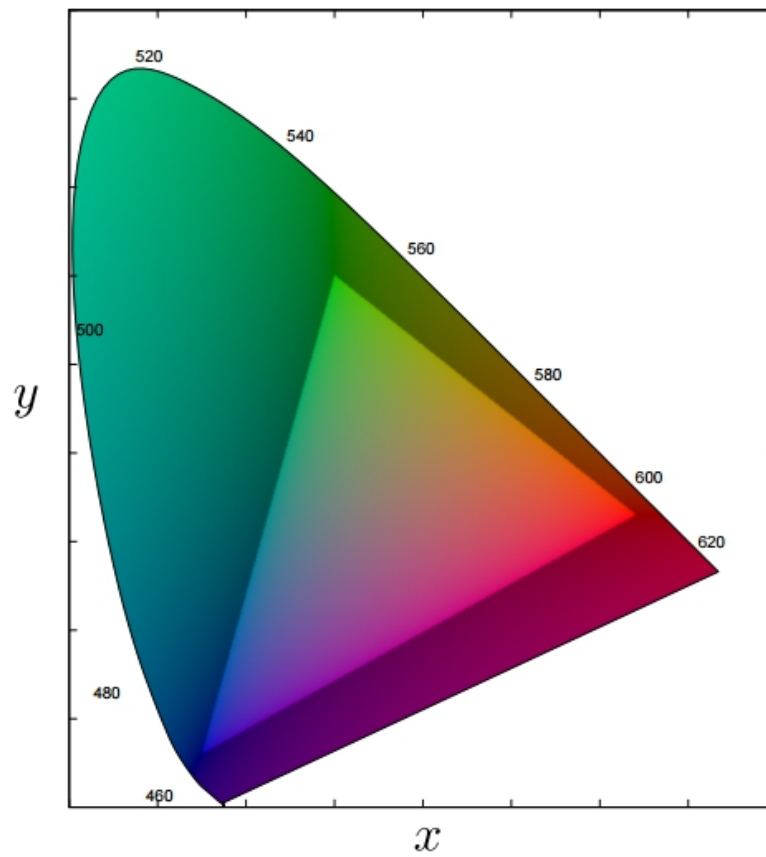


(b) CIE 1931 chromaticity diagram [38]

Figure 10: Modulations mechanisms proposed in the IEEE 802.15.7

green and blue. These three colors, together, are used to generate white light. The OOK and VPPM modulations have low data rates, so the IEEE 802.15.7 standard proposes CSK modulation as a solution to increase data rates, specifically for Visible Light Communication systems. The CSK modulation is based on the CIE 1931 chromaticity diagram [74]. There are seven wavelength bands available, from which the RGB source can be chosen. This origin determines the vertex of a triangle in which the constellation points of the CSK symbols are. The color point of each symbol is produced by modulating the intensity of the RGB chips. Singh *et al.* performed a detailed study where they present the first evaluation of CSK modulation proposed in [12] for different combinations of color bands (CBC), taking into account parameters such as energy efficiency and bit error Rate (BER) [75].

**Orthogonal Frequency Division Multiplexing (OFDM)**: In this modulation, the channel is divided into multiple orthogonal sub-carriers, and data is sent in modulated sub-streams on top of the sub-carriers. One of the great advantages of this modulation method is the reduction of inter-symbol interference.

The use of LEDs in VLC enables **MIMO (multiple-Input-Multiple-Output)** communication because many light bulbs are made up of multiple LEDs. Each LED can be considered a transmitter, thus having multiple transmitters per light bulb. MIMO techniques are widely used in radio-frequency communications, to increase data rates. Among the MIMO algorithms used in VLC are Repetition Coding, Spatial Multiplexing, and Spatial Modulation [23]. Many papers in the literature implement this technique with the objective of increasing communication speed, reaching rates of up to 1.1 Gbps [59].

In general, the main features of Visible Light Communication lie in the physical layer. The VLC physical layers propose new approaches by taking into account the properties of visible light, which differs significantly from radio frequency. There is an effort on the part of the academic community and members of standardization institutions so that the main issues related to the VLC physical layer are solved, especially with respect to aspects such as modulations and coding mechanisms, as well as their influence on factors such as oscillation and dimming of the light.

### B. MAC Layer

Many VLC applications target multiple access (MA) or scenarios that support multiple transmitters and receivers. For example, in an indoor environment, such as corporate buildings and residential buildings, there may be more than one person connected to a VLC access point (LED light bulb). With many devices connected at the same time, it is necessary to create mechanisms to control access to the medium, manage device to access point association and to allow mobility [21]. This section covers the main approaches in multiple access mechanisms and Visible Light Communication, which includes traditional orthogonal multiple access adopted in VLC (Time Division Multiple Access (TDMA), Carrier Sense Multiple Access (CSMA), Orthogonal Frequency Division Multiple Access (OFDMA) and Code Division Multiple Access (CDMA)) and new approaches proposed in literature in recent works, which consider the adoption of Non-Orthogonal Multiple Access (NOMA) for Visible Light Communication. Bawazir *et al.* presented a survey in which several multiple access mechanisms are explored [76]. In the present section, we also explore CSMA, which is a common mechanism used in several works in literature.

**Time Division Multiple Access (TDMA):** TDMA is a traditional multiple access mechanism and works by dividing the signal into multiple time slots, which are given to the users who share the same frequency channel but use the time slots separately to guarantee individual use of the channel. TDMA is famous for being used at the beginning of cellular networks (2G and 3G) and has been adopted for Visible Light Communication as well. Kim *et al.* proposed the usage of TDMA optical beamforming in VLC systems in order to accommodate multiple users [77]. By developing TDMA along with optical beamforming, the authors were able to reach longer distances while enabling communication with multiple devices.

**Space Division Multiple Access (SDMA):** SDMA is often proposed to optimize the use of the spectrum by adopting directional characteristics for channel access. In SDMA, the transmitter generates multiple signals according to the position of the users that are active. Thus, the fact that transmitters in VLC scenarios are hugely based on directionality (LEDs) is an advantage for the adoption of Space-Division multiple access [78].

**Carrier Sense Multiple Access (CSMA):** In IEEE 802.15.7, two types of CSMA protocols are proposed. In the first, the signals emitted by the coordinator are disabled. Thus, an unallocated random access channel is used for the CSMA. Therefore, if a device wants to transmit, it must first wait for a random time, known as a back-off period, and then check whether the channel is free. If the channel is busy, the device waits again for a random period before attempting to access the channel again. In the second type of CSMA proposed in the standard, coordinator signals are enabled, and time is divided into signal intervals. A frame within a signal range contains information such as Contention Access Period (CAP) and Contention Free Periods (CFP). If a device wants to transmit on the channel, it must first locate the start of the next back-off slot and wait for a random number before executing the Clear Channel Assessment (CCA). If the channel is idle, the device starts broadcasting. Otherwise, wait for more back-off slots before running the CCA again. This protocol has already been implemented in some research in the literature, such as enhanced CSMA/CA to guarantee bidirectional communication between LEDs [79].
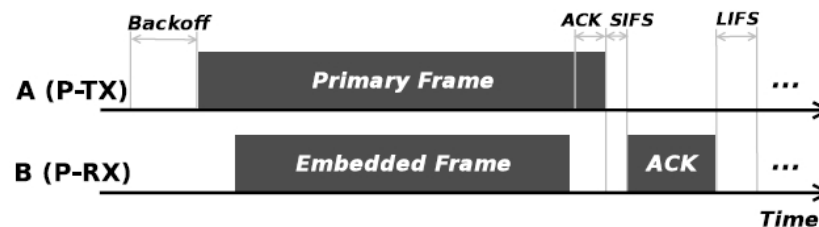


Figure 11: CSMA/CD-HA protocol [80].

A recent work on Carrier Sensing Multiple Access/Collision Detection and Hidden Avoidance (CSMA / CD-HA) protocol ensures fair channel use among all VLC nodes connected to the network(Fig. 11) and reduces the impact of collisions and hidden nodes [80]. In their work, hidden nodes problem is mitigated to a large extent because frames of the protocol have dual-usage: on the one hand, they send additional information in bandwidth, and on the other hand, they act as an active acknowledgment of data reception, protecting the primary transmitter from hidden nodes. Channel utilization is increased by terminating the main frame transmission when HIGH-HIGH signal detection occurs (an invalid sequence) for a predefined number of times.

**Orthogonal Frequency Division Multiple Access (OFDMA):** In OFDMA, multiple users receive different resource blocks for communication, the subcarriers. Just as OFDM modulation is used at the Physical layer, OFDMA is used for multiple access. The main challenges in implementing this protocol in VLC systems concern energy efficiency and decoding complexity [81]. A recent OFDMA-based VLC system achieved data rates of up to 13.6 Mbps [82]. another work proposed a bidirectional VLC system where the NOMA-OFDMA protocol is used to achieve a high data rate, as well as flexible bandwidth and greater user capacity [83].

**Code Division Multiple Access (CDMA):** CDMA for Visible Light Communication, also called Optical CDMA (OCDMA), consists of orthogonal optical codes (OOC) which are distributed in order to have access to the same channel by different users, a technique already used in fiber-optic networks [21]. In OCDMA-VLC, a code is assigned to each device so that the data can be coded in the time domain through the on and off LED states. OOC codes tend to be long, ensuring optical efficiency, which can reduce the performance of communication.

**Non-Orthogonal Multiple Access (NOMA):** The concept of NOMA was first introduced for 5G wireless networks [84], and involves the adoption of power-domain multiplexing (PDM) to provide multiple access. In other words, each user is able to use the entire bandwidth by allocating different power levels based on the channel conditions. TDMA, OFDMA, and other Orthogonal Multiple Access (OMA) techniques tend to be inefficient in terms of resources usage. NOMA differs significantly from traditional techniques, since it offers full use of time and frequency domains resources during the transmission [85], as shown in Figures 12a and 12b. At the transmitter side, superposition coding (SC) is used. At the receiver, to properly detect the signal, NOMA employs successive interference cancellation (SIC).

Despite being considered for the future of wireless technologies, NOMA techniques can also be integrated with OMA approaches, such as TDMA and OFDMA [83]. In [86], NOMA techniques are compared to classic OFDMA techniques in aspects such user and topology optimization, channel fairness and performance. According to the authors, some of the advantages of NOMA are better service quality, interference mitigation and a higher number of user allocation.



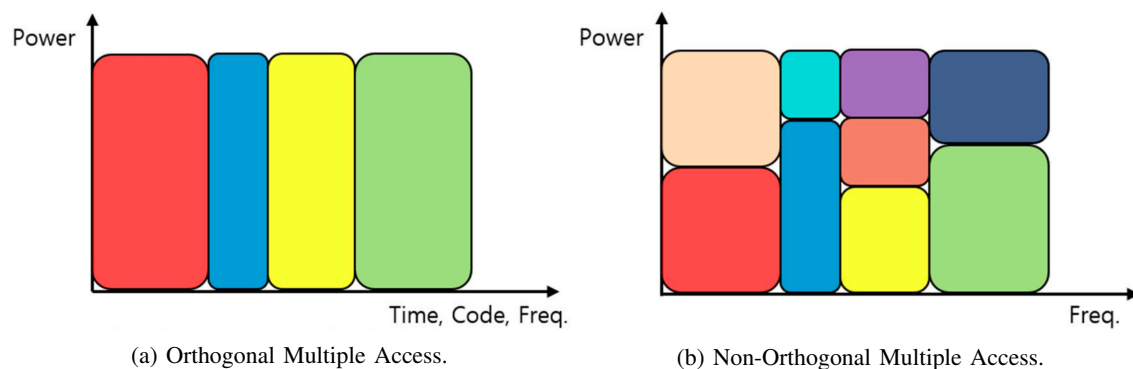(a) Orthogonal Multiple Access.　　　　(b) Non-Orthogonal Multiple Access.

