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Review

Visible Light Communications: A Survey on Recent High-Capacity Demonstrations and Digital Modulation Techniques

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Abstract: In order to deal with the increasing number of mobile devices and with their demand for Internet services, particularly social media platforms, streaming video, and online gaming, Radio-Frequency (RF) wireless networks have been pushed to their capacity limits. In addition to this, 80% of the total data traffic is carried out by users inside buildings. Therefore, new technologies have started to be considered for indoor wireless communications. Visible Light Communications (VLC) can provide both illumination and communications, appearing as an alternative or complement to RF wireless networks. VLC offers high bandwidth and immunity to interference from electromagnetic sources. This manuscript reviews recent high-capacity VLC demonstrations. The main focus of this work is to present digital-signal-processing techniques used in VLC systems. Different modulation formats are analyzed, which can be divided into two large groups, namely single-carrier and multi-carrier modulation schemes. Finally, some recently proposed capacity-achieving strategies are presented. We discuss how to implement these techniques and how they will be useful for the continued development of VLC systems.

Keywords: 5G and beyond; visible light communications; optical wireless applications; laser diodes; light-emitting diodes

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1. Introduction

With the emergence of 5G, a series of new applications have been introduced, such as autonomous driving, communication between objects, and industrial automation. All these applications are achieved due to high data rates, low latency, and ultra-reliable communications. Therefore, it is expected that these requirements will be even higher in the coming years [1]. Furthermore, considering that more than 80% of the total mobile data traffic is generated indoors, it is important to introduce a new technology that works mainly inside buildings and complements Radio-Frequency (RF) networks, which are rapidly becoming highly congested and also limited by electromagnetic interference [2].

In order to tackle this challenge, the possibility of introducing optical wireless communications has emerged as a potential alternative [3]. The optical band includes infrared, visible, and ultraviolet light. The most-common use of light for communications is in fiber optics, which utilizes optical wavelengths, typically infrared, to transmit data over fiber. Moreover, several works have demonstrated wireless infrared communications, known as Free-Space Optics (FSO) [4,5]. However, the performance of FSO communications is highly dependent on the directivity of the optical beam, making it unusable in indoor mobile communications. In contrast, ultraviolet is generally not considered for communications because of the risks introduced. Light emitted at this wavelength can be harmful to human eyes if protection is not used. Furthermore, prolonged exposure can lead to serious health problems, where UVA and UVB are the most dangerous, since they are not absorbed by the Earth's atmosphere. Therefore, Visible Light Communications (VLC) is seen as a potential technology for indoor short-range communications, because optical beams do not need to be very directive to provide good communications, nor are there great risks to human health when exposed to visible light. Moreover, lights are normally used in closed spaces (shopping centers, offices, and houses), where most mobile communications are performed [6].

VLC takes advantage of hundreds of terahertz (430–790 THz) of unlicensed bandwidth in the visible band to perform wireless communications. On the other hand, for the RF band, mainly sub-6 GHz, the frequency allocation is restricted and regulated in each country, making it impossible to explore these bands to provide faster communications [7]. WiFi technology offers two frequency regions to be used by unlicensed devices, 2.4 GHz and 5 GHz, which is quite limited when compared to the hundreds of terahertz available in VLC. Moreover, visible light causes no electromagnetic interference, so it does not affect the performance of other electronic devices [8]. Thus, VLC can be employed in places where sensitive electronic equipment is used, such as hospitals and aircraft, where any significant interference could have tragic effects. Additionally, in this type of communication, the generated signal will be confined within the room, since light cannot penetrate opaque objects, providing secure wireless communications. In contrast, RF communications are characterized by signal propagation for hundreds of meters, passing through walls and other solid surfaces, thus facilitating its intrusive interception [3]. Lastly, this technology offers the possibility of reusing the already implemented lighting infrastructure, thereby reducing installation and operation costs.

This survey focuses mainly on presenting recent high-capacity VLC demonstrations. Throughout the article, several currently used modulation techniques are highlighted and some high-speed VLC systems reported in recent years are presented. The rest of this work is organized as follows. We start in Section 2 by briefly presenting the evolution of VLC standards and the main VLC applications. In Section 3, modulation methods typically used in VLC are addressed. Section 4 presents some state-of-the-art capacity-achieving strategies for VLC indoor applications. Finally, the challenges and future research directions are discussed in Section 5.

2. Progress on Standardization and VLC Applications Scenarios

Recently, the interest in VLC has increased exponentially, as can be easily verified by the number of papers published over the recent years. Figure 1 presents the number of documents published over the years that used the expression "Visible light communication" or the keyword "VLC" within the body or title of the paper. We can see that the number of publications using these expressions in the title reached a halt after 2020, likely influenced by the pandemic, but on the other hand, the number of articles referring to VLC has increased successively every year, demonstrating a clearly growing interest in this topic. This increase is also due to the appearance of the first standards, which validates the potential of this technology and motivates both industry and academia to invest in it.

2.1. VLC Standardization

The VLC standardization process started in 2003 with the creation of the Visible Light Communication Consortium (VLCC) in Japan, aiming at creating the first VLC standard. However, only in 2007, the VLCC proposed the first two standards to the Japan Electronics and Information Technology Industries Association's (JEITA): JEITA CP-1221 and JEITA CP-1222, which introduced the basics of VLC systems [7]. Despite these efforts, none of the referenced standards focus on flickering and dimming mitigation. Therefore, in 2011, the IEEE 802.15.7 standard for the link and physical layer of a VLC system was proposed to address some practical issues associated with VLC systems [9]. First is the integration of the VLC system with the already-standardized wireless communication technology, for example, WiFi. Secondly, this standard solved the interference problem with ambient light sources. Subsequently, mobility issues, such as handover, were properly assessed. Then, Forward-Error-Correction (FEC) schemes were selected in order to improve communication performance. Finally, interference between VLC devices was considered [8]. Broadly speaking, the IEEE 802.15.7 standard is divided into three Physical (PHY) types for VLC: PHY I, PHY II, and PHY III. PHY I works from 11.67 to 266.6 Kbit/s; PHY II operates from 1.25 to 96 Mbit/s; PHY III offers bit rates between 12 and 96 Mbit/s [7]. The first two modes of operation use a single light source, supporting On–Off Keying (OOK) and variable Pulse-Position Modulation (VPPM). On the other hand, PHY III uses multiple optical sources with different wavelengths, introducing the Color-Shift-Keying (CSK)-modulation scheme. For the different modulation format options, there is a trade-off between high bit rates and flickering and dimming mitigation [10].

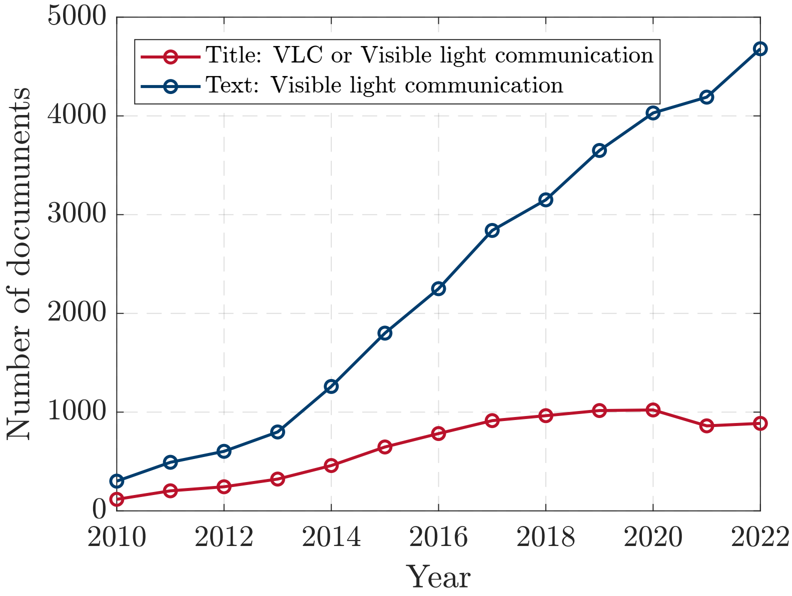


Figure 1. Number of VLC publications over the years. These data were obtained from the Google Scholar search engine.

