Visible Light Communications (VLC) Technology

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Abstract

This article reviews the visible light communications (VLC) technology. It presents the VLC communication system: the transmitter, the channel, and the receiver. The single and multi-channel transceivers are presented. The channel for a system that uses a single light emitting diodes (LED) and the matrix representing the multi-colour channel are discussed. Various modulation schemes are reviewed. Basic techniques used to implement a VLC system are highlighted and different causes of impairment are underlined. A word is given on the standardisation of the VLC technology. Numerous applications of VLC technology are given. Challenges for VLC practical implementation and commercialisation are reviewed. Advances in VLC and future research issues are discussed.

Index terms: VLC technology, VLC, Modulation methods, Dimming control, MIMO, Optical wireless communications.

1 Introduction

Visible light communications (VLC) is a communication technology in which the visible spectrum is modulated to transmit data. Due to the propagation distance of the light emitting diodes (LEDs), VLC is a short-range communication technology.

In the electromagnetic spectrum, the visible spectrum covers between 350 nm and 800 nm of wavelength and the frequencies are comprised between 4.3 x 10^{14} Hz and 7.5 x 10^{14} Hz. In VLC technology, LEDs are used because their currents intensity are easily modulated, with respect to their counterparts i.e. incandescent and fluorescent light bulbs. LEDs are based on a doping process, consequently their efficiency and their durability are improved, and they have longer lifetime in comparison to the incandescent and fluorescent light bulbs [1]. In any lighting application (general lighting, signage, displays, vehicles' lights to mention only a few), it is predicted that LEDs are going to overtake the usual light bulbs. They are going to provide double applications, namely lighting and communication. As in the case of any communication technology, transmission in VLC technology is generally characterised by a transmission matrix, which is a mathematical representation of the channel impulse response. The size of this matrix varies with the number of groups of LEDs and with the number of LEDs per group. With multiple blocks of multiple LEDs, very high data rate transmission can be performed. When the transmission is corrupted by noise and interferences from unwanted sources, equalization techniques for channel pre-compensation, knowing the channel behaviour, help to recover the symbols. VLC technology faces many implementation challenges: some are related to the communication system design and others are related to the practical implementation. To properly implement a VLC communication system, some constraints have to be met: the lighting constraints related to the average optical power and the communication objective related to the throughput. During transmission, LED flickering is to be avoided and under dimming conditions, the data rate has to be reduced considerably [1], [2] and [3].

VLC technology has been around for a while. The history started in 1880, when Alexander Graham Bell invented the photophone [4]. This instrument was used to transmit speech by modulating the sunlight. In the 1960s, optical communications were born. Light amplification by stimulated emission of radiation (LASER) and light emitting diodes (LEDs) were invented [5]. Later, in 2003, recent work began on VLC technology. Natagawa Laboratory, in Keio University, Japan, used LEDs to transmit data. In 2006, the center for information communication technology research (CICTR), Pen State, USA, proposed the first combination of power line communications (PLC) and white LED to provide broadband access for indoor applications. Since then, there have been numerous research activities on VLC. Among them, light fidelity (Li-Fi), founded by Harald Haas from the University of Edinburgh in the United Kingdom [4], is one of the most interesting achievement of VLC for the several years.

This article is organised as follows: The structure of the VLC transceiver, the transfer matrix, the channel response and the signal-to-noise ratio (SNR) are presented in Section 2. Section 3 presents the latest suggestions of the standardisation organisations (SDOs) on VLC technology. The techniques proposed by the IEEE 802.15.7 standards are highlighted and the efforts of the Japanese organisation on VLC technology named visible light communications consortium (VLCC) are presented. In Section 4, the VLC modulation methods are detailed. Due to the fact that VLC technology is characterised by a high SNR [3], techniques applied to systems with high SNR work in VLC systems. In this section, we present some examples. Pulse position modulation (PPM) and on-off keying (OOK), suitably used for low and medium data rate applications, are presented. Some complex modulation such as the orthogonal frequency division multiplexing (OFDM) and color shift keying (CSK), deployed for high data rate communication systems, are also presented. Section 4 also highlights the use of the spatial diversity in VLC technology. Section 5 focuses on the challenges of VLC practical implementation. Dimming and LEDs control methods are presented for the above-mentioned modulation techniques. This is followed by the potential applications of VLC technology presented in Section 6. In Section 7, the article presents the challenges of the commercialisation of VLC technology. Followed by the recent advances in VLC technology in Section 8. Section 9 looks at the unsolved problems in VLC and discusses future directions.