Figure 12: Difference between OMA and NOMA techniques [87].

There are plenty of literature reviews on NOMA and NOMA-VLC, due to its novelty and advantages, especially for new technologies. Table VIII presents the main aspects explored in each survey published in the last 3 years.

Surveys with focus on promises and challenges of NOMA techniques applied to new wireless technologies (5G) are explored in [88]–[90], which have been presented in 2016, 2017 and 2018, respectively. In [88], authors present the fundamentals of NOMA techniques, design and research challenges. In addition, the authors provide a comparative table between OMA and NOMA techniques. Islam *et al.* [89] offers a deep survey on NOMA with a high number of sources to discuss implementation issues and challenges. The survey also highlights the application of NOMA along with other wireless technologies such as MIMO, cooperative communication, network coding, and space-time coding. The same authors offer a more concise perspective of NOMA in 5G systems in [91], by superficially exploring the main concepts such as application, challenges, limitations, existing solutions, and standardization efforts. A more recent survey on NOMA for 5G can be found in [90]. Authors provide analytical results and discussions to explore some of the main benefits of NOMA (system performance and spectral efficiency), and a deep review of Coding NOMA is also given by the authors.

In the VLC field, reviews no NOMA have been developed in [18], [19], [76]. All these works provide a review focused on Multiple Access in Visible Light Communication, and they present NOMA as a promising mechanism capable of improving system performance in many ways, especially when its basic concepts are applied to the specific scenario of VLC. It is important to highlight that these surveys differ significantly from this current work: they provide an in-depth review of multi-user techniques (including NOMA), and concepts of VLC are explored in order to set the background to these contributions (limitations and challenges in the context of multi-user VLC, for example). For example, in [76], authors explore traditional (OFDMA, OCDMA, OSDMA) and novel (NOMA) multiple access mechanisms based on VLC limitations. In [19], authors explore multiple access in VLC through two different perspectives: single-user and multiple-user VLC systems. In [18], a review of the literature is performed, and authors agregate information about VLC modulatino schemes and multiple access techniques, delving into mathematical aspects of MIMO NOMA, while offering simulation results to show application the relationship between users FOV and multiple access schemes.

| | Year | NOMA Concepts | NOMA-VLC | NOMA-MIMO | Cooperative NOMA | NOMA Beamforming | Cognitive Radio-NOMA | Security in NOMA |
|---|---|---|---|---|---|---|---|---|
| Wei *et al.* [88] | 2016 | ✓ | | ✓ | ✓ | ✓ | | |
| Islam *et al.* [89] | 2017 | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| Islam *et al.* [91] | 2017 | ✓ | | ✓ | | | | |
| Dai *et al.* [90] | 2018 | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| Bawazir *et al.* [76] | 2018 | ✓ | ✓ | ✓ | | | | |
| Al *et al.* [19] | 2018 | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Obeed *et al.* [18] | 2018 | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |

Table VIII: NOMA reviews in literature

Given the importance and novelty of this multiple access technique, we dedicate a separate section of this survey to further explore NOMA concepts, challenges, and applications in Visible Light Communication.

### C. NOMA - Non-Orthogonal Multiple Access

In this section, we offer a comprehensive analysis of NOMA. First, we present its basic concepts and then, we show its applications in the wireless field, including Visible Light Communication. This survey offers a broader perspective of the entire Visible Light Communication field, therefore we do not delve into the mathematics and technical particularities of NOMA mechanisms.

**Basic concepts:** There are two different solutions for NOMA: the first one uses the power domain and the other explores the code domain. Code-domain NOMA works similarly to CDMA techniques, in which users share frequency and time domains. However, in this case, NOMA uses a user-specific spreading sequence. There are a number of variations of code-domain NOMA, such as low-density spreading CDMA, low-density spreading-based OFDM and sparse code multiple access (SCMA).

In [92], authors explore for the first time the concepts of NOMA for indoor Visible Light Communication using multiple LEDs. Authors use gain ratio power allocation (GRPA) to implement the power allocation mechanism which enhances communication performance and discuss aspects such as handover, user allocation and adjusting LEDs angles to maximize throughput. Marshoud *et al.* [93] also explored NOMA scheme for Visible Light Communication. In this case, the authors provide a complete framework for indoor NOMA-VLC multi-LED DL networks. NOMA mechanism for indoor communication has also been explored in [94], where authors applied NOMA to indoor VLC channels and pointed higher performance achieved when compared to the OFDMA scheme.

Marshoud *et al.* provide a short literature review of NOMA techniques for VLC applications [95]. In this work, the authors provide (i) a discussion on OMA techniques and its limitations, (ii) a literature review on NOMA-VLC works, (iii) challenges for NOMA to be considered in commercial applications and (iv) an evaluation of NOMA-VLC performance considering error rate, the impact of CSI errors and the effect of dimming support.

A power allocation mechanism using fuzzy logic has been addressed by Tao *et al.* [96]. Authors proposal analyze user priority and assign resources based on multi-dimensional features. In this work, the authors evaluate two different scenarios: static and dynamic user priority, showing the advantages of NOMA to ensure higher throughput and fairness in resource allocation.

Note that power-domain NOMA techniques are more common in literature, and they work based on two main principles: superposition coding (SC) at the transmitter and successive interference cancellation (SIC) at the receiver. The idea behind SC is to enable a transmitter to send information to different users at the same time by encoding information relevant to each user [97]. In SIC, parallel signals that arrive are decoded successively, based on the signal strength. In SIC, the receiver handles one of the user signals and treats other signals as noise. After decoding the signal with the highest strength, this signal is subtracted from the combined signal, giving space to decode the next signal. SIC techniques work because transmitters are ordered according to their signal strengths, which makes it possible for the receiver to identify each signal. In [98], authors designed a multiple access scheme based on user locations, considering a multi-cell VLC network. By using that scheme, interference is reduced and the power allocation within each cell is optimized.

In the following, we highlight two techniques that are vastly explored along with NOMA schemes in Visible Light Communication.

**Cooperative NOMA:** Cooperative techniques in wireless networks have become very popular in the last few years, especially when considering the benefits for low-power devices and communication range, and these types of solutions are being adopted in various scenarios, from underwater cooperative communication to 5g [99]. NOMA techniques can offer advantages to the network because users with higher power (better channel conditions) can decode messages and act as relays [100].

**NOMA, MIMO and Beamforming (BF):** MIMO techniques are applied to systems because they can increase the system throughput. However, a series of challenges arise with the addition of MIMO techniques. In special, we highlight the interference between signals. Beamforming (BF) is a technique applied to increase directionality of communication [101]. This is a very important concept, especially for VLC, due to the high limitation given the directionality of LEDs. BF is offered as an enhancing mechanism for MIMO systems, because each user will be supported by one single orthogonal vector, eliminating interference from other users. In [102], VLC downlink throughput, and fairness are investigated by adding Coordinated Beamforming (CB) to it. By applying NOMA techniques to MIMO-BF, one can take the advantages of both the power domain and spatial domain, by sending signals to specific clusters. Users can be assigned to the same cluster, consequently sharing the same beamforming vector. Intra-beam and inter-beam interference are mitigated with the usage of NOMA techniques such as clustering and power allocation algorithms. In [83], authors demonstrate experimentally the application of NOMA techniques in VLC scenarios. The results showed that by applying such techniques, interference cancellation and MIMO demultiplexing were achieved for the system while offering higher throughput and fairness.

### D. Multi-hop VLC

The rapid adoption of LEDs and consequent popularization of Visible Light Communication applications has given space to many new research topics during the last decade. Multi-hop VLC is one of these topics, and it has been proposed by several works in literature as a solution to some of the main issues regarding communication. In this chapter, we give a detailed review of the state-of-the-art related to our proposal, which is also shown in a succinct way in Table IX.

Le *et al.* [103] proposed a cooperative MAC protocol for LED-ID Systems. This was one of the first research to present a model for cooperative transmission in a LED-ID VLC network. The protocol is based on the IEEE 802.15.7 MAC standard [12] and proposes multi-node cooperation in which relay nodes between the sender and receiver work cooperate when the current link fails and becomes unable to offer enough bandwidth and QoS requirements for the network. Cooperation begins when the number of packets lost reaches a pre-defined threshold, and follows the following pattern: (i) Sender and Receiver broadcast *relay request* messages, (ii) an intermediate node receives both messages, and if they are received with high quality, keep the ID addresses, (iii) the node decides to act as a relay and broadcast their information with receiver and sender nodes. The authors perform both theoretical and simulation evaluations, achieving significant enhancements and reliability to the network modeled.

Another model for VLC applications is presented in [104], where the author proposes a multi-hop solution for multiple access in indoor VLC scenarios, taking into consideration two main challenges in such scenarios: (i) LOS and (ii) directionality. Based on these challenges, the author offers two different network solutions: peer-to-peer and peer-to-host. These protocols are equipped with a simple network routing construction, in which when a device wants to communicate with another, it tries to build a route by checking its neighbors, looking for a rendezvous node to act as a relay. These protocols don't have mechanisms to assure loop freedom, route freshness, route maintenance, and metric information. We go further by proposing a new dynamic routing protocol and implementing it in a real-world scenario. In other words, we further explore the characteristics of the routing protocol in a VLC scenario.

| | Type | Platform | Application | Cooperation | Dynamic |
|---|---|---|---|---|---|
| [103] | Theoretical and Simulation | ns-2 (Simulation) | Indoor | Yes | Yes |
| [105] | Simulation | - | Underwater | No | No |
| [106] | Practical | Custom | Indoor | Yes | No |
| [107] | Practical | Arduino Uno | Indoor | Yes | No |
| [108] | Practical | Generic / Arduino | Indoor | Yes | No |
| [67] | Practical | Arduino | Indoor | Yes | No |

Table IX: State-of-the-art of multi-hop VLC research.

The idea of a multi-hop VLC network has also been considered to mitigate two common issues in this type of scenario: signal coverage and communication range. In this sense, the work of [105] analyzed the multi-hop technique using relay nodes to increase VLC connectivity. The authors first developed a coverage model for indoor VLC considering parameters such as radiant intensity, LED angle and degree of uniformity. Then, simulations were performed using the Monte-Carlo method, while taking into consideration relay selection and mobility. According to the results obtained, multi-hop communication using relay nodes improve the overall network performance. The work of [67] also evaluated the use of multi-hop communication to increase communication range, reaching a distance of up to 4 meters between transmitter and receiver, while using two intermediate nodes as relays. Authors used Optimized Link State Routing to build a static route between source and destination and did not evaluate the impact of obstacles in the communication. Authors in [107] presented The Repeater, an approach that uses a relay node to increase communication range. The authors implemented a transceiver equipped with LEDs and photodiodes, and a repeater, which is basically two sets of transceivers: one that is responsible for getting the light signal and forwarding it to the other set, which forwards the signal. The main idea of this work is to increase communication range by putting repeaters as intermediate nodes between source and destination.