Recently, the IEEE 802.15.7 standard started to be revisited by a new task group (IEEE P802.15.13) in order to increase the data rate for specialty applications [11]. The main objective of this new standard is to define a PHY and Media Access Control (MAC) layer using wavelengths from 10,000 nm to 190 nm to achieve a multi-gigabit/second optical wireless communication system [12]. The current standard version establishes two options for VLC, the energy-efficient Pulse Modulation (PM)-PHY and the spectrally efficient High-Bandwidth (HB)-PHY. The first option is indicated for low-power applications, such as uplink, the IoT, and Industry 4.0. It offers up to a 200 MHz bandwidth using the low-spectral-efficiency OOK modulation format. Instead, the HB-PHY is based on Orthogonal Frequency Division Multiplexing (OFDM) and offers a bandwidth of up to 1 GHz, also allowing the use of bit loading [11].

However, the IEEE P802.15.13 standard is being designed mainly for industrial applications and is not compatible with existing wireless networks. Therefore, the 802.11 Working Group, dedicated to the development of standards for communications in wireless networks, created the Task Group bb (TGbb) to study the possibility of integrating LiFi into the WiFi standard. 802.11bb intends to introduce a VLC system to the WiFi network, allowing it to address more use cases than IEEE 802.15.7 and IEEE P802.15.13, where just low data rate communications and industrial applications were considered, respectively [13].

These evolutions in standardization have motivated both industry and academia, as mentioned above. While the number of scientific articles easily measures interest in academia, in industry, this can be seen by the appearance of commercial products. Currently, the global leader in VLC technology is pureLiFi. They brought to market the first commercial visible light antennas operating at more than 1 Gbit/s in the downlink direction and 600 Mbit/s in the uplink direction. Their system is compatible with the IEEE 802.11 standard and has been tested in classrooms, hospitals, and real-time sensor monitoring [14]. In turn, other companies started to demonstrate high-speed VLC solutions, such as the Fraunhofer Heinrich Hertz Institute and Oledcomm [15].

2.2. VLC Application Scenarios

Beyond the aforementioned indoor mobile communications, VLC presents a wide range of applications and potentialities. The use of visible light can also be essential for underwater communications, vehicular communications, and indoor localization.

2.2.1. Indoor Wireless Communications

LiFi provides a high-speed bidirectional communication, equivalent to WiFi, but with visible light. Currently, most homes and buildings are equipped with Light-Emitting Diodes (LEDs), which can become LiFi access points, where the lamps are used for both room illumination and communications. Therefore, considering a room with several VLC transmitters, they can be organized in a way to reduce interference, allowing the introduction of coordinated multi-point transmission, which offers the possibility of applying Multiple-Input, Multiple-Output (MIMO) techniques. In the literature, this is the most-explored application, with thousands of works exploring different system approaches in an indoor scenario.

In the early 2000s, the first VLC works began to appear, using the visible light of LEDs to illuminate and carry out communications in indoor scenarios [16,17]. One of the most-common strategies to generate white light relies on the use of a blue LED with a yellow phosphor [18,19]. Although this single-LED approach has captured significant attention mainly owing to its simplicity and low cost, the most-common approach in recent VLC works is based on the use of at least three LEDs with different colors, usually Red, Green, and Blue (RGB), to produce white light [20,21]. Despite the progressive improvement of the LED-based VLC system, the performance is limited by the low bandwidth of the source (typically tens to hundreds of megahertz), not allowing it to exceed 20 Gbit/s. Therefore, more recently, VLC systems using Laser Diodes (LDs) have been proposed to improve the performance of these systems. In LD-based systems, there are some different approaches, but, similar to the implementations with LEDs, most of the works tend to combine the color of multiple transmitters, currently allowing exceeding 40 Gbit/s [22,23]. On the other hand, several modulation formats are explored, always aiming to maximize the system's capacity. In the next section, several modulation techniques used in VLC systems will be presented.

2.2.2. Underwater Wireless Communications

The growing investment and interest in underwater wireless communications is fostered by the increase in underwater human activities, namely oceanography studies, oil exploration, and military warship-to-submarine communication [24]. Traditionally, acoustic waves have been used in these scenarios, being able to support transmission distances in the order of a few kilometers. However, the main drawback of acoustic communications is the slow propagation of sound waves, resulting in a large latency. Moreover, the data rate is limited to tens of Kbit/s due to the strong attenuation of sound in seawater, as verified by some works [25–27]. Alternatively, the use of electromagnetic waves was suggested, initially in the RF band, allowing increasing the capacity of the system in relation to acoustic waves, but on the other hand, the distance is considerably smaller due to the very high attenuation [24]. In order to improve the performance of RF underwater communications, a large-sized antenna is needed, considerably increasing the costs of the system [28]. Therefore, Underwater Optical Communications (UWOC) has been proposed as an alternative to acoustic and RF underwater communication links for short and moderate distances. Visible light has a great potential for this type of communication due to the low absorption of seawater in the blue-green region (400–550 nm) of the visible spectrum, allowing providing data rates up to a few Gbit/s [24,29,30]. Hassan M. Oubei et al. experimentally demonstrated an underwater wireless VLC system with a bit rate of up to 4.8 Gbit/s over a tank of water with 60 cm, achieving a distance of 5.4 m with the help of mirrors. The authors verified that the transmission distance can be increased since the attenuation coefficient at this wavelength is very small [29]. Tsai-Chen Wu et al. decided to experimentally study the performance of these systems using tap water and seawater. A bit rate of 7.2 Gbit/s for a distance of 6.8 m was demonstrated when the light passed through a tank of seawater. On the other hand, as expected, using tap water, the achieved bit rate was 9.2 Gbit/s due to lower attenuation of the light beam [24]. Alternatively, Jianyang Shi et al. experimentally demonstrated a net data rate of 14.6 Gbit/s over 1.2 m of underwater distance using five primary-color LEDs, validating the viability of this alternative approach [30]. For a more-detailed analysis of UWOC systems, several comprehensive surveys can be found in the literature, describing the fundamentals, main research problems, and future directions of this technology [28,31–33].

2.2.3. Vehicular Communications

In recent years, the number of cars on the road has increased exponentially, resulting in a greater number of road accidents, making it one of the main causes of death. Therefore, several government institutions, the automobile industry, and the scientific community have joined efforts to improve road safety. One of the best ways to prevent road accidents is to introduce real-time wireless communications to facilitate the interaction between vehicles and traffic infrastructure [34]. Although some RF-based technologies have been proposed as a solution to this problem, such as WiFi and Bluetooth, they are not ideal due to the very-low-latency synchronization requirements. Therefore, other technologies were studied, with VLC emerging as a promising alternative [34]. VLC can be used in vehicular communication since its environment offers a large number of light sources, such as vehicle lights and traffic lights. Currently, the automobile industry is adopting LEDs as light sources, enabling the introduction of VLC. Therefore, by implementing VLC transmitters/receivers in cars, traffic lights, and streetlights, it will be possible to create a network capable of extracting and exchanging information among multiple users [7]. In this type of scenario, there can be two types of communications, vehicle-to-vehicle and vehicle-to-infrastructure. For example, traffic lights can be used to transmit information about vehicle safety and traffic [6]. In the literature, there are some works demonstrating communication between road infrastructures and moving vehicles [35,36]. In [35], Ning Wang et al. experimentally demonstrated an intelligent transportation system based on VLC. The proposed communication system controls the traffic lights to ensure that large vehicles do not need to perform emergency braking. Furthermore, D. Marabissi et al. presented one of the first experiments using 5G in a VLC system for vehicular communications [36]. In another case, streetlights can offer wireless data communications to cars and pedestrians while also being used to light the streets. Regarding vehicle-to-vehicle communications, this can be used to transmit data between the various vehicles to enhance road safety [37,38]. In this scenario, both headlights and taillights on automobiles can be used as VLC transmitters/receivers to provide reliable communications [6]. Unlike indoor applications, where data rates reach multiple Gbit/s and distances are only a few meters, in this scenario, the distances can exceed one-hundred meters, obviously resulting in lower data rates, also due to interference from other light sources [34]. Nevertheless, the viability of this system for higher distances was demonstrated in [38], where reliable communications were established at 75 m.

2.2.4. Visible Light Positioning with Integrated Communications

Lastly, visible light is seen as a potential solution for indoor localization where the Global Positioning System (GPS) usually fails. GPS is known to be the most-widespread technology for localization applications, owing to its ubiquity and high precision in outdoor environments. However, inside buildings, it has limitations due to the effect of reflections and the difficulty of penetrating walls, offering only an accuracy of several meters, which limits its applicability [3]. Currently, indoor localization based on WiFi is seen as the most-attractive alternative. This technique uses access points to estimate the user's position. However, the main advantage that VLC has over WiFi is the higher number of LEDs when compared to WiFi access points [6]. The higher density of LEDs offers better accuracy. Furthermore, this visible-light-based localization system offers the interesting possibility of integrating wireless communications. This possibility has already been experimentally tested in several works [39–41]. In [41], Kottke et al. experimentally demonstrated LiFi-based positioning and communication with data rates up to 500 Mbit/s and positioning accuracy of more than 7 cm. There are numerous positioning algorithms that allow centimeter accuracy, namely resorting to the Time Of Arrival (TOA) [41], Received Signal Strength (RSS) [42], and Angle Of Arrival (AOA) [43], which are among the most-popular positioning methodologies for VLC systems [44,45].

As exposed above, there are many interesting applications that can use visible light. The application with the greatest potential for use is indoor communications, where it can be used for both lighting and high-speed wireless communications. However, the other mentioned scenarios also present interesting advantages, which could increase the interest in their implementation. Thus, in the next sections, digital modulation techniques typically used in VLC will be presented, which allow reaching higher bit rates in different VLC applications. Recently proposed techniques that could improve the system's capacity will also be highlighted.

3. Modulation Techniques for Visible Light Communications

Contrary to RF communications, in VLC, it is not possible to encode data in the phase and amplitude of the light signal. The information is transmitted using variations in light intensity, and reception is performed by direct detection [46]. This technique is named Intensity-Modulated Direct Detection (IM-DD). Moreover, in VLC, the modulation scheme has to simultaneously ensure high data rate transmission and good lighting quality. Consequently, two factors need to be considered, dimming and flickering [8]. Depending on the activity, different luminosity values have to be considered to enable a good human experience. There are some scenarios where an illuminance in the range of 30–100 lux is sufficient (public places), but others require a higher level of illuminance in the range of 300–1000 lux, such as offices [6]. This means that the considered modulation formats have to support different lighting values without significantly affecting the communications. On the other hand, residual changes of brightness caused by light modulation cannot be detected by the human eye. Therefore, the luminous intensity has to vary at a frequency greater than 200 Hz, as specified by the IEEE 802.15.7 standard [9]. Physical-layer-modulation techniques typically used in VLC can be divided into two groups, single-carrier- and multi-carrier-modulation schemes. Throughout this section, a survey of the most-relevant modulation and signal-processing techniques for high-capacity VLC systems is carried out.

3.1. Single-Carrier Techniques

Single-carrier-modulation techniques have been widely used in VLC systems over the years. The most-widely employed include On–Off Keying (OOK), Pulse Amplitude Modulation (PAM), Carrier-Less Amplitude and Phase Modulation (CAP), Pulse-Position Modulation (PPM), Pulse-Width Modulation (PWM), and Color-Shift Keying (CSK), which we will briefly review in the following.

3.1.1. On–Off Keying and Pulse Amplitude Modulation

The OOK method is the simplest and the easiest to implement, where the data bits "0" and "1" can be transmitted with two different levels of light intensity [46]. Most early VLC works used OOK modulation [47,48]. For example, H. Le Minh et al. applied the OOK modulation format to experimentally demonstrate data transmission at 40 Mbit/s for a link distance of 2 m [47]. On the other hand, in [48], J. Vucic et al. demonstrated an indoor VLC link using white LEDs operating at 125 Mbit/s over a 5 m free-space distance. However, as verified, these works suffered from the limited data rate, which has motivated the development of new modulation techniques, such as pulse-amplitude-modulation methods [8]. PAM is a more-advanced format with higher spectral efficiency, where the data are modulated into the amplitude of the signal. The PAM modulation format has been experimentally demonstrated with bit rates close to 1 Gbit/s using PAM-4 and PAM-8, clearly improving the performance compared to other works using OOK [49,50]. In addition to these works, higher-order modulation formats were considered with bit rates up to 10-Gbit/s using PAM-32 data encoding [51].

3.1.2. Carrier-Less Amplitude and Phase Modulation

A modulation format often used in VLC systems is CAP [19,52–54]. CAP was proposed to be an option to generate a real-value signal. For instance, complex-value signals such as QAM need to be hardware up-converted to an RF frequency at the transmitter in order to directly modulate the VLC transmitter. However, the typical VLC transmitter has a very limited bandwidth, making this approach not recommended [19]. CAP is very similar to this strategy, having both the same spectral characteristics and theoretical performance [19]. It uses two digital filters with an orthogonal impulse response to generate two separate data streams, in-phase and quadrature. The resulting signal is centered at an intermediate frequency. In this way, a real-value signal is generated using a simpler and less-expensive system. In Figure 2, we can see the block diagram of CAP modulation and demodulation. First, the bit stream is encoded and mapped into the constellation, and then, the in-phase ($s_I[n]$)- and quadrature ($s_Q[n]$)-generated signals are separated, taking the real and imaginary parts of the signal. The next step is the orthogonal filters, which are obtained by multiplying, in the time domain, the shaping filters and a sine/cosine:

$$f_I(t) = g(t)\cos(2\pi f_c t), \quad f_Q(t) = g(t)\sin(2\pi f_c t), \tag{1}$$

where $g(t)$ is the impulse response of the shaping filter, for example a square-root-raised-cosine function [54]. The frequency of sine and cosine represents the bandpass frequency of the transmitted signal. After adding both signals, the final step is to convert the signal from digital to analog ($s(t)$). The CAP signal is expressed by:

$$s(t) = s_I(t)f_I(t) - s_Q(t)f_Q(t). \tag{2}$$

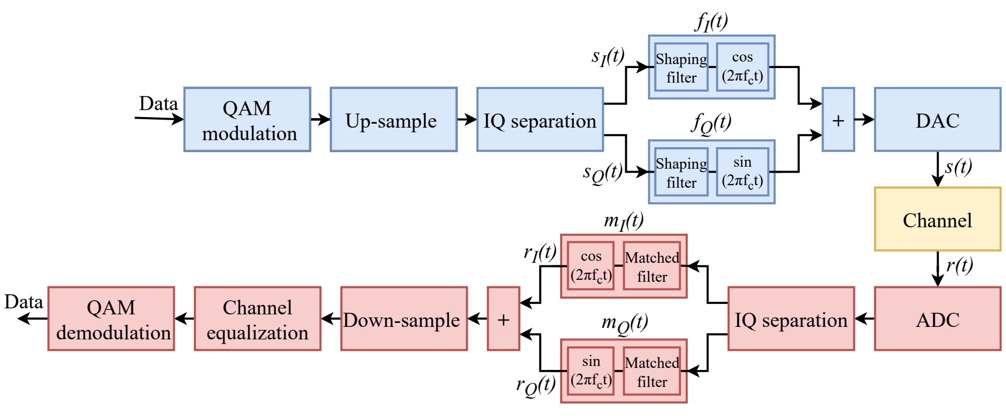


Figure 2. Block diagrams of the CAP modulation and demodulation.

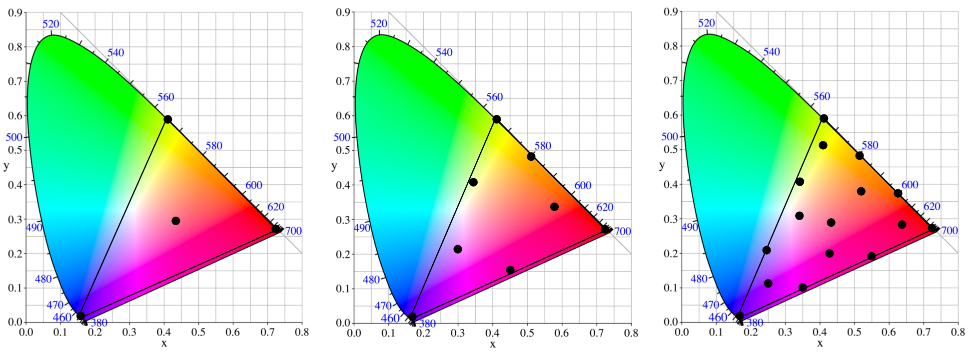
Regarding the CAP demodulation, the inverse operations of the modulation are performed, with only the application of an equalizer, which improves the frequency response and the performance of the system [19]. In [52], the CAP scheme was compared with OFDM in a VLC system. The authors verified that CAP has the potential for low power consumption, low cost, and low complexity. Therefore, it was concluded that the CAP scheme is a good alternative with competitive performance for VLC systems. The main disadvantage of CAP is the poor performance with non-flat frequency channels, with the need to use very complex equalizers, which would reduce its simplicity. In order to solve this problem, Multiband CAP was proposed, where the CAP signal is divided into smaller sub-bands [55]. This alternative was experimentally demonstrated in a VLC system by P. Haigh et al., demonstrating gains over the conventional CAP modulation scheme [56].