Visible Light Communication has also been considered to be a complementary technology to underwater applications. However, one of the main drawbacks of optical waves in such scenarios is the high scattering of the signal, which is absorbed in a few meters [109]. Multi-hop techniques can be used to increase communication range in such scenarios, which has been shown in [106], [110]. Kim *et al.* [106] propose a multi-hop relay VLC system for maritime applications and evaluate by performing simulations under realistic sea state parameters (e.g. wind speed, average wave period) and different atmospheric turbulence conditions (weak, moderate and strong). The authors analyzed the bit error rate (BER) considering three different combining schemes: selection combining, equal gain combining and maximal ratio combining, which provided good link quality in a distance of up to 5 km, with 4 relay nodes. A more practical work was presented by Ahmad *et al.* [110], where the authors developed and demonstrated a full-duplex underwater multi-hop VLC system in a real scenario considering three different types of water (tap, canal, and sea). Authors measured the received optical power at direct link scenario and compared it to the multi-hop scenario. Authors concluded that, by adding a relay node, the frame success rate increases and the link distance can be further increased within the multi-hop scenario.

The authors behind OpenVLC 1.0 also made some experiments regarding multi-hop communication [63]. However, at the given time, OpenVLC 1.0 was still in early development, therefore the maximum throughput achieved in a direct link scenario was 1.6 kb/s. Considering a two-hop topology, the maximum throughput achieved is near 0.6 kb/s. According to the authors, one of the reasons behind the drop in data rate is the higher number of channel collisions, due to the adoption of CSMA at the MAC layer. Unfortunately, the authors did not give more information about the routing mechanism as well as the setup configuration for experiments.

Another example of a research platform used for VLC multi-hop communication is presented in [108]. The Shine is a generic Arduino-based platform that explores the coverage issue in the VLC application by using 20 LEDs as transmitters and 4 photodiodes as receivers, providing a 360° communication coverage. In terms of data rate, the Shine platform is limited to the micro-controller sampling rate, which is 1 MHz. In practical terms, the achievable data rate is 1 Kbps. The authors explore the exposure and directionality of LEDs to implement a multi-hop scenario in which mechanisms such as packet forwarding and neighbor discovery are implemented. The algorithm has been built in C++ on top of the MAC layer.

## V. VLC Applications

VLC presents a wide range of applications, from high-speed Internet access through LED light bulbs to interplanetary communication. VLC applications are very diverse and bring a new perspective to what is considered ubiquitous and pervasive computing. In this section, we will discuss the potentialities of Visible Light Communication, focusing on the following applications: Indoor VLC, localization systems, underwater communication, vehicular communication.

During the past years, several surveys dedicated their work to study applications in an in-depth perspective. In [15], authors explore indoor Visible Light Communication applications, as well as its main challenges. Authors in [111] explore the literature regarding the adoption of VLC in vehicular communication. Positioning and localization systems are carefully analyzed in [112], [113]. The use of visible light communication in underwater scenarios has been explored in [114], [115].

### A. VLC Indoor Systems

Most homes and corporate buildings are now equipped with LED bulbs, as discussed in Section II. Illumination is the main function of LED light bulbs, which limits the way we use them in communication. There are a number of limitations and regulations for VLC systems to meet both lighting and communication requirements [116]. Therefore, communication channels and the behavior of indoor light waves must be carefully designed to follow existing regulations properly. In this sense, Lee *et al.* analyzed the light dispersion characteristics in indoor environments, considering LED spectral reflectance in the visible spectrum [117]. Works involving indoor VLC systems are common in literature and contemplate other applications such as localization systems, which will be further discussed separately.

In 2003, Komine *et al.* presented a work that studied the possibilities of using LED bulbs in VLC systems [118]. The authors highlight all the advantages of LED light bulbs, which until then were novel. In addition, they proposed

| Work | Data rate | Distance | Transmitter | Receiver | Modulation | Observations |
|------|-----------|----------|-------------|----------|------------|--------------|
| Komine *et al.* [118] | 200 Mbps without tracking 10 Gbps with tracking | 1.65 m | White LED | Photodiode | OOK | |
| Grubor *et al.* [119] | 200 Mbps | 1.65 m | White LED (phosphor-coated) | Photodiode | M-PAM, M-QAM | |
| Dambul *et al.* [120] | 2 Mbps/channel | 2 m | White LED (phosphor-coated) | Photodiode | 2x2 MIMO - NRZ OOK | |
| Azhar *et al.* [121] | 220 Mbps | 1 m | White LED (phosphor-coated) | Photodiode | 2x1 MIMO - OFDM | |
| Azhar *et al.* [59] | 1.1 Gbps | 1 m | White LED (phosphor-coated) | Photodiode | 4x9 MIMO - OFDM | |
| Burton *et al.* [122] | 50 Mbps | 2 m | White LED (phosphor-coated) | Photodiode | 4x4 MIMO - NRZ OOK | |
| Li *et al.* [123] | 10 Kbps | 2.4 m | ViReader (LED + Photodiode) | ViTag (Photodiode + LCD) | OOK | Full-duplex based on a reflector |
| Tian *et al.* [124] | 1.6 Kbps | 1.3 m | LED (CREE CXA2520) | Photodiode (OPT101) | OPPM | Communication with lights off |

Table X: Summary of works related to indoor VLC in literature.

a VLC system that uses these LED bulbs to transmit data in an indoor environment using On-Off Keying modulation (OOK). In their experiment, four devices equipped with 3600 LEDs (60x60) were installed in a room of dimensions 5.0 m x 5.0 m x 3.0 m. By the end of the work, the authors discussed all requirements the proposed system should have to satisfy to act both illumination source and communication system. Authors also discussed the influence of light reflected on the walls and inter-symbol interference. The authors showed that it is possible to establish wireless communications using visible light at very high data rates, reaching 200 Mbps considering a field of view between 40 and 50 degrees. In addition, they showed that, by using tracking techniques, it is possible to drastically reduce the field of view, reaching values close to 5 degrees. In this case, the VLC data rate is up to 10 Gbps.

Later in 2007, Grunor *et al.* —based on Komine *et al.*'s work— conducted a series of experiments considering commercial LED bulbs (blue LED with yellow phosphor). Their theoretical analysis raised the potentials for high-speed transmissions in indoor environments using two different modulation types: baseband and DMT. Grunor *et al.* reached up to 200 Mbps [119], using off-the-shelf LED light bulbs.

The existing illumination infrastructures in homes and corporate buildings present LED light bulbs equipped with multiple LEDs, which offers the possibility of applying MIMO techniques. In this sense, many papers focus on indoor systems with MIMO. Dambul *et al.* carried out research using image receivers to extract the light information from the transmitter, in this case, a 2x2 array of LEDs [120]. In this work, the modulation used is NRZ OOK, and the proposed channel speed reached 2 Mbps. Azhar *et al.* also proposed a system using image sensors as a receiver, although they use a different modulation. The 2x9 MIMO-OFDM system achieved a speed of 220 Mbps, with the receiver at a distance of 100 cm from transmitters [121]. Two years later, the same author presented a similar system (4x9 MIMO-OFDM), optimizing the modulation. In this case, the VLC system was able to communicate at Gbps range (for example, 1.1 Gbps at 1 m distance [59]). In [122], authors perform an experimental demonstration of MIMO in an indoor environment, reaching 50 Mbps over a distance of 2 m.

An important issue that must be addressed in indoor environments is the need for continuous data transmission with dimming control. In other words, in indoor scenarios, data transmission even when the lights are dimmed or turned off by the users. On bright days, for example, lights are usually turned off. Another example is at night, before bedtime, when the light is not needed, but often there is a need for Internet connection. Depending on the point of view, such situations may invalidate works that consider Visible Light Communication that require the lights to be on.

With the possibility of using VLC on mobile devices, another problem arises: the use of LEDs for VLC systems in smartphones can be costly in terms of energy [123]. Considering these problems, Tian *et al.* proposed a primitive

for VLC systems where the exchange of data through light occurs even if the light bulb remains "turned off", or with low intensity [125]. According to the authors, the main idea of the work is to encode the data into very short pulses of light at a very high frequency. This way, the light wave is imperceptible to human eyes but it can still be detected by photodiodes. Among the contributions of this work, we highlight the new paradigm in which there is Visible Light Communication even though the light bulb is apparently switched off and the energy consumption of the devices is reduced, allowing new applications for VLC, as indoor communication using smartphones. A more recent work presents a significant improvement when compared to the author's previous work. While the former system was able to communicate at only a 10 cm distance, the newer system can communicate at a 1.3 m distance, at a data rate of 1.6 Kbps [124].

Considering the inevitable adoption of LED bulbs in the world, and the infrastructure that this type of light bulb offers for VLC systems, the future of indoor VLC is very promising. The challenges are still diverse, ranging from oscillations in light to noise and interference caused by natural light. Still, the continuous research advance in the area is likely to solve those problems and make it feasible to provide Internet access through an LED light bulb.

### B. Transport and vehicular systems

Industry segments that are rapidly adopting LED bulbs are potential places for using VLC. For example, LEDs are widely used in automobiles. The use of Visible Light Communication in vehicular systems can be very advantageous. The cost associated with implementing VLC systems where infrastructure already exists is relatively low, and less complex when compared to RF systems. In this sense, roads offer a rich environment in light sources, considering traffic lights, light poles, and car headlights. In addition, VLC systems operate based on LOS (Line of Sight), in other words, the receiver must be in the field of view of the light emitted by the transmitter, which can easily be adapted for vehicular systems. Such communication capability is part of the solutions involving Intelligent Transport Systems (ITS) [126].

| Work | Data rate | Distance | Transmitter | Receiver | Modulation | Observations |
|------|-----------|----------|-------------|----------|------------|--------------|
| Liu *et al.* [127] | 100 Kbps | 1.5 m | White LED | Photodiode | OOK | Prototype experiments + simulation |
| Akanegawa *et al.* [128] | 207 Kbps - 3.56 Mbps | 75 m | LED traffic light | Photodiode | SC-BPSK, OOK | |
| Kim *et al.* [129] | - | 20 m | LED traffic light | Photodiode | OOK | |
| Takai *et al.* [130] | 10 Mbps | 20 m | LED | CMOS Image sensor | - | |
| Luo *et al.* [131] | 2 Mbps | 20 m | Headlamp LED | Photodiode | OOK | Authors considered both LOS and NLOS V2V communication |
| Okada *et al.* [132] | Up to 2 Mbps | 60 m | Array of LEDs | Photodiode | QPSK, 16QAM | |

Table XI: Summary of Vehicle communication related works.

In general, a Vehicle Visible Light Communication (V2LC) consists of one or more mobile nodes, represented by vehicles, and fixed structures, such as traffic and street lights. Both the type of nodes can be equipped with transmitters and receivers, which work simultaneously, thus building a dynamic communication network, capable of collecting and sending information collected by the different sensors coupled in the vehicles and in surroundings [127].

In a Vehicle Visible Light communication system developed in 2001, the authors developed a traffic information system based on LED bulbs [128]. In addition, instead of using the infrared spectrum to transmit information, the
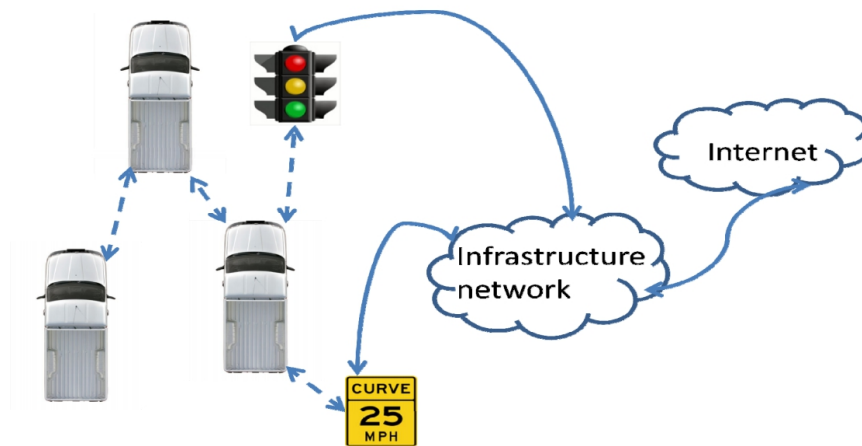
Figure 13: V2LC overview [127].

authors innovated by choosing to use the visible light emitted by the LEDs, in order to collect information such as traffic control, number, and location of traffic lights, as well as, movements toward LED bulbs.