3.1.3. Pulse Width/Position Modulation

PWM is an efficient method to modulate the light and control the dimming since the widths of the pulses can be adjusted. Instead, in PPM, the symbol duration is divided into t slots and the pulse is transmitted in one of the t slots, where each position of the pulse represents a different symbol [6]. However, transmitting only one pulse per symbol duration is spectrally inefficient. Therefore, Overlapping PPM (OPPM) and Multipulse PPM (MPPM) were proposed to solve this limitation and transmit more than one pulse per symbol duration [6]. Finally, Variable-PPM (VPPM) is a modulation scheme that controls the dimming of light and, at the same time, enables communications. VPPM has the simplicity and robustness of PPM and can change the dimming by adjusting the pulse width [57].

3.1.4. Color-Shift Keying

Alternatively, in order to overcome the lower data rate and limited dimming support issues of other modulation schemes, the IEEE 802.15.7 standard proposed CSK modulation [9]. It uses multiple optical sources with different colors (wavelengths) [58]. The data are transmitted through the variation of color emitted by RGB VLC transmitters [59]. CSK modulation uses the "Commission Internationale de l'éclairage" (CIE) 1931 color space, which is a graphical representation of all colors perceived by humans, and it is represented in two chromaticity coordinates—x and y—as can be seen in Figure 3 [60]. In Figure 3a–c, an example of the 4CSK, 8CSK, and 16CSK constellations is presented based on the specifications provided by the IEEE 802.15.7 standard. Each symbol represents a different combination of the three colors, resulting in different CIE 1931 coordinates. This approach allows a white color to be produced by joining the three colors, which is the desired color for illumination in indoor and outdoor applications. The main advantage of CSK is that it supports dimming and flickering control. First, by simply varying the driving current of the transmitter, the brightness of the resulting white light is adjusted, while the transmitted power is constant. Therefore, there are no fluctuations in light intensity, reducing potential complications in human health, such as nausea or epilepsy [59]. Over the years, many works have been published using CSK modulation, mainly with the aim of developing algorithms to optimize the constellation points [59,61,62]. Interestingly, different approaches with four LEDs (blue, cyan, yellow, and red) began to appear, different from the three transmitters used in conventional CSK [63]. In this way, it was possible to create square constellations identical to QAM.



(a) (b) (c)

Figure 3. CSK constellations provided by the IEEE 802.15.7 standard: (**a**) 4-CSK; (**b**) 8-CSK; (**c**) 16-CSK.

3.2. Multi-Carrier Techniques

The main limitation of the previous single-carrier modulation methods is that, for higher data rates, the Inter-Symbol Interference (ISI) rises considerably due to the nonlinear frequency response of the VLC transmitters [46]. In order to improve the performance and data rate of band-limited VLC systems, multi-carrier signals can be used. In RF systems, the solution to this problem is to use OFDM. In VLC, OFDM is also frequently used in various works; however, other multi-carrier options can also be considered, as will be described throughout this section.

3.2.1. Orthogonal Frequency Division Multiplexing

An OFDM signal consists of a set of orthogonal sinc-shaped subcarriers in the frequency domain with a minimum inter-subcarrier distance of $\frac{1}{T_s}$, where T_s is the subcarrier symbol period. Figure 4 depicts the diagram of a typical OFDM transmitter and receiver. Firstly, the complex data signal, $X = [X_0 \quad X_1 \quad X_2 \quad \ldots \quad X_{N-1}]$, is generated with a length N, where N is the size of the Inverse Fast Fourier Transform (IFFT) and X_k is a complex value associated with a QAM constellation point. Note that, in an OFDM symbol, each X_k represents the data to be carried on the k-th subcarrier. The output of the Inverse Discrete Fourier Transform (IDFT) is calculated as follows:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi kn}{N}\right) \quad for \quad 0 \leq n \leq N-1, \tag{3}$$

where x_n is the time domain complex value obtained through the frequency domain M-QAM signal. A Cyclic Prefix (CP) is considered in OFDM signals to avoid ISI, where the last N_{CP} samples are added at the beginning of the OFDM symbol, $x = [x_{N-N_{\text{CP}}} \ldots x_{N-1}, x_0 \ldots x_{N-1}]$. Note that, although the use of the CP reduces the data rate due to the introduced redundancy, it allows the equalization at the receiver to be simple. However, to avoid inter-subcarrier interference and preserve the subcarrier orthogonality, time and frequency synchronization are needed [64].

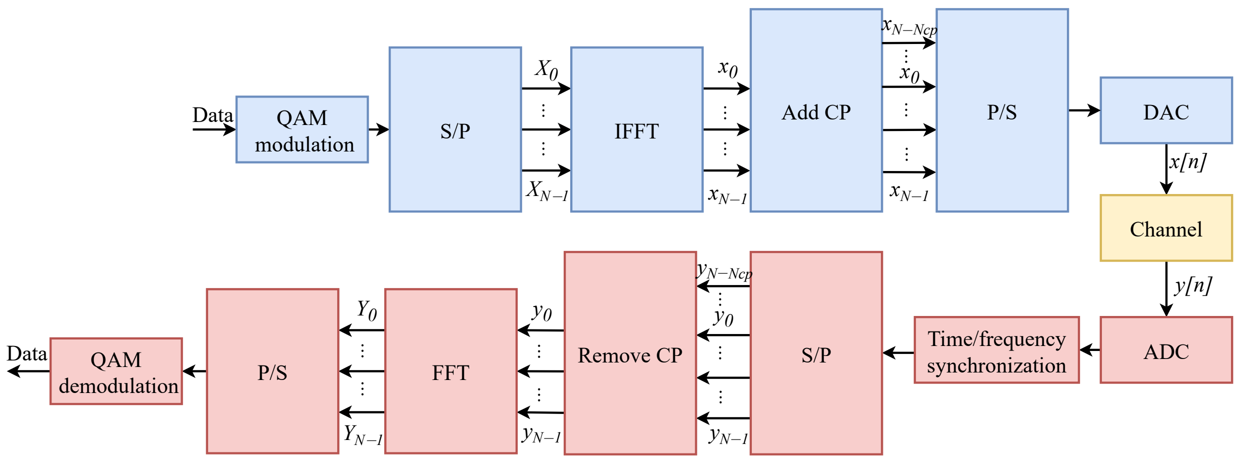


Figure 4. Block diagram of an OFDM communication system with a cyclic prefix.

After transmission through the wireless channel, the CP is removed and the Discrete Fourier Transform (DFT) is performed. Therefore, the received frequency domain signal is represented as follows:

$$Y_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y[n] \exp\left(\frac{-j2\pi kn}{N}\right) \quad for \quad 0 \leq k \leq N-1, \tag{4}$$

where $Y = [Y_0 \quad Y_1 \quad Y_2 \quad \ldots \quad Y_{N-1}]$ is the received frequency domain signal and $y[n]$ is the received time domain signal. This process ends with the receiver Digital Signal Processing (DSP), where the QAM symbols' de-mapping is performed.

The OFDM signal can also be used in VLC with some modifications to be compatible with IM-DD, where the signal directly modulates the intensity of the light. OFDM in VLC was proposed for the first time in [65]. In a typical RF system, OFDM is transmitted through an electrical signal, which can be positive or negative. Furthermore, the receiver includes a local oscillator supporting the coherent detection of the transmitted complex signal, unlike VLC systems, which only allow direct detection. The first modification is associated with the fact that the generated signal is a bipolar complex value. Therefore, it is necessary to convert it to a unipolar real signal. Real OFDM signals can be obtained with the Hermitian symmetry constraint on the subcarriers, resulting in a bipolar real-valued signal [66]. Besides that, the two most-used ways to obtain a unipolar signal are Direct Current (DC)-biased Optical OFDM (DCO-OFDM) and Asymmetrically Clipped Optical OFDM (ACO-OFDM). In DCO-OFDM, a positive DC bias is added, making the signal unipolar [65,67]. In contrast, in ACO-OFDM, the signal is clipped to zero and only the positive parts are transmitted [68]. Both the ACO-OFDM and DCO-OFDM methods were compared by Raed Mesleh et al. through simulation tests [69]. In a VLC system, the authors verified that the distortions are more serious for DCO-OFDM, mainly considering high modulation orders, with the LED clipping effect being the most predominant. However, in [70], the authors suggested the use of a third method named Flip-OFDM. In this strategy, the positive and negative parts are separated and transmitted in two consecutive OFDM symbols, with the negative part being flipped. In the same work, Fernando et al. concluded that Flip-OFDM and ACO-OFDM have the same spectral efficiencies and BER performance. A common phenomenon presented in optical OFDM systems is the high Peak-to-Average-Power Ratio (PAPR), and one of the simplest ways to reduce it is to introduce signal clipping [3]. However, clipping introduces significant distortion, which can lead to poor Bit Error Rate (BER) performance. Consequently, some strategies were introduced to mitigate clipping noise in optical OFDM systems [71–73].

The majority of recent VLC works tend to use OFDM [21,74–76]. Liang-Yu Wei et al. experimentally demonstrated a collimated VLC system using tricolor RGB LDs to produce a bit rate of 20.231 Gbit/s over a channel with 1 m. In this work, a downstream OFDM signal was used [74]. Yi-Chien Wu et al. presented a red/green/violet-LD- and yellow-LED-based four-color white-lighting module with high illuminance of 12,800 lux and a Color-Rending Index (CRI) of 60. In this work, the authors experimentally demonstrated a data rate of 20 Gbit/s using OFDM over a transmission link of 0.8 m [75]. Interestingly, Changmin Lee et al. used a DCO-OFDM signal to modulate the light of two LDs in different optical bands, demonstrating an aggregated bit rate of up to 26 Gbit/s [76]. In 2022, Gutema et al. studied the performance of OFDM for optical wireless communications and applied the technique to Wavelength-Division-Multiplexing (WDM)-based visible light communication. They independently modulated three LEDs of different colors (red, green, and blue) for parallel and simultaneous data transmission. The use of OFDM resulted in an aggregate bit rate of 10.81 Gbit/s with a link of 50 cm [21]. Therefore, with the support of the OFDM waveform, these works reached bit rates of more than 10 Gbit/s, clearly surpassing the works with single-carrier modulation formats.

3.2.2. Modified OFDM Waveforms

A multi-carrier modulation format also commonly utilized in various VLC works is Discrete Multitone (DMT) [77–79]. DMT is a variation of OFDM proposed for the Asymmetric Digital Subscriber Line (ADSL). Due to the slowly varying nature of this type of channel, it allows spectral shaping by bit and power loading, to improve the system performance [3]. Xin Zhu et al. experimentally demonstrated a WDM VLC system operating at 10.72 Gbit/s over 1 m indoor free-space transmission. The authors used a single package with Red, Green, Blue, Cyan, and Yellow LEDs (RGBCY). The light of the LEDs was modulated independently using the 64QAM-DMT modulation format [77]. Alternatively, Wei-Chung Wang et al. showed a total data rate of 34.8 Gbit/s over a free-space with a distance of 0.3 m. This was achieved using Red, Green, and Violet (RGV) LDs modulated with the DMT format, resulting in respective WDM data rates of 18/7.2/9.6 Gbit/s [78], thus demonstrating that DMT can also be a competitive alternative to OFDM.

An interesting possibility is to combine different modulation formats, such as CSK and OFDM. CSK only acts on the polarization current of the transmitters, so it is possible to modulate the transmitted light in the same way. This possibility was suggested by Gunawan et al. in their work, allowing them to reach a bit rate of 26.65 Gbit/s with 1.25 m free-space transmission [80]. In addition to this, the use of a hybrid OFDM-PWM scheme was proposed by Tian Zhang et al. for intensity modulation of the VLC transmitter as a possibility to address the issue of the high PAPR of O-OFDM signals [81]. This hybrid scheme combines O-OFDM with PWM, where the OFDM samples are converted into the pulse width of the signal. The authors concluded through simulation and experimental results that hybrid OFDM-PWM had a better BER performance, lower PAPR, higher luminance, and better resilience to the transmitter nonlinearity compared to the original ACO-OFDM scheme. In turn, Ebrahimi et al. extended this study by converting the most-common ACO-OFDM and DCO-OFDM into the PWM and PPM modulation formats [82]. The authors concluded that the hybrid DCO-OFDM-PWM/PPM schemes had a lower PAPR and BER than the ACO-OFDM and ACO-OFDM-PWM/PPM schemes.

In the literature, there are also some lesser-known modified OFDM implementations that are currently being proposed as potential candidates for VLC, despite being initially proposed for RF, such as filtered OFDM and Filter Bank Multi-Carrier (FBMC) [83–85]. Filtered-OFDM, based on the original OFDM, was proposed in 2015 [86]. This method filters the OFDM signal using digital filters. These filters cause no distortion in the pass-band signal while filtering the Out-Of-Band (OOB) part. In this way, the OOB emission is reduced, resulting in a lower inter-sub-band interference, presented in the OFDM waveform. In [83], filtered-OFDM was proposed for VLC. Yanyan Wang et al. verified through simulations that the filtered-OFDM has better BER performance than ACO-OFDM and DCO-OFDM. In contrast to filtered-OFDM, FBMC applies a filter per subcarrier. Therefore, the side lobes of each subcarrier are much weaker, resulting in even lower OOB emission [84]. In [85], FBMC was experimentally demonstrated in a VLC system with a blue LED using a pre-equalization method to improve the modulation bandwidth, achieving a bit rate greater than 2 Gbit/s.

3.2.3. Generalized Frequency Division Multiplexing

Recently, new modulation formats have started to appear as an alternative to OFDM, namely Generalized Frequency Division Multiplexing (GFDM) and Digital Subcarrier Multiplexing (DSCM). Interestingly, they were proposed by two different scientific communities, RF and optical fiber, respectively. The main disadvantages of OFDM are a high PAPR, high OOB emissions, and the requirement to use large CPs, considerably decreasing the spectral efficiency. All these issues have been partially solved in these waveforms [87]. The block diagram of the GFDM transmitter and receiver is shown in Figure 5. Contrary to OFDM, in GFDM signals, multiple pulse-shaped subcarriers with low symbol rates are multiplexed in the frequency domain in order to produce a high bandwidth signal, allowing each subcarrier to be individually modulated having its own bandwidth, pulse shaping, frequency, and CP, avoiding the use of the Fast Fourier Transform (FFT) or IFFT. The transmit signal, $x[n]$, is obtained through the summation of all transmit symbols:

$$x[n] = \sum_{k=0}^{N_{SC}-1} (d_k * g_k) \exp(j2\pi \frac{k}{N_{SC}} n) \quad for \quad 0 \leq n \leq N-1, \tag{5}$$

where d_k is the QAM symbols transmitted on the k-th subcarrier and g_k corresponds to the impulse response of the pulse-shaping filter applied to the k-th subcarrier. The Root-Raised

Cosine (RRC) filter is widely used as a pulse-shaping filter in GFDM. The total number of QAM symbols is $N = N_{SC}M$, where N_{SC} is the number of subcarriers and M is the number of symbols per subcarrier. Furthermore, GFDM takes advantage of the simple equalization of OFDM, adding the flexibility of occupying the desired frequencies and controlling OOB emission. GFDM is a multi-carrier modulation technique that was initially proposed for RF wireless communications in 2009 [88]. As verified for OFDM, the transmitted light signal needs to be unipolar and real. Therefore, the optical GFDM appears with two different approaches, with the same working principle of DCO-OFDM and Flip-OFDM, giving rise to DCO-GFDM and Flip-GFDM [89,90].