The wave propagation channel plays a very important role in the quality of communication, especially in a dynamic environment such as in-vehicle communications. Cheng *et al.* developed a work comparing light and radio waves, as well as their capacities and limitations. The first aspect analyzed by the author is the pattern of radiation and path loss. According to the author, some of the advantages of the optical channel over RF are the high transfer rate, low cost, and spatial efficiency, a consequence of the devices acting in LOS (line of sight) [133]. Modeling of the channel in Visible Light Communication is important at this moment since those that deal with the radio channel are already well known in the literature.

One of the applications of VLC in vehicular networks is the direct communication between cars, known as Car-to-Car (C2C), or Vehicle-to-Vehicle (V2V) communication. The headlamp of a car may act as a transmitter, while photodiodes can be equipped and play the role of receivers in bidirectional communications, as shown in Figure 13. The viability of VLC in this type of scenario has already been confirmed in some works present in the literature [129]. In 2013, Takai *et al.* developed a VLC system in a V2V scenario in which an image sensor is used to capture light waves, reaching speeds up to 20 Mbps/pixel [134]. The performance for different distances and light conditions was also measured and presented, in addition to limitations involving noise from peripheral circuits. The same authors presented a more robust system a year later, which was resistant to noise and interference [130]. In this work, one of the main aspects that guaranteed performance improvement was the use of a flag image, where objects of low light intensity are eliminated, while high-intensity objects such as LEDs are captured, eliminating a large part of the noise and unnecessary objects. In 2014, a mathematical model for Visible Light Communication was presented in a V2V scenario, in which the performance of the system was measured for different configurations [131]. In order to perform the experiments, the author used a beam model of a market headlamp, and both LOS and NLOS links were incorporated into the model.

Liu *et al.* identified and classified the types of services involving V2LC in five different categories, in addition

to developing a prototype based on three principles: (i) use of accessible devices for hardware composition, (ii) use of analog techniques to increase the resistance of the prototype to the noise, and (iii) the provision of a flexible programming environment for the implementation of algorithms. The authors experimented with the programming environment proposed in each proposed category and showed that V2LC is feasible in vehicular environments. In addition, they showed, through a series of simulations, that V2LC meets the latency and distance requirements of high-density vehicle scenarios. The only previous experimental work with similar focus was carried out in 2009, where the authors proposed a unidirectional V2LC system between traffic lights and vehicles [132].

Yoo *et al.* proposed and performed a practical demonstration of a vehicle system using VLC in 2015. Authors used car headlights as communication devices in their experiments in a vehicle-to-vehicle environment (V2V). More precisely, authors employed a commercial off-the-shelf LED headlamp and a driver module. Therefore, it is already within the necessary regulations in terms of radiation and distribution of light, as defined by the law. In order to guarantee control of the emitted light intensity and data transmission, the authors used the Inverse M-ary Pulse Position Modulation (I-M-PPM). The receiver consists of a photodiode, a lens, and a color filter. One of the challenges found by the authors was the interference caused by other light sources, especially during the day, with sunlight. The sunlight can be distributed in all regions of visible spectrum, infrared and ultraviolet light. This makes it difficult to filter the signals. The color filter was used in order to reduce interference. In their experiments, they achieved rates of up to 10 Kbps, at a distance of over 30 meters, during the day.

As it can be seen, Vehicular environments are one of the areas that benefit from the popularization of Visible Light Communication. In fact, the vehicular environment offers a very rich ecosystem of components and light sources to be explored, varying from vehicle-to-vehicle communication to traffic lights-to-vehicle communication. However, this application has many drawbacks, considering the usage of LED lights in outdoor environments and multiple sources of light, which increases interference.

### C. Indoor Positioning Systems

To perform a high precision positioning using VLC, a receiver must pick up the signals from the LEDs in a room and calculate the distance from them, using various algorithms to establish the exact position of the receiver. One of these techniques is based on RSS (received signal strength), which is commonly used in radio frequency systems. However, the greater the distance between the transmitters and the receiver, the weaker the signal, and obstacles may interfere with RSS as they block or reflect the waves, thus limiting the accuracy of this method. Another widely used method is performed by calculating the Time of Arrival (TOA). However, this technique requires the transmission of rigidly synchronized signals between transmitter and receiver, which may require more expensive features. Finally, there is a method which considers the Angle of Arrival (AOA). This technique is not common in radio frequency systems since it requires Line of Sight (LOS). In VLC systems, on the other hand, LOS is required for communication so AOA methods are also feasible.

The first indoor, high-precision, practical tracking system was introduced in 2014 [135]. Driven by factors such as a large amount of indoor LED bulbs and the new paradigm based on lighting/communication offered by VLC, Liqun Li *et al.* created the Epsilon system, which provides a high-precision, low-cost and easy-to-implement localization

service. The localization algorithm used by the system is trilateration, where the position of the receiver is calculated from the received signal strength (RSS) measured between multiple transmitters. Epsilon is able to calculate a location with an error of 0.4 m. Such small errors are difficult to achieve using radio frequency-based localization systems.

Another example of an indoor localization system is the Luxapose, presented in 2014 [136]. While the Epsilon system uses photodiodes as receivers, Luxapose uses image sensors as receivers, such as the camera of a smartphone. The system consists of three main components: light signals sent by LEDs using On-Off Keying modulation, smartphones and a server in the cloud, as can be seen in Figure 14. The light signal sent by each LED contains its coordinate identity. Based on the angle-of-arrival (AoA) of the transmitted signal and smartphone camera orientation, triangulation is done in order to locate the receiver. The server located in the cloud is used to aid in image processing and orientation in the coordinate system. Luxapose can perform localization with an error rate of 0.1 m, while also providing the orientation of the device.
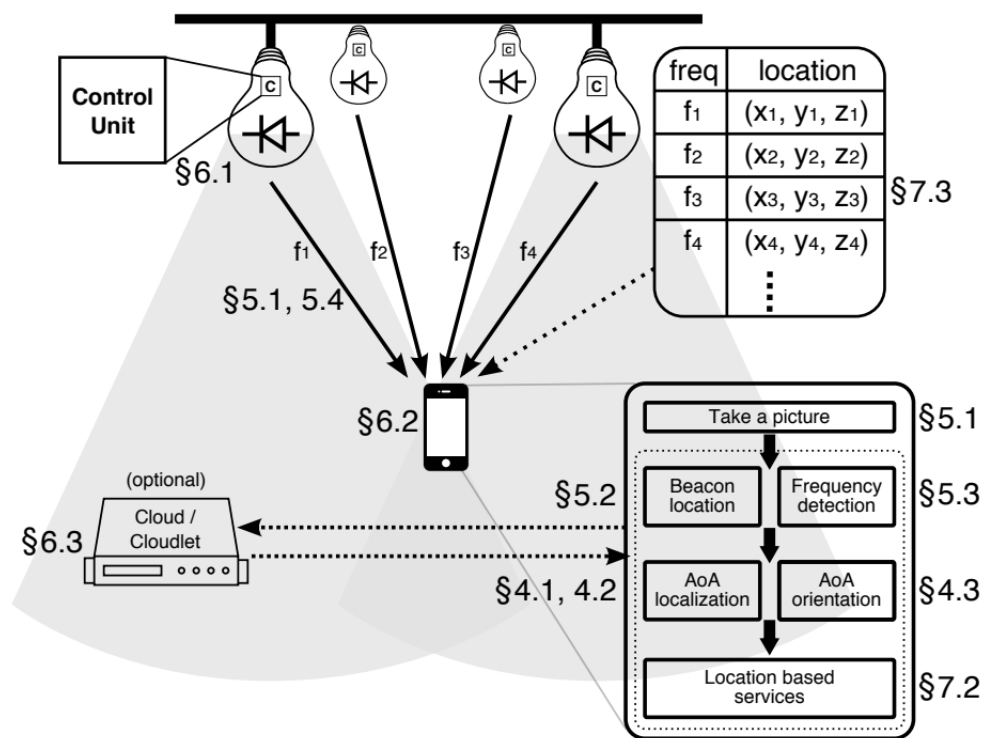


Figure 14: Luxapose's architecture. [136].

Hybrid positioning systems take advantages of VLC and former approaches as Bluetooth or RFID. For example, Prince *et al.* proposed a localization algorithm where both RSS (Received Signal Strength) and AoA (Angle-of-Arrival) are used to determine the position of the receiver using hybrid VLC positioning [137]. In 2014, Yang *et al.* modeled the communication channel of a VLC system with multiple receivers and transmitters and the proposed algorithm that also uses RSS and AoA to measure the position of the receiver with high precision [138].

VLC-based positioning is undoubtedly a very important application that will be part of the technologies in the

near future. They provide a significantly more accurate localization, compared to existing approaches. The industry has also shown interest in VLC localization applications. For example, ByteLight[13] is a commercial VLC positioning system, which shows how the industry is currently exploring VLC. In terms of indoor wireless networks, Liu *et al.* present some performance metrics that are important benchmarks for this type of communication. Taking into account the systems discussed in this Section, VLC-based localization can provide great improvements in metrics such as precision and accuracy, while there are still open issues in addressing robustness, scalability, and complexity.

### D. Underwater Communication

Underwater communications are employed in a wide range of applications, from oil and gas exploration to remotely operated vehicles (ROVs) and communication between divers [139].

Water presents many challenges when compared to traditional wired and wireless communications through the atmosphere. For example, in an underwater environment, radio frequency presents a quick fading and is not suitable for almost all underwater applications. Underwater communication requires sophisticated communication devices to achieve relatively low transmission rates, even over short distances.

Researchers have studied the feasibility of acoustic and optical communication in an underwater environment. Some recent work also considers electromagnetic to perform underwater communication. Acoustic communication is the most common underwater communication technology. When using acoustic communications, devices can transmit at longer ranges compared to optical communications [140]. However, acoustic medium presents limited propagation, which incurs limited bandwidth and high energy consumption for transmissions and reception. Moreover, acoustic communication is prone to noise interference and is also impacted by water temperature, especially near the surface. In turn, the use of electromagnetic waves in radio frequency is naturally limited by the properties of the medium. Frequencies used in common radio frequency applications (2.4 GHz ISM) have limited wavelengths and speeds due to high attenuation in water, especially in salt water. On the other hand, optical communications can provide higher bandwidth with lower energy consumption, but suffer from highly limited communication range (i.e., lesser than 50m) [140].

| Parameters | Acoustic | Radiofrequency | Optical |
|---|---|---|---|
| Speed (m/s) | 1500 | 2.255 x 10^8 | 2.255 x 10^8 |
| Data Rate | ~ Kbps | ~ Mbps | ~ Gbps |
| Distance | ~ km | ~ 10m | ~ 10m - 100m |
| Frequency | kHz | MHz | MHz |
| Transmission power | Dozens of Watts | Dozens of Watts | Few Watts |
| Performance Parameters | Pressure | Conductivity | Absorption, turbidity |

Table XII: Comparison between types of underwater communications, adapted from [115].