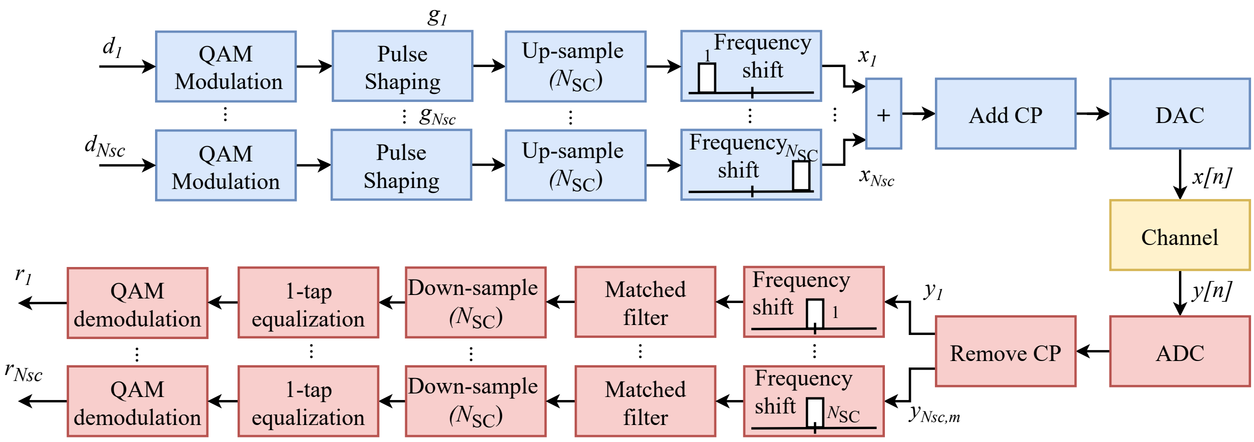


Figure 5. Block diagram of the GFDM transceiver.

In the literature, there are some works that propose the adoption of this waveform in VLC, but contrary to RF-based wireless communications, there are only a few studies on GFDM for VLC [87,89,90]. In [87,89], the authors showed that GFDM and OFDM have a similar BER performance in a VLC system, but the main advantage verified for GFDM was the lower OOB emission. Saengudomlert et al. proposed a Flip-GFDM modulation scheme with dimming support for VLC. Unlike DCO-GFDM, where dimming is adjusted by changing the DC bias, the proposed method avoids signal clipping and provides wider dimming ranges [90].

3.2.4. Digital Subcarrier Multiplexing

On the other hand, DSCM is also a multi-carrier modulation technique, but is more commonly used in fiber optics systems [91–93]. Similar to GFDM, in DSCM, usually, each subcarrier is pulse-shaped using an RRC filter, with a minimum subcarrier spacing of $(1 + \alpha)/\text{Ts}$, where α is the roll-off factor of the pulse-shaping filter, to enable the orthogonality between subcarriers. Furthermore, due to the low OOB emission, no guard bands are needed between adjacent channels, as with OFDM. Despite the many similarities with GFDM, DSCM uses wider subcarriers, so it needs to implement a single-carrier-compatible DSP, which is more complex than the single-tap equalization used in GFDM. In contrast, GFDM needs to use CP to achieve this lower complexity, reducing the spectral efficiency.

DSCM signal modulation and demodulation are presented in Figure 6. After data generation and QAM modulation, the signal is up-sampled. Then, a set of symbols of each subcarrier is pulse-shaped using an RRC filter. Finally, each subcarrier is shifted to its respective central frequency, producing a signal identical to (5). The signal demodulation of each subcarrier is performed individually, each being downconverted to the baseband, filtered with a matched filter, and finally, the QAM symbols are decoded. Recently, record high bit rates were obtained in a VLC system with diffused light using the DSCM waveform [23,94].

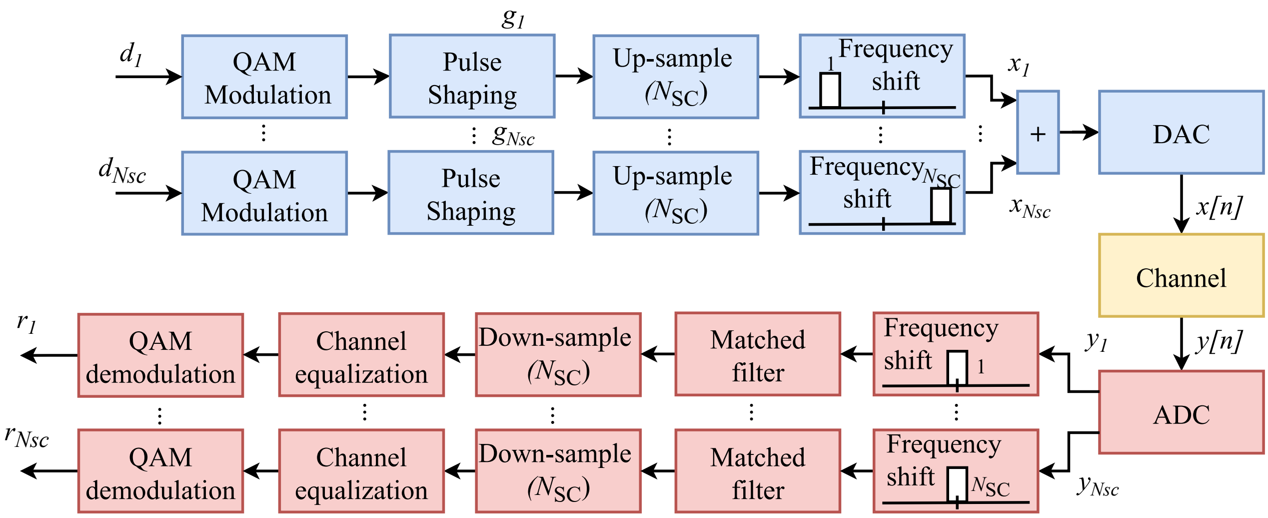


Figure 6. Diagram of the DSCM multiplexing and de-multiplexing.

3.3. VLC MIMO Systems

So far, it has been assumed that the VLC system is composed of a single transmitter and receiver. However, currently, a typical room in a home or office contains several LEDs to ensure sufficient lighting. Therefore, in a visible light communications scenario, MIMO can be implemented due to the multiple transmitters [6]. The introduction of MIMO in VLC allows improving the reliability and bit rate of the system, which is currently limited by the transmitters' bandwidth [95]. However, contrary to RF MIMO systems, which have multiple different channels between the transmitter and the receiver, in VLC systems, this is not verified due to the similarities of the channels. The transmitters and receivers are often confined to a single room, resulting in high channel correlation [6]. Therefore, the angular diversity receiver was introduced in some works to improve the performance of VLC-MIMO systems through the decorrelation of the optical channels [96–99]. An angular diversity receiver is composed of a set of narrow field-of-view detectors that point in different directions [98]. In [96], the authors presented two designs of angle diversity receivers, pyramid receivers and hemispheric receivers. The authors concluded that the proposed receivers outperformed the spatially separated photodiode array. C. Chen et al. demonstrated the operation of a different topology, the generalized angular diversity receiver, which consists of a detector in the middle and multiple inclined detectors around it, in which its inclination is adjustable [97]. Furthermore, some techniques have been also studied to alleviate the channel correlation issue and improve the performance of the VLC-MIMO systems. The proposed VLC-MIMO techniques are based on those used for RF-MIMO systems, where three methods stand out, namely Repetition Coding (RC), Spatial Multiplexing (SMP), and Spatial Modulation (SM) [100].

The main feature of the first method is its simplicity since the same data stream is used in all transmitters, thus allowing increasing the robustness of the system [99,101]. In [101], M. Safari et al. investigated the performance of RC and simple Orthogonal Space–Time Block Codes (OSTBCs), such as the Alamouti scheme. The authors concluded that a multiple-input single-output system with RC outperforms OSTBCs because the signal power from the transmitters constructively adds up at the VLC receiver. Therefore, with this work, it was concluded that the use of OSTBCs is not necessary for VLC. In addition, Reference [99] studied the performance of the RC for a VLC-MIMO system using angular diversity receivers under imperfect channel state information. For different receiver locations and semi-half angles, the analytical results showed that this system has better error performance than a multiple-input, single-output VLC system.

On the other hand, in SMP, the transmitters employ different signals, increasing the spectral efficiency of the system [102,103]. U. Siddiqi et al. proposed an adaptive bit and power loading for a DCO-OFDM VLC MIMO system. The adaptive algorithm chooses between RC and SMP MIMO modes and applies bit- and power-loading methods to improve the data rate for a given target BER [102]. In [103], Guo et al. proposed a novel superposed 64QAM constellation scheme for a 2×2 VLC-MIMO system using the SMP scheme. The authors experimentally demonstrated that the proposed superposed constellation combined with the SMP technique in VLC-MIMO systems achieves multiplexing gains, even in highly correlated VLC channels, thus providing better performance than the traditional superposed 64QAM constellation.