Table XII gives a brief comparison of the types of communication cited above. The use of optical communication offers high data rate underwater communication. Light waves frequency is up to 1000 times greater than radio

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[13]ByteLight $^{TM}$ Services: Indoor Positioning - http://hydrel.acuitybrands.com/sitecore/content/acuitybrandscorporate/home/solutions/services/bytelight-services-indoor-positioning, 2017.

frequency. As a consequence result, optical communication can reach, theoretically, up to a Gbps. However, optical signals are also absorbed by water, and easily spread due to suspended particles and planktons [141]. Nevertheless, different light waves frequencies have different behavior in water. For instance, red light spectrum region presents greater absorption in water, while the violet region of light spectrum presents lower absorption. Therefore, the environment and the application become important factors when choosing the wavelength of the system [15].

In general, not only the light frequency but a number of factors must be taken into account to deploy an underwater VLC system correctly. First, absorption and scattering are phenomena that incur on optical intensity loss and direction change in water. When the water is illuminated with a beam of light, a fraction of the light is absorbed, while another fraction is scattered, leaving the rest of the beam of light unaffected. The absorption values change according to the aquatic environment in which the light is emitted. Clear ocean imposes less absorption than a turbid polluted river. At sea, inorganic materials (salts and water molecules) and organic (phytoplankton) also contribute to increased absorption and scattering of light. Finally, water turbulence also interferes with light waves due to the variation in the refraction of waves caused by changes in water density and salinity [142].

VLC systems depend on line-of-sight (LOS). In other words, the receiver and transmitter must be in the field of view of each other. In this sense, devices alignment is necessary for underwater light-based communication. Clearly, the line-of-sight (LOS) can be narrow due to optical beam constraints and the interference of ocean currents. As a consequence, additional approaches must be performed to overcome such issue, as the use of intelligent transmitters and receivers which are able to align and adjust the field of view according to parameters such as water quality [143].

The most widely used modulation algorithm in underwater VLC is based on intensity modulation (IM), where data is digitally modulated by changing the light intensity. This type of modulation, coupled with the direct detection scheme, is simple and inexpensive. Techniques such as On-Off Keying, Pulse Position modulation are very common in underwater systems. Oubei *et al.* developed a system capable of transmitting data in underwater environments using the OOK-NRZ modulation. The system operates satisfactorily at distances of up to 7 m between the receiver and the transmitter and reaches speeds up to 2.3 Gbps [144]. MIMO techniques associated with OOK modulation were also presented in the literature with the aim of reducing the effects of turbulence [145]. Other types of modulation like OFDM are also used in aquatic applications [146].

Finally, advantages such as higher data rate and low power consumption, when compared to other methods, make Visible Light Communication one of the best options for underwater environments. In addition, hybrid systems that act with both acoustic and optical communication are able to send data at higher speeds and change the mode of operation according to the properties of the water and can be used in marine robots, for example. As in other VLC applications, the research community is actively addressing the challenges of underwater VLC systems.

## VI. Challenges

In this section, we present and discuss the main challenges of VLC communications, from light-specific issues (flickering, dimming, line of sight, and interference) to wireless communication-related challenges that must be addressed to achieve a good performance, such as uplink and mobility. We also discuss existing proposals to overcome such challenges and open issues.

## A. Line of Sight (LOS)

In indoor VLC based systems, it is assumed that the user is within the line of sight of the light source. In many indoor scenarios, illumination is done deliberately by reflection or refraction and are covered by lamp shades, covers and are turned towards walls or other objects. Such lighting settings that do not allow a direct view of the light source from indoor locations can have an impact on the communication and user experience.

Most of the applications involving indoor VLC systems propose a direct LOS based mechanism, as shown in Figure 15a. The receiver must be within the line of sight of the transmitter. The main advantage offered by this mechanism is the reception of a stronger signal [71], [118], [147]. Other configurations found in the literature involve non-direct LOS mechanisms (Figure 15b) and diffuse light (Figure 15c). However, these configurations have limitations in terms of data rate, due to signal loss. The main difference between the LOS configuration and non-LOS configuration is the intensity of the received light, which is greatly impacted by the angle and direction of the transmitter, where a wider angle leads to a weaker signal, while a narrower angle leads to a stronger signal.



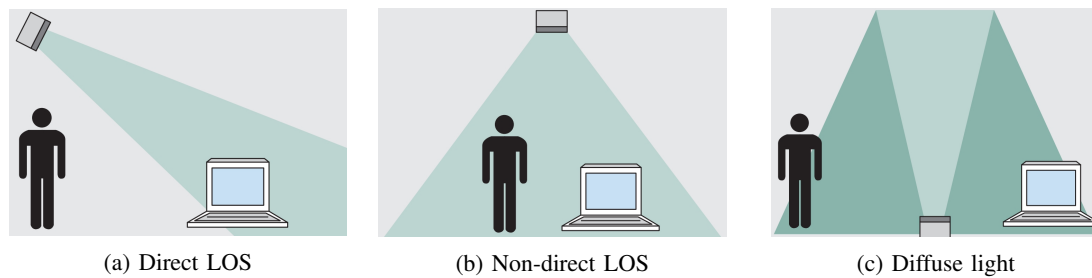(a) Direct LOS        (b) Non-direct LOS        (c) Diffuse light

Figure 15: Visible Light Communication channel and light propagation, adapted from [147].

Users may move through an environment while using VLC applications. When the receiver's device is a mobile device such as a smartphone, the user can constantly change direction and orientation. Thus, there is a need to develop techniques for high-speed communication even if the receiver is not in direct view of the transmitter. Presence of shadows can drastically reduce the light that reaches the receiver. In this case, the light reflected by obstacles could be used so that the system reacts efficiently during light blocking moments. In practical terms, commercial systems such as Li-Fi already have mechanisms to adapt to shadow and other obstacles.

## B. Flickering

Flickering is a major challenge for VLC and can be defined as the fluctuation in the brightness of the light perceptible by humans. Usually, this problem is addressed in work that implements indoor VLC systems, such as an office or supermarket. Depending on the modulation mechanism of the light waves, there may be oscillations perceptible by the human eye, which may cause discomfort and health risks [148]. Thus, there is a need to modulate the waves so that the smallest of their frequencies is greater than the threshold at which the human being perceives them, which is around 3 KHz. There is a duality between low-frequency communications that result in lower data rates and the flickering caused by them [36].

| Modulation | Intra-frame flicker | Inter-frame flicker |
|---|---|---|
| OOK | RLL (Run-length limited) | Idle pattern |
| VPPM | No | Idle pattern |
| CSK | Same power for different sources | Idle pattern |

Table XIII: Types of modulation and its flickering control methods.

IEEE 802.15.7 standard for short-range VLC defines some methods to mitigate the flickering problem. Flickering can be categorized into intra-frame and inter-frame flickering [12]. The intra-frame flickering is the brightness oscillation detected between frames, whereas inter-frame flickering is the oscillation between adjacent transmissions. In the case of intra-frame flicker, the solution employs certain techniques for each type of modulation presented XIII. In On-Off Keying modulation, for example, flicker can be avoided by applying a run length limiting coding to it. A practical example of such scenario can be found on the OpenVLC platform [63]. The platform uses On-Off Keying method with Manchester encoding in order to modulate data signals. This solution solves the problem of intra-frame flickering because in this technique there are always symbols 0 and 1 to represent a signal, and in OOK the signals are represented by the LED on or off. VPPM inherently does not cause any inter-frame flicker. Finally, CSK may cause flickering if different power is applied to the multiple light sources. In the case of inter-frame flickering, the oscillation occurs between the idle time of the LED and the time to send information [149]. To mitigate this type of oscillation, the IEEE 802.15.7 standard proposes the following: during the time when the LED is idle, the brightness is maintained at a frequency above that detected by humans, known as idle pattern, as seen in Table XIII.

*C. Noise and interference*

In a Wi-Fi network, devices that transmit on the same frequency can interfere with each other. When light is used as a communication medium, natural light becomes a source of interference in communication, degrading VLC, especially in the case of outdoor applications. In addition to natural light, artificial lights also interfere with communication, and may even saturate the receiver. Another factor that causes interference at the receiver is the multi-path problem. Different from a wired communication, where the propagation of the signal is mainly restricted to the wire, in Visible Light Communication the signal can propagate in the environment in the direction of the LED lamps, but also including refraction and reflection, reaching the receiver more than once.

VLC systems that work in environments with other light sources (LED, incandescent, fluorescent) used for illumination will be under the influence of noise. Moreira *et al.* [150], characterize the interference produced by artificial lights and propose a model to describe the light interference. The authors identified three classes of light bulbs that offer interference: incandescent, and two types of fluorescent lamps [150]. Despite being a relatively old work (late 90's), the types of lamps studied are still in use nowadays.

The solutions to mitigate interference and noise includes the use of optical filters. Through the use of filters, noises from natural sources of light can be removed [150]. This is a common approach, which can be found in several works where VLC systems are implemented [151]. Signal amplifiers were also used to mitigate noise [65].

We can also choose particular types of receivers to avoid specific types of noise and interference. Photodiodes tend to be extremely sensitive because, in addition to capturing light in the visible spectrum, they also capture infrared and ultraviolet waves. On the other hand, when using an LED as a receiver, the situation changes. As discussed in section III, LEDs are also sensors, however, they only pick up waves close to the ones they transmit, serving, for example, as a filter for natural lights. In practice, a very interesting example of the difference between the photodiode and LED can be found in [63], where they evaluated in indoor and outdoor environments, using both the photodiode and LED as receivers. According to the authors, in outdoor environments, the photodiode became saturated rapidly, while the LED could successfully receive the data.

In general, interference and noise are unavoidable for VLC systems, due to natural and artificial light.

### D. Uplink

A useful communication system built with VLC must allow uplink and downlink. LED light bulbs can be used for both, as a VLC transmitter and as a light source. In the receiver, a simple photodiode can be used to receive modulated light, which will be further decoded. In this sense, the downlink, i.e. the transmission from a LED light to devices, is straightforward. However, sending data from devices to a LED light bulb is more challenging.

In fact, many works in the area focus on unidirectional communications [152], [153]. The uplink becomes a problem when one has, for example, a broadcast topology with several receptor cells. VLC applications for smartphones and other low-power devices also present many issues related to sending information back to the LED light bulb transmitters. In an indoor environment, the use of visible light for uplink is very challenging and may not be appropriate. Adding multiple light sources on mobile devices, most of them in random opposite directions may cause discomfort to human eyes. Nevertheless, visible light is one of the approaches to deal with the uplink in a VLC architecture [154]. In addition, technologies such as radio frequency [6], infrared [147] and retro-reflexive transceivers [155] can be used to establish the uplink.

The use of radio frequency as an alternative to VLC uplink offers some advantages. For example, we do not need visible light transmitters on personal devices. However, RF transceivers will have to be coupled in both VLC devices, the transmitter, and receiver. This approach may incur a higher communication system cost. In addition, in some environments, the use of RF is not the best solution if the spectrum is limited.

A number of research papers consider the use of Visible Light Communication for both downlink and uplink. To remove the effect of signal reflection interference, researchers propose the use of techniques such as Time-division-duplex(TDD) [9]. TDD decreases the data rate since slots of specific duration are allocated both for downlink and uplink. However, high-level modulation mechanisms, such as OFDM [156], can achieve better performance.

Researchers have also used the ultraviolet (UV) spectrum for both downlink and uplink channel [157]. UV causes little interference with visible light and does not cause discomfort to human eyes. However, these work focus on short distance communication, where there is NLOS (Non-Line of Sight) [158]. Considering that most VLC systems require LOS, UV-based systems can be more robust because it works in NLOS scenarios. UV communication can be used to provide links between wireless nodes, which includes unattended ground sensors, for example, [159]. The UV NLOS link is possible because of two particular phenomena: first, atmospheric gases absorb most of the

waves between 200 nm and 280 nm, which is part of the UV spectrum. Therefore, near the ground, the radiation in this wavelength is very low, generating a "solar-blind" region, which leads to the second phenomena: in this region, UV light is heavily scattered by the gases in the atmosphere [160]. The use of infrared (IR) spectrum waves is also interesting, as they do not interfere with VLC [9]. Moreover, IR devices are cheap and accessible. Perez-Jimenez *et al.* conducted a practical work in which VLC uplink occurred through IR during a flight. Authors were able to achieve up to 512 kpbs data date.

Finally, Komine *et al.* presented an indoor VLC system using white LED bulbs. The novelty of their work consists of a new technique for uplink: the use of a surface with high reflection characteristics to modulate the information and return it to the transmitter [155]. Another scenario in which reflective surfaces are used is Wang *et al.* approach [161], where natural light is used as the main source, and the reflected light from mainstream objects is received by strategically located photodiodes. Thus, depending on the object type of surface (from a mirror to regular cloth), and consequently, on the light reflected by it, the receiver can detect and identify it [161]. One of the great advantages of such a system is the sustainability because components can be reduced to a simple photodiode. However, the number of factors that influence the downlink and uplink channel increases considerably. Aspects such as surface reflectance and bad weather can affect the performance, and cannot be controlled by the system itself.

### E. Dimming

When using LED lamps in a VLC system, the communication signal power is directly related to the light intensity. Thus, theoretically, the lower the light intensity, the smaller the communication range and the data communication rate [162]. Dimming is the control of the perceived light source brightness, according to the requirements of the user. In many places, dimming is an essential feature, creating benefits such as comfortable environments and energy saving.

VLC systems must support dimming. IEEE 802.15.7 standard defines a series of mechanisms to tailor the modulations in order to enable dimming control. All modulations presented in Section IV support dimming. For instance, according to the IEEE standard, On-Off Keying modulation is always sent with a symmetric symbol due to the Manchester encoding. In that case, to provide dimming control, a compensation time must be put in the frames in order to adjust the average light intensity. This is done as follows: a frame is split into sub-frames, where offset time is inserted along with re-synchronization fields, to maintain the integrity of frames.

Variable Pulse Position Modulation is also adapted for dimming control, as well as providing protection against intra-frame flickering. VPPM modulation is the combination of two modulations: Pulse Position Modulation (PPM) and Pulse Width Modulation (PWM) [163]. In this case, dimming control is achieved by changing the duty cycle, as discussed in Section IV. Therefore, as shown in Figure 16, the position of the pulse determines the bit, and the width determines the duty cycle required for dimming control.

Finally, Color Shift Keying modulation (CSK) is a very particular type of modulation and can be achieved only by RGB LEDs. The dimming control is achieved by manipulating the current through the LEDs [12]. However,
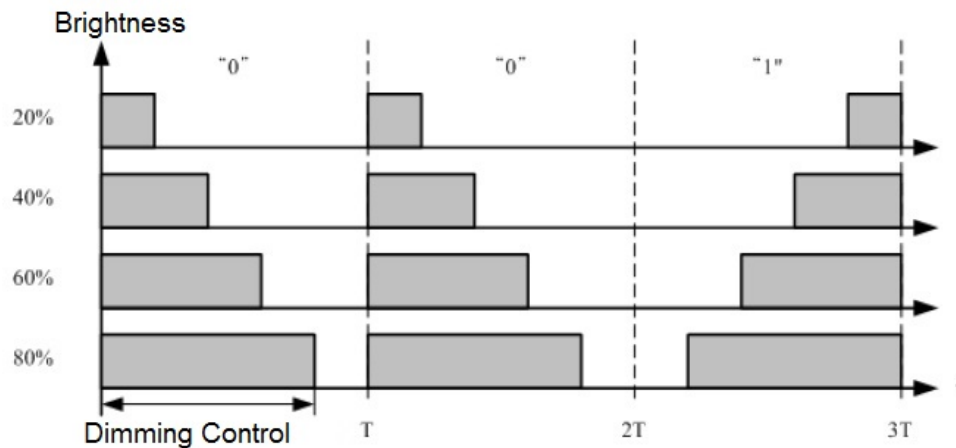
Figure 16: VPPM with dimming control [12].

the color may change due to this difference in current, which is an issue because CSK relies on color in order to modulate signals [149].

### F. Mobility

Just like in Wi-Fi, some VLC-based systems must support mobile devices. Therefore, for Visible Light Communication to become a ubiquitous technology, mechanisms are required to ensure a high-speed connection in an uninterrupted manner, within the coverage area of the system. In other words, the receiver must be able to detect light signals from the transmitter anywhere in a room, for example, and for that, a larger emission angle is needed at the transmitter and a higher FOV at the receiver, which may cause greater interference by the refracted waves [15].

Visible light Communication differs significantly from radiofrequency in terms of signal propagation, because it relies heavily on LOS, in addition to the orientation of the receiver relative to the transmitter. Signal-to-Noise Ratio (SNR) of the light can vary greatly when the receiver moves, even within the light coverage area [164].

Burton *et al.* [165] presented an optical and geometric design evaluation of an internal VLC system using white LEDs that enables full mobility within the transmitter's coverage. For this, an angular diversity receiver (ADR) is used, in which photodiodes are coupled geometrically, in order to obtain a spherical coverage of the environment. In addition, the receiver implements selective combination (SC), so the receiver with the highest signal is used for signal detection. In a closed environment of 5 m$^2$, the system was able to offer complete mobility and has a satisfactory operation at speeds up to 55 Mbps.

Handover techniques are important to support user mobility without information loss. LiFi-based systems allow multiple access points to form a network with the integrated handover. In addition, LiFi has a dynamic handover mechanism for hybrid (Wi-Fi/Lifi) systems, which can reduce the number of handovers in the network and can reach higher speeds [48]. Vehicular systems are also strongly based on handover mechanisms since most nodes are constantly moving. Zhu *et al.* [45] simulated the handover RSP method in a vehicular network, where communication between moving vehicles and LED traffic lights occurs.

For VLC systems to be commercially successful, particularly in the consumer market, the challenges related to signal coverage and mobility need to be addressed.

## VII. VLC Research Platforms

Over the past years, academic researchers have made an effort to develop open-source general platforms to popularize VLC studies. These platforms differ in terms of hardware and software design, as well as in terms of capabilities and features they offer, as summarized in Table XIV. This table summarizes some of the main elements of these platforms, such as hardware and software components, as long as well-known challenges of the area, which includes operational range and data rate. Most of the platforms present low data rates when compared to the PHY I specification (11.67 kbps), which is the lowest data rate presented in the IEEE 802.15.7 standard. The only exception is the most recent work developed by Yin *et al.*, which reaches a data rate of 100 kbps.

In general, the purpose of such platforms is to promote studies and researches in the field. Therefore many of them are open-source initiatives, which are being constantly updated to improve technical elements and add new features [67], [80]. In other words, these platforms are a great opportunity to study and develop new approaches for real-world Visible Light Communication systems.

As previously stated, a VLC system works by modulating signals using the light as a medium. In general, we can divide the hardware part of any VLC system into three modules: the baseband generator, responsible for converting information into modulated signals, the driver circuitry, which controls the current flow and transforms the modulated signals into electrical fluctuations and the light source/receiver, which transfer the electrical current to visible light waves [166]. Microcontrollers (MCUs) are widely used in VLC general platforms, but other components such as FPGA and even single-board computers are also used.

| | Dietz | Wang | Klaver | Hewage | Schmid | Yin | Wu | Tian |
|---|---|---|---|---|---|---|---|---|
| Year | 2003 | 2014 | 2015 | 2016 | 2016 | 2018 | 2017 | 2016 |
| Platform name | iDropper | OpenVLC | Shine | modBulb | Enlighting | PurpleVLC | SmartVLC | DarkLight |
| Hardware | MCU (PIC16LF628) | BeagleBone Black + OpenVLC Cape | Arduino (ATMega 328p) | FPGA (AGLN250) MCU (CC3200) | Arduino + Atheros AR9331 | BeagleBone Black | BeagleBone Black | FPGA |
| Software | Firmware code | Kernel module | Firmware code | Firmware code | Firmware code | Kernel module + PRUs | Kernel module | Firmware code |
| Range | Few centimeters | ~6~m | ~1~m | 1~m | 5~m | 6~m | 3.6~m | 1.3~m |
| Data rate | 250~bps | 12~Kbps | 1~Kbps | 1~mbps | 600~bps | 100~Kbps | 100~Kbps | 1.6~Kbps |
| Features | Bidirectional LED-to-LED | Bidirectional Multiple transceivers TCP/IP integration | Bidirectional Multi-hop | Hybrid Architecture (FPGA + MCU) | Localization system | Full-duplex Channel Isolation | Dimming control | Ambient Light Adaptation Ultra-short light pulses |

Table XIV: State-of-the-art of VLC platform researches.

The remainder of this section covers the main aspects of each platform presented in Table XIV. We cover from hardware components, such as electronic devices, microcontrollers and types of transmitters and receivers to software components, where we discuss the main approaches regarding the development of the driver, Physical and MAC layers. It is important to note that many VLC platforms are developed for more specific challenges, such as the DarkLight [124], which was developed to explore the possibility of LEDs communicating while being apparently off.

## A. iDropper

The iDropper [49] was presented in the early 2000's, and is one of the first initiatives to deal with both lighting and communication using LEDs. In their work, Dietz *et al.* first analyzed the use of LEDs as light sensors. They consider LED due to its inexpensive and simple nature. Furthermore, the authors proposed *iDropper*, a bidirectional communication system that uses LEDs as both transmitters and receivers, conceptualized primarily as a replacement for RFID (Radio-Frequency Identification) systems.

The *iDropper* hardware is composed of a simple PCB containing a button, an MCU (Microchip PIC16LF628), an LED, a coin-cell battery, a capacitor, and two resistors. The system was designed in a way that *iDroppers* could be used as intelligent keys, capable of peer-to-peer communication. Authors follow a different approach to design their protocol, considering the popularity of OOK modulation techniques: data is exchanged using pulse-width modulated data bidirectionally. In the presented protocol, two unsynchronized devices are able to sync with each other by adopting a mechanism in which each device takes turns flashing the light. A short flash means 0 (SPACE), and a long flash means 1 (MARK). After synchronization, data is transmitted by sending a SPACE as a start bit, 8 bits of data and a MARK as an end bit. Authors were able to communicate with 250 b/s data rate. In addition, many applications are envisioned, from cellphone to vehicle communication. In sum, the main contribution of this work is the adoption of LEDs as bidirectional communication devices, and the novel idea presented in which every LED could become a potential communication mean.

## B. Shine

The Arduino is one of the most well-established MCUs and offers many advantages when used to prototype VLC systems. A fully functional VLC system between two Arduinos was developed by Jonathan Piat, using only off-the-shelf LEDs and a pair of resistors [14]. At the transmitter side, data is encoded using Manchester encoding and modulated using OOK mechanism, to avoid flickering. At the receiver side, a reverse-biased LED is used to capture light. The system can reach data rates up to 600 bps, and works in distances up to 3 m, depending on the type of LED used.

Arduino is known for being a cheap and simple alternative to custom made hardware and, as a consequence, a number of robust systems based on this MCU can be found in the literature. For instance, Klaver *et al.* developed Shine, a platform that can function as an Arduino, by loading the bootloader, or as a generic ATMega 328p processor [108]. One of the great advantages of this approach is the creation of a generic platform, which differs significantly from other approaches as OpenVLC, SmartVLC, and PurpleVLC. Some important features adopted by Shine include synchronization mechanism, carrier sense implementation, adaptive symbol thresholding and an API that offers three different types of messages.