Lastly, in SM, only one transmitter is considered at each time slot. In this technique, each VLC transmitter is associated with a particular symbol of the constellation; therefore, whenever it is necessary to transmit that symbol, the corresponding transmitter is activated and the remaining are turned off. In this way, when the receiver receives a certain symbol, it is easy to estimate the transmitter. The main advantage is that, in this way, the information is encoded in two dimensions. In addition to the information encoded in the signal, there is also a modulated signal in space, thus increasing the spectral efficiency of the system. Furthermore, only one transmitter is connected at any one time, thus avoiding cross-channel interference, simplifying receiver complexity [6]. In [100], the authors compared the three MIMO techniques using different 4×4 MIMO setups, with different transmitter and receiver positions. The RC technique presents the worst spectral efficiency due to the use of the same signal in all transmitters, but this results in easier system alignment. Contrarily, SMP requires a low channel correlation between the transmitter and the receiver, but provides the highest data rates. In turn, SM provides improved spectral efficiencies even at a low Signal-to-Noise Ratio (SNR) and it works efficiently at high channel correlation.

4. Capacity-Achieving Strategies

As highlighted in the previous section, impressive progress has been made during the last couple of decades in the development of advanced modulation formats and signal-processing techniques to maximize the performance of VLC systems. Notoriously, the adoption of multi-carrier modulation has enabled the efficient exploitation of the available bandwidth, thus optimizing the spectral efficiency of the system.

Following this trend, in this section, we delve in more detail into the recent adoption of advanced multi-carrier modulation techniques that aim at approaching the ultimate limit set by Shannon's capacity. Namely, by adaptively optimizing the allocation of transmitted information over different frequency bands, significant capacity gains can be achieved. Employing traditional QAM formats, this can be achieved through bit- and power-loading techniques. Instead, resorting to capacity-achieving modulation formats such as Probabilistic Constellation Shaping (PCS), it is possible to squeeze out the ultimate spectral efficiency limits of VLC systems.

4.1. Bit Loading and Power Loading

With that problem in mind, some articles suggested the application of adaptive Power Loading (PL) and Bit Loading (BL) in multi-carrier signals for VLC systems. In this way, it was possible to improve the system bit rate and reduce the filtering effect introduced by the channel [104]. In the BL process, the main objective is to adapt the size of the QAM constellations of each subcarrier. In turn, PL applies scalar power ratios to each subcarrier, adjusting the transmitted power. The power ratio between subcarriers emphasizes some subcarriers, at the expense of decreasing the transmitted power in others. In [105], the authors studied the application of both BL and PL for optical fiber systems, obtaining gains when BL and PL were applied independently. However, the best case was found in the joint application of PL and BL, mitigating the filtering penalties. In VLC, R. Bian et al. experimentally demonstrated an RGBY-LED-based system with a bit rate of 15.73 Gbit/s, where each wavelength was modulated using DCO-OFDM with adaptive BL [20].

Some algorithms have been developed to perform a bit-and-power-ratio allocation in order to optimize the bit distribution and the transmitted power of all subcarriers based on the measured SNR. One of the most-well-known algorithms for allocating power across sub-carriers is the water-filling algorithm [106]. Furthermore, other widely used PL/BL approaches are Chow's algorithm [107] and the Levin–Campello algorithm [108,109]. The Levin–Campello algorithm, which was designed to reduce the nonlinearities introduced by ADSL systems, solves both the bit rate maximization and the margin maximization (minimum transmitted power) problems with low complexity. Contrary to the water-filling algorithm, which distributes the power over the subcarriers, the main objective of this algorithm is to allocate bits to each subcarrier. Then, after allocating bits, a power adjustment is made for each sub-carrier.

4.2. Entropy Loading

Despite their simplicity and widespread use in various studies, PL/BL methods have significant limitations, mainly because uniform QAM modulation formats have an integer number of bits per symbol, resulting in an entropy of the constellation equal to:

$$\mathrm{H} = \log_2(\mathrm{M}), \tag{6}$$

where M is the order of the QAM modulation. Therefore, these methods do not have the flexibility to adapt to the distortions introduced by the channel, and in many cases, the bit rate is not being maximized, thus increasing the gap to Shannon capacity. In order to solve this problem, some works proposed the use of continuous entropies instead of discrete numbers of bits, using PCS [110,111]. The main goal of this method is to adapt the probability distribution function of the QAM constellation, in order to maximize the net bit rate of the system. Usually, in a QAM constellation, all symbols have the same probability, so the constellations have an integer number of bits per symbol. Instead, with PCS, it is possible to continuously adjust the entropy and the average signal power by assigning a probability distribution function [112]. According to Shannon's theory for Additive White Gaussian Noise (AWGN) channels, the Maxwell–Boltzmann distribution requires the minimum signal power to achieve a given bit rate. Therefore, the QAM symbol probabilities can be calculated as follows [110]:

$$\mathrm{P}_{x_n} = \frac{\exp(-\lambda|x_n|)}{\sum_{k=1}^{M}\exp(-\lambda|x_k|)}, \tag{7}$$

where $\lambda \geq 0$ is the shaping parameter and x_n is the symbol n in the M-QAM constellation. Therefore, for $\lambda = 0$, the probability the all symbols will be $\mathrm{P}_{x_n} = \frac{1}{M}$, resulting in a uniform distribution. For higher λ values, the probability of outer QAM symbols decreases and the probability of inner ones increases, resulting in a lower number of bits per symbol. The source entropy of an M-QAM constellation (number of bits per symbol), H, represents the transmitted information rate and depends on the probability distribution [113]:

$$\mathrm{H} = -\sum_{n=1}^{M} \mathrm{P}_{x_n}\log_2(\mathrm{P}_{x_n}). \tag{8}$$

In Figure 7, we can see four 64QAM constellations for entropies between 3 and 6 bit/symbol. As expected, for lower entropies, the outer constellation symbols start to have a much lower probability compared to the rest. For the Maxwell–Boltzmann distribution, a Distribution Matcher (DM) is needed to convert an input uniformly distributed bit stream into an output non-uniformly distributed symbol sequence. Currently, various options to implement the PCS DMs have been proposed, but the Constant Composition Distribution Matcher (CCDM) is by far the most-used algorithm [114].

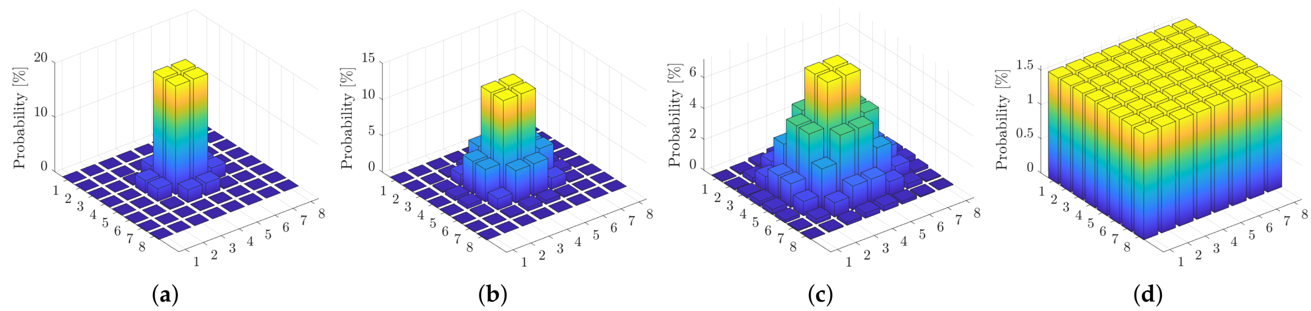


Figure 7. Graphical illustration for PCS in a 64QAM constellation with four different entropies: (**a**) 3 bit/symbol; (**b**) 4 bit/symbol; (**c**) 5 bit/symbol; (**d**) 6 bit/symbol.