The Shine platform can establish communication at a distance of up to 1 m. In terms of data rate, Shine is limited to the microcontroller sampling rate, which is 1 MHz. In practical terms, the achievable data rate is 1 Kbps. Shine explores the coverage issue in VLC application by using 20 LEDs as transmitters and 4 photodiodes as receivers,

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[14]Arduino simple Visible Light Communication - https://github.com/jpiat/arduino/wiki/Arduino-simple-Visible-Light-Communication, 2017.

providing a 360° communication coverage. Based on these functionalities, the authors were able to develop a multi-hop mechanism, providing a preliminary study of a miniature SmartCity, in which static nodes have to communicate with mobile nodes.

### C. modBulb

The modBulb [166] is an open-source VLC transmitter platform developed to serve as a tool for VLC research. One of the main features of modBulb is its modular design. In fact, its design enables the adaptation to user-specific requirements, by adding modules to it, for example.

There are three main components in modBulb: (i) a baseband generator, responsible for transforming the information to modulated signals. Authors have adopted a modular perspective in the design of the baseband generator, which can be realized either on FPGA or MCU. Each alternative has its advantages and drawbacks. MCUs are more common in literature, and can be found in platforms such as Shine [108] and enLighting [166]. They are more flexible and easier to implement but are limited to their clock frequency. FPGAs allow higher precision when controlling the baseband signal, and offer higher throughput due to the higher clock frequency, (ii) driver circuit, responsible for transforming the baseband signals to electric current and (iii) the light source, which depends on user needs and can be from multiple sources.

The difference between the FPGA and MCU approaches is notable and has a significant impact on the VLC platform performance. The MCU (Texas Instrument CC3200 SoC), is able to achieve a maximum clock frequency of 80 MHz, and it includes an integrated WiFi radio. In the FPGA (Microsemi AGLN250), the authors adopted a clock frequency of 20 MHz in order to support high throughput. For both approaches, a series of modulation schemes are developed, such as On-Off Keying, Binary Frequency-shift Keying, and Pulse Position Modulation.

The system developed was evaluated as a whole, adopting FPGA as the baseband generator, using a clock frequency of 500 KHz for all different types of modulation. Authors showed that the FPGA-based approach outperformed the MCU-based considering all types of modulation schemes. However, FPGA-based approach consumes more energy when compared to MCU-based. Moreover, their results evidenced the success of data transmission under ambient light.

### D. enLighting

Schmid *et al.* [67] developed a practical and interesting approach for VLC. The enLighting platform is a fully functional VLC system which uses commercial LED light bulbs. This platform is an evolution of previous research presented by the same authors [32], [56], [62], which we will briefly discuss in order to understand the complexity of enLighting.

In [32], Schmid *et al.* revisit the concepts explored by Dietz *et al.* [49], exploring the fundamentals of LED sensing. In this case, Schmid *et al.* uses iDropper as a base for LED-to-LED VLC networks. In sum, the main contributions of Schmid *et al.* [32] are: (i) the design and implementation of a software-defined Physical Layer and (ii) the design of a low complex MAC layer.

At the physical layer perspective, communication works based on time slots that are interpreted as ON or OFF, depending on the presence of light. Devices can be on TX (transmitting), RX (receiving) or Idle mode. Periodically, LEDs are turned in Idle mode to enlight the environment (i.e., LED is ON). Incoming light is received and later identified as ON or OFF by using an adaptive threshold parameter (THRS). The THRS is a very important feature in this work because LEDs, when acting as receivers, continually update this parameter considering the ambient light in order to be able to detect symbols from incoming light. In addition, the carrier sensing mechanism implemented uses the THRS to detect if a channel is busy or not, by comparing it to the current level of ambient light. Synchronization is achieved by using the Idle pattern (device constantly measures the amount of light detected and is able to identify if another device is present, and then start synchronization with it), which decreases delay due to the lack of a dedicated synchronization preamble in the data structure.

The low-complex MAC layer is defined in order to interact with the PHY layer. Frames can be of two different types: data or acknowledgment. Data frame contains the payload, and ACK frames are used to confirm reception. Authors design CSMA/CA, a common multiple access mechanism for the MAC layer. In that way, when a device wants to communicate, it first senses the optical medium for a certain number of time slots (Contention Window slots).

Aspects evaluated include single link performance, network, and power consumption. Their results show that communication was performed at up to 2 m distance, achieving 800 bps data rate. This idea evolved during the years [56], [62], [65], following a path that leads to the conceptualization of enLighting [67].

In terms of software, enLighting implements the PHY and MAC layers presented in earlier works by the authors. The enLighting platform presents two hardware elements: the VLC firmware is developed in an ATmega328p, and it is connected via UART to an Atheros SoC AR9331, which runs a Linux distribution for an embedded wireless system (OpenWrt). Physical and MAC protocols are implemented on the MCU. A conventional LED light bulb was modified to be attached to the platform, as shown in Figure 18b. The platform allows multi-hop communication, and a localization service was also implemented and evaluated. The system is able to communicate at distances up to 5 m, with a data rate of 600 bps.

*E. OpenVLC*

Another example of VLC-related research platform is the OpenVLC [63], an open-source general-purpose software-defined networking platform OpenVLC runs on top of the BeagleBone Black board (BBB), a cost-effective, easy to use and powerful embedded board [55]. This platform has considerably evolved since its first design, presented in 2014 [79]. Indeed, the main concepts of OpenVLC LED-to-LED communication date from 2012, where Giustiniano *et al.* [167] developed communication and networking protocols for LED-to-LED simple communication devices.

The main novelty of OpenVLC is its integration of all Physical and MAC layers protocols present on the front-end to an embedded Linux networking platform. This design enables the evaluations of VLC system in real world scenarios, where users could access the Internet through the light.

The front-end of the OpenVLC platform is built as a cape for the BBB. In terms of transceivers, the cape consists of a High-Power LED (HL), a Low-Power LED (LL), and a photodiode (PD), which are used to establish communication between two or more platforms. The components are connected to the BBB GPIO headers through the cape. Both HL and LL can be chosen as the transmitter, through the software-defined selector. The cape also a DC/DC converter in order for the HL to work properly. Besides consuming more power than the LL, the HL also transmits light in all visible spectrum, as it is usually represented by a white LED. The LL are the simplest types of LEDs (5mm), with very low power consumption, in order of mW, and they emit light in a narrower optical spectrum, according to their color, as discussed in Section II. The relationship between transmitters and receivers, as well as the software-defined configurations, can be seen in Figure 17.
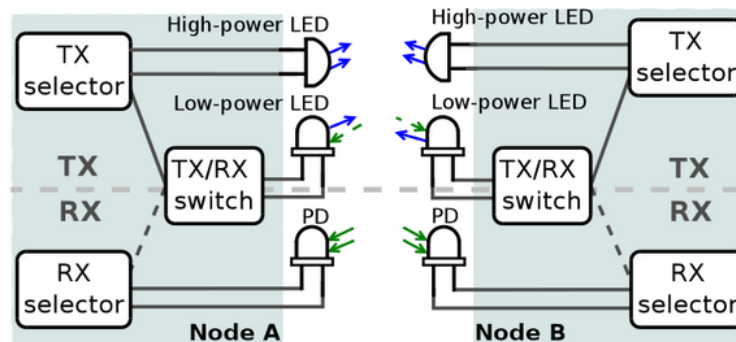


Figure 17: OpenVLC 1.0 transceivers [55].

In more details, aspects such as symbol sampling and detection, coding, decoding, multiple access mechanisms communicate with the Internet (network) layer of the Linux OS. The flexible interface (which allows the same LED to work as both transmitter and receiver) is possible due to the design of the front-end circuits, allowing a switching mechanism between TX and RX and the support from a software-defined controller which is part of the physical layer.

The MAC layer is similar to the one presented in enLighting [32]. It supports two types of frames: DATA (which has a Length field containing the size of the payload) and ACK (when the Length field is 0). Along with the Length field, frames also include a Payload field, which varies from 0 to 255 bytes, Destination Address, Source Address, and Protocol. This information is encapsulated and a 2-byte CRC field is appended to the end of the frame. A carrier-sensing mechanism is implemented at the MAC layer, which is used by the CSMA/CD protocol designed. In that way, devices are capable of detecting the state of the channel through two different mechanisms: basic sensing (device reads a certain number of continuous symbols) and fast sensing (per-symbol basis). Usually, basic sensing is used before transmitting, while fast sensing is used during the transmission. Lower layers are implemented as a Linux driver module, which is attached to the OS in a way in which packets can travel between Linux network stack and OpenVLC lower layer primitives.

Authors conduct a performance evaluation of OpenVLC using well-known Linux network tools (iperf and ping). Metrics such as throughput, round-trip time, CPU usage and packet loss ratio were analyzed by the authors. The first version of OpenVLC was capable of transmitting data at a rate of 1.76 Kbps, and authors evaluated both

single and multi-hop scenarios. During the last years, the concept of OpenVLC was deeply upgraded, and the more recent version (OpenVLC 1.3) has many new features and it further explores BBB capabilities in order to increase performance.
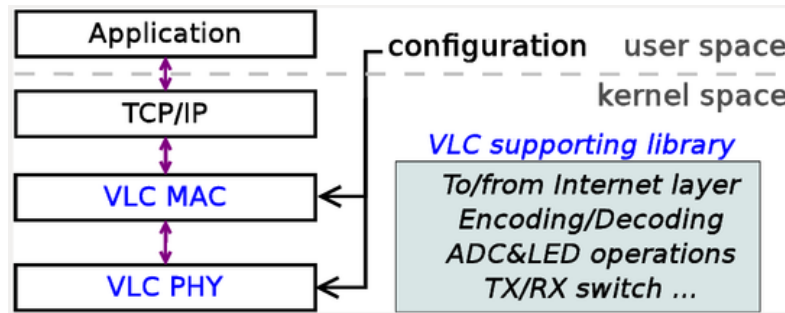


(a) OpenVLC software architecture [55].
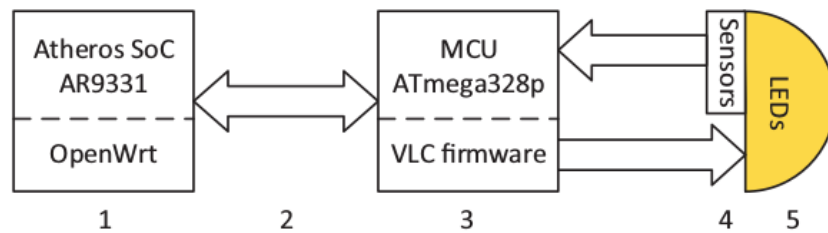


(b) Enlighting architecture [67].

Figure 18: OpenVLC 1.0 and EnLighting system architectures.

OpenVLC 1.3 front-end was completely re-designed by improving its architecture and adding different components, some of which are interesting to highlight: more powerful LEDs were added as transmitters, filters have been attached to the photodiode in order to reduce noise, a MOSFET is used to enable faster modulation of the light and a lens has been attached on the top of an LED to increase the focus of light, consequently increasing the distance between devices. The firmware was improved by making it run in the PRUs of BBB. The BeagleBone Black has two Programming Real-Time Units (PRUs), which operate in higher frequency (200 MHz), have an individual memory and a shared memory between them. By using the PRUs, data can be handled faster, due to the faster signal sampling and the accuracy achieved by using assembly as the programming language. This strategy increased data rate from  18 Kbps (OpenVLC 1.1) to  400 Kbps, at a distance of 3.5 m. However, PRUs have a limited memory, which requires careful design of upper-layer communication. Despite limiting the design and implementation of the OpenVLC to the BeagleBone Black, this platform is the most complete research platform found in literature, as it covers all layers considering VLC, enabling the design and research from Physical layer protocols to application involving VLC.