In order to take advantage of PCS and multi-carrier signals, some works implemented an Entropy-Loading (EL) method, demonstrating a capacity-achieving solution [21,94,115]. EL is a method that aims to maximize the data rate of the system. The ideal entropy per subcarrier is estimated based on the measured SNR per subcarrier and a performance metric that guarantees an error-free system after FEC. This entropy is estimated through several iterations until it converges to the optimal value. However, considering that the implementation of an ideal DM is complex, it will hardly be possible to converge to the optimal entropy for the measured SNR [94]. The EL method was demonstrated for the first time by Di Che et al. for colored SNR optical channels with band-limited cascaded-Reconfigurable Optical Add–Drop Multiplexers (ROADMs) [116]. The authors demonstrated the advantage of the EL method over the single-carrier PCS in band-limited systems. In VLC systems, the EL scheme was implemented for the first time in 2018 by Xie et al. In their work, the authors experimentally demonstrated a bit rate increment of 26.8% in comparison with OFDM using a bit-loading technique [115]. In turn, using OFDM and PCS together, Gutema et al. achieved a 25% higher transmission rate than the adaptive bit–power-loading algorithm under the same channel conditions [21]. Furthermore, our group experimentally demonstrated an RGB-LD-based VLC system capable of both lighting and high-speed communications. An EL method based on PCS was proposed to maximize the net bit rate of a DSCM signal. A bit rate of 31.2 Gbit/s over 0.90 m of free-space distance was presented [94]. In [23], we extended the first work by presenting a distance-adaptive VLC system. Using again together DSCM and PCS, we experimentally demonstrated a maximum bit rate of 46 Gbit/s at 50 cm, linearly decreasing over distance, down to 26 Gbit/s after 200 cm.

From what has been mentioned above, currently, this modulation technique appears as the main candidate to be used in future VLC systems, as it allows obtaining data rates closer to Shannon's capacity. Moreover, this method allows continuous adaptation to distortions introduced over time in the channel. In a VLC channel, there are usually many lights external to the system (sunlight or indoor lighting) that can affect the performance of the communication link, introducing a variation of the channel characteristics over time. In [112], the authors experimentally demonstrated the application of time-adaptive PCS to change the bit rate according to the conditions of an outdoor FSO channel, adjusting the source entropy of the single-carrier over time. Therefore, in addition to the ability to adjust entropy over frequency (subcarriers), in the EL method, there is also the possibility of making this adjustment over time when there are variations in the channel.

4.3. Geometric Constellation Shaping

In many of the recent works, the use of PCS has been increasingly considered, mainly because it is currently the method that guarantees the best spectral efficiency. However, in addition to this method, which focuses on adjusting the probability of symbols, there is also the possibility of adjusting the geometry of the constellation in order to maximize the data rate of the system. The presented PCS method is ideal for AWGN channels using a Maxwell–Boltzmann probability distribution of symbols. However, for non-AWGN channels, for example, due to the nonlinear response of the VLC transmitter, the adaptation of the constellation geometry can achieve better results. Geometric Constellation Shaping (GCS) is a capacity-achieving technique that uses non-uniformly spaced constellation symbols, and by adjusting the location of the symbols, it is able to closely approximate Shannon's capacity [117]. Recently, the use of autoencoders, based on end-to-end deep learning, has been used to obtain the optimum constellation [118]. Compared to more-traditional methods, it stands out for taking into account the state of the channel at a given moment, with the possibility of adjusting it over time, which can be fundamental in VLC systems. The GCS has been demonstrated for different applications, mainly in fiber optics communications [119–121]. However, in VLC, there are currently few works that use this technique [122,123]. Therefore, the use of this technique, its comparison with other methods (PCS for instance), and its joint use with PCS have to be studied. The performance of future VLC systems can be improved since the system will become even more robust, making it more of a candidate for beyond-5G wireless communications.

5. Summary and Future Work

In the last decade, many VLC articles have been published, and it is expected that it will be a new type of wireless communication present in 6G. However, at the moment, there are a number of key issues. Based on this survey of recent trends and technologies for indoor VLC, we present some challenges that should be studied in the near future. First, there are some commercialization challenges due to the need to make modifications to the lamps, which may diminish the interest of manufacturers. For mobile device manufacturers, integrating new hardware into phones can result in a higher cost, driving up cell phone prices. Therefore, to achieve the goal of integrating VLC in future wireless communications, it is crucial to improve the energy efficiency of current VLC transmitters, as well as their cost to allow their large-scale implementation. Furthermore, it will also be important to clarify the best approach, whether with LEDs, LDs, or even a hybrid solution that uses both possibilities in order to offer good-quality lighting and communications. Moreover, considering that VLC is seen as a good technology to complement RF-based wireless systems, the authors think that the development of a hybrid RF-VLC approach could be a trend in VLC systems, where ways of joining both technologies and how they can cooperate with each other should be studied. This should also be performed without discarding the various applications that VLC can have, including high-speed communications with indoor localization, communication between vehicles, and underwater communications.

Additionally, one of the main problems with indoor VLC is the continuous need for data transmission, while indoor lights may be dimmed or turned off by users. For example, on bright days or before bedtime, light is not needed, but the Internet connection is. For this reason, VLC should be seen, at the moment, as an alternative to WiFi, but not as its replacement, as there will be situations where VLC will not work as a standalone solution. However, it will be interesting to develop strategies to solve this problem. The obvious solution is to use infrared as a backup in these situations, but the performance of non-collimated IR communications is not sufficient. Therefore, the solution will have to go through the use of visible light. Currently, there are some works proposing the operation of the VLC system with the light off [124,125]. The idea of these works is to produce an average brightness of light so low that it cannot be detected by humans, appearing as if the light sources are turned off, but it is possible that the receivers detect these light variations [126]. In [124], Borogovac et al. through simulations concluded that very low light emission is sufficient to maintain data rates of several megabits/second. However, with the system proposed by Tian et al., it was only possible to achieve a data rate of 1.6 Kbit/s at a distance of 10 cm [125]. Therefore, at the moment, there is no clear solution to this problem, and from the authors' perspective, it is important to address this issue in future works.

Regarding the modulation techniques for visible light communications, we currently observe a clear trend for a transition from single-carrier to multi-carrier modulation formats. Several multi-carrier modulation formats were recently presented, each with its advantages and disadvantages, but so far, it is not clear which could be the best approach. OFDM is the accepted modulation technique for WiFi, but for VLC, this is an open research area. Thus, an area of study in the future will be to compare the different formats in a VLC system under different practical scenarios, such as background light interference, since conventional lamps or even sunlight can coexist in the same room as the VLC link.

In summary, VLC is expected to deliver high-speed communications with good energy efficiency and secure communications. However, there is still a way to go to improve the current state of technology and increase its popularity both within industry and the general population.

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Abbreviations

The following abbreviations are used in this manuscript:

ACO-OFDM	Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing
ADSL	Asymmetric Digital Subscriber Line
AOA	Angle Of Arrival
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BL	Bit Loading
CAP	Carrier-less Amplitude and Phase modulation
CCDM	Constant Composition Distribution Matcher
CIE	Commission Internationale de l'éclairage
CP	Cyclic Prefix
CRI	Color-Rending Index
CSK	Color-Shift Keying
DCO-OFDM	DC-biased Optical Orthogonal Frequency Division Multiplexing
DM	Distribution Matcher
DMT	Discrete Multitone
DSCM	Digital Subcarrier Multiplexing
DSP	Digital Signal Processing
EL	Entropy Loading
FBMC	Filter Bank Multi-Carrier
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FSO	Free-Space Optics
GCS	Geometric Constellation Shaping
GFDM	Generalized Frequency Division Multiplexing
GPS	Global Positioning System
HB	High Bandwidth

IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IM-DD	Intensity Modulated Direct Detection
ISI	Inter-Symbol Interference
JEITA	Japan Electronics and Information Technology Industries Association
LD	Laser Diode
LED	Light-Emitting Diode
MAC	Media Access Control
MIMO	Multiple-Input, Multiple-Output
MPPM	Multi-Pulse Position Modulation
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-Of-Band
OOK	On–Off Keying
OPPM	Overlapping Pulse Position Modulation
OSTBC	Orthogonal Space–Time Block Code
PCS	Probabilistic Constellation Shaping
PHY	Physical
PM	Pulse Modulation
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average-Power Ratio
PL	Power Loading
PPM	Pulse Position Modulation
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
RC	Repetition Coding
RF	Radio Frequency
RGB	Red, Green, and Blue
RGBCY	Red, Green, Blue, Cyan, and Yellow
RGV	Red, Green, and Violet
ROADM	Reconfigurable Optical Add–Drop Multiplexer
RRC	Root-Raised Cosine
RSS	Received Signal Strength
SM	Spatial Modulation
SMP	Spatial Multiplexing
SNR	Signal-to-Noise Ratio
TGbb	Task Group bb
TOA	Time Of Arrival
UWOC	Underwater Optical Communications
VPPM	Variable-Pulse-Position Modulation
VLC	Visible Light Communications
VLCC	Visible Light Communication Consortium
WDM	Wavelength Division Multiplexing

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