### F. PurpleVLC

PurpleVLC has been developed by Yin*et al.*, and it follows the same principles of recent versions of OpenVLC. This platform was designed to be attached to the BeagleBone Black, and the main idea of Purple is to increase

the data rate by offloading I/O operations to the PRU unit. The main motivation for this work, by the time it was conceptualized, was the limitations of existing VLC platforms in terms of data rate, due to the adoption of three main approaches in hardware design: micro-controller, FPGA or single-board computers.

The transceiver architecture of PurpleVLC follows the same baselines of OpenVLC, but Purple can use multiple LEDs and photodiodes in concurrent channels, enabling full-duplex VLC communication. The data rate is increased by performing I/O offloading from CPU to PRU. LED transmitters can be controlled simultaneously or independently, depending on application needs, and because of that, a synchronization mechanism between LEDs was designed by using the PRUs. Each PRU in BBB is able to control GPIO pins independently by using an IO register. Therefore, multiple LEDs in different pins can be toggled on and off synchronously. Interference is avoided by using polarizers, enabling data to be sent from multiple channels without mutual interference.

To evaluate the platform, authors attached the cape developed to a BBB. Metrics such as packet loss ratio (PLR), bit error rate (BER) and throughput were chosen to be studied. Up to 4 LEDs were used as transmitters in a single-link topology, achieving a throughput of 50 Kbps in a distance of up to 6 m (for the 4-LED configuration). PLR follows the same behavior, achieving a better performance for the 4-LED scenario. One of the main contributions of this work is the evaluation of concurrent VLC communication in embedded platforms. For that case, the throughput of up to 95 Kbps was achieved for a dual-link configuration.

### G. SmartVLC

SmartVLC [169] has been designed as generic and flexible as possible, such as Shine and OpenVLC, in order to facilitate and standardize studies in the field. SmartVLC is a robust system, capable of supporting dimming. It also maintains acceptable throughput, which is still a challenge research topic in VLC.

SmartVLC hardware implements both transmitter and receiver. The transmitter uses an LED, a photodiode and a MOSFET, which are connected to BBB's GPIO pins. Uplink is achieved by integrating a Wi-Fi module to the system, in order to transmit ACKs back to the transmitter. The receiver is designed by using an ADC, an amplifier and a photodiode. Two important hardware design approaches differ SmartVLC from other research platforms in literature, and can be addressed here: (i) the photodiode present in the transmitter is responsible for sensing the ambient light (differently from OpenVLC, for example, which adopts photodiodes to enable bi-directional communication) and (ii) the photodiode at the receiver (OSRAM SFH206K) is different from the one at the transmitter (OPT101), because of two requirements for the receiver: low response time and high sensitivity. At a software level, SmartVLC also explores the advantages of the PRUs to enable higher throughput.

The main contribution of SmartVLC is the design, implementation, and evaluation of the Adaptive Multiple Pulse Position Modulation (AMPPM), a new modulation scheme with dimming support for Visible Light Communication. This modulation uses features from two types of modulation approaches relevant to VLC scenarios: (i) compensation-based, in which frames are divided into data and compensation fields, favoring a fine-grained control of the dimming level, and (ii) compensation-free, which increases throughput by removing compensation fields. The modulation proposed by the authors was capable of providing better performance when compared to the state-of-the-art mechanisms.
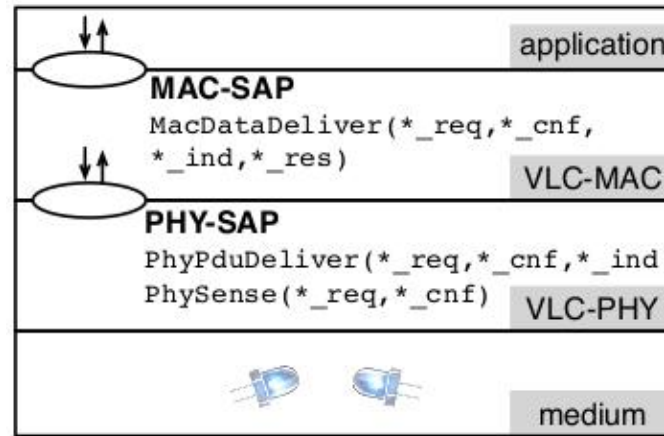
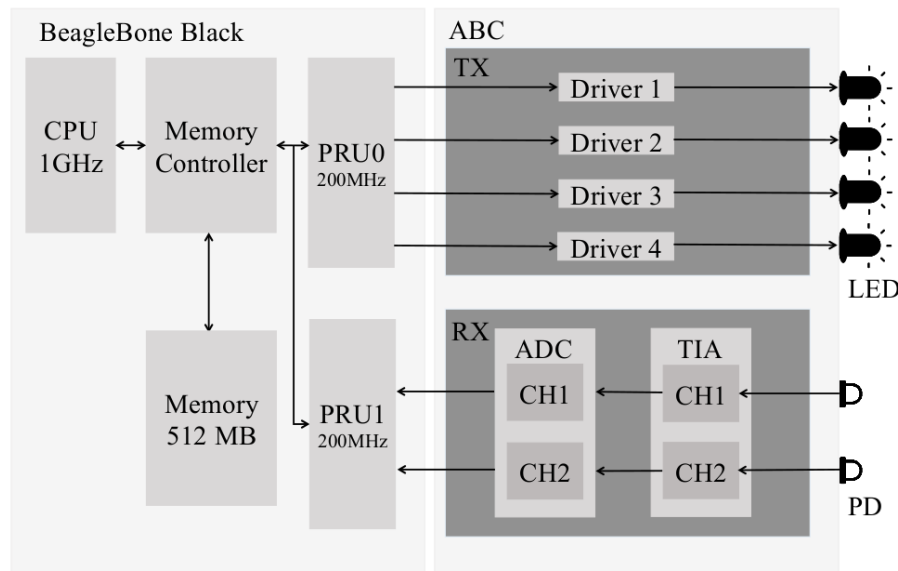Figure 19: Reference model proposed by Schmid *et al.* [32].



Figure 20: System architecture of the Purple platform [168].

## H. *DarkLight*

Along with SmartVLC, DarkLight has a very specific design goal. In a nutshell, the main idea behind this platform is to provide communication while lights are off. In order to be able to achieve that, DarkLight explores the difference in the response time of human eyes and photodiodes. By encoding data into very small light pulses and changing the LED light duty cycle, authors were able to trigger photodiodes with minimal human eyes stimulation. This is done by using a specific type of modulation, Overlapping Pulse Position Modulation (OPPM), a variation of Pulse-Position Modulation in which time slots can be shorter than one pulse, allowing more bits to be encoded in one single pulse. Along with the modulation scheme chosen to be effective for ultra-short pulse lights, DarkLight uses a photodiode to sense the ambient light and trigger a modification in the LED duty cycle according to the sensed value. At the receiver side, demodulation is done by analyzing the preamble of a frame, which contains the

current duty cycle, and adapting to it.

DarkLight is implemented using an FPGA due to its higher clock frequency, enabling ultra-short pulses. Off-the-shelf components are used for both transmitter (an LED and a photodiode) and receiver (photodiode). Evaluation is performed at a user perception level, in which users are asked if they can see the pulses being transmitted by the DarkLight, and at system perspective. Some of the metrics explored by the authors in a single link scenario are throughput, adaptation, power consumption and viewing angle. At a multi-link scenario, authors analyze the synchronization of transmitters and receivers. DarkLight was capable of achieving data rate of 1.6 Kbps at a distance of 1.3 m, following all premises presented by the authors.

## VIII. PERSPECTIVE OF FUTURE WORK

During the past decade, Visible Light Communication went from a very narrow and limited research field to an academic and commercial promise to the future of wireless communication. In the meantime, LEDs became more popular, while wireless bandwidth demand became more severe. This scenario boosted VLC research. Indeed, during this last decade, we are aware of a number of efforts to standardize VLC.

The future of this technology depends, in the first place, on the clarification of the real benefits (free, unlicensed spectrum, low cost communication, security, green-technology) of VLC when compared to RF-based communication, in a way that both academia and market can reach a broad scale point of adoption of this technology [170].

Up today, the main document that summarizes VLC aspects is the IEEE 802.15.7 [12]. However, this standard dates from 2011, and many of the techniques proposed in the document are obsolete. Along with the popularization of VLC, new modulation schemes and multiple access mechanisms were developed, which consequently lead to the need of a revision and future release of a novel standard, which can cover higher speed systems. To summarize, some of the future directions for VLC research are as follows:

- Standardization of research: During the last decade, we have seen many researches related to VLC. However, the lack of experimental testbeds poses a challenge to researchers. In fact, distinct research groups implement their our VLC hardware and testbeds and as consequence, actual solutions might not interoperate. In this sense, we highlight efforts to standardize VLC research as a future trend. Efforts in this direction, as [171], may organize and optimize the research field.

- Popularization through commercial initiative: The union of academic and commercial VLC-related efforts had its first significant representation during the year of 2018, with the official adoption of the Li-Fi technology by Signify (former Philips Lighting), one of the most renowned light companies in the world[15]. In that sense, the future of VLC will be built on top of these commercial movements, while academic efforts will also benefit from the standardization of light infrastructure.

- LED sensing: As discussed in this survey, LEDs have interesting properties when used as sensors. The rapid adoption of VLC by the academy has brought attention to this particular characteristic. Following the guidelines

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[15]https://www.signify.com/global/about/news/
press-release-archive/2018/20180316-philips-lighting-introduces-lifi-broadband-data-through-light

of very recent works [172], [173], the use of LED in both VLC and sensing will gather more attention in the next years.

- Hybrid systems: One of the premises of Visible Light Communication is its adoption as a complementary technology to RF-based mechanisms. In this sense, we point the development of new hybrid VLC systems as a future trend. Cooperation between VLC and wired base network devices, concurrent transmission between VLC and RF or Ethernet networks, the use of multiple paths and, the implementation of network coding can enhance the quality of communication.

## IX. Conclusion and discussions

In this work, we have presented the concepts, applications, and challenges of Visible Light Communication. We have explored the literature in an extensive and comprehensible way, discussing the existing works and envision the future of VLC and Smart Lighting. VLC is a great opportunity to provide wireless communication. We observe a high demand for wireless resources, driven by the popularization of mobile devices. This increasing demand for wireless and ubiquitous communication raises a series of issues related to the current infrastructure of wireless networks. In this sense, we can identify an upcoming Wi-Fi spectrum crunch, where the demand for resources becomes greater than the capacity offered by the network.

Among the alternatives proposed recently to complement the current infrastructure of wireless networks, VLC stands out due to the great advantages it provides. Free spectrum, high frequencies, availability of infrastructure and LED light bulbs are advantages that draw attention to visible light. However, many obstacles still prevent VLC-based technologies and applications from being commercialized. Flickering, dimming control, uplink, and interference are some of these challenges.

VLC offers a great opportunity to complement the current wireless infrastructure, as it offers increased performance especially in environments such as offices and homes, where distance is short. In addition to that, indoor positioning, underwater and vehicular communication systems are some examples of applications that can utilize visible light.

In summary, VLC is a broad research area which also attracts the interest from the industry. Even so, the research area still demands more exploration, which should happen in the next years, considering the popularization of the area and the increasing adoption of concepts such as the Internet of Things and Smart Lighting.

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