2 VLC communication systems

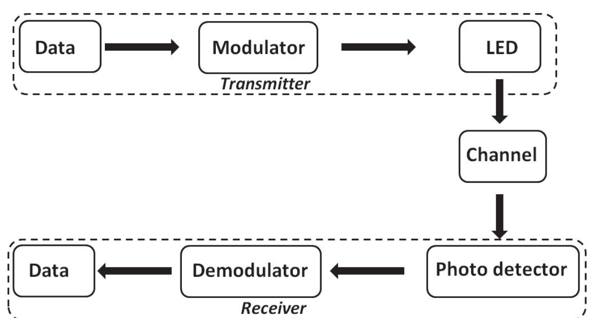

Figure 1: Basic transmission blocks in a VLC systems

VLC technology is part of the set of optical wireless communications (OWC). Hence the physical optical principles can be applied to the VLC systems. In fact, the carrier in VLC is the visible rays used for illumination. VLC is typically characterised by a non negative and non-coherent signal transmission. It respects the communication principle in which three main parts are considered: a transmitter, a channel and a receiver. Fig. 1 shows the basic blocks of a VLC transmission system. It is made of the transmitter, the channel and the receiver, and , for a system corrupted by the additive white Gaussian noise (AWGN), the transmission is always governed by

$$\mathbf{r}_i = \mathbf{H}\mathbf{s}_i + \omega_i, \tag{1}$$

where $\mathbf{r}_i$ and $\mathbf{s}_i$ are the received and the transmitted sets of symbols respectively, $\mathbf{H}$ is the channel response and ω_i the channel noise. A suitable model for VLC communication systems is depicted in Fig. 2. It shows two electrical domains and one optical domain. The modulated signal, added to a DC voltage is used to power the LED, this constitutes the transmitter. The LED in its operation produces the light and at the same time, convey the information through the channel. The receiver is made of the the photodetector (PD) and the demodulator. The PD detects the light and produce an electrical signal composed of the message plus noise. Part of the noise here is produced by the channel even though in the model, we represent the total noise in the electrical domain. This is due to the fact that the PD converts both the message and the optical noise into an electrical current.

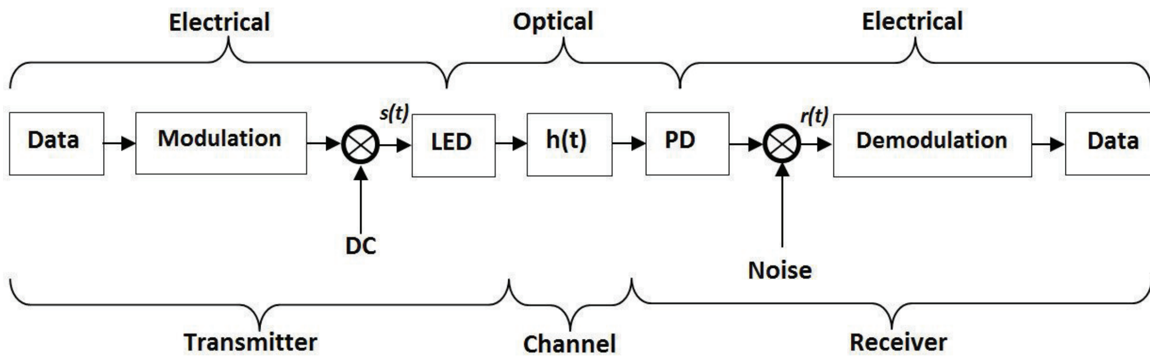

Figure 2: Model of VLC communication system

In most modulation schemes highlighted in this article, the model exploited does not inject any DC offset. It uses the message signal to power the LED. nevertheless, in the case of frequency shift keying (FSK) and OFDM techniques for example, the model in Fig. 2 is well indicated to be used.

2.1 The VLC transmitter

In VLC systems, the transmitter groups, in one module, the data source, the modulation module and the LED. The last two elements are the very important elements in a VLC transmitter. Two types of LEDs are used in VLC systems: The single-colour LED and the multicolour LEDs. The multicolour LED groups in one package multiple single-colour LEDs. The most used multicolour LED is the red-green-blue (RGB) LED. In multi-carrier systems, each of the colour LEDs included in the package represents an antenna, corresponding to one channel. There are as many channels in the system as there are LEDs in the package. Hence, a given number of colour-LEDs will provide the same number of distinct channels. Consequently, the RGB-LED transmitter is seen as a special multichannel transmitter that can be used to deploy multicarrier modulation techniques. For example, with a single RGB-LED, a three-by-three multiple inputs-multiple outputs (3×3 MIMO) technique is applicable over the VLC channel [6], [7]. Fig. 3 depicts the two common types of VLC transmitter: Fig. 3-a, a single VLC transmitter and Fig. 3-b, a 3 channel VLC transmitter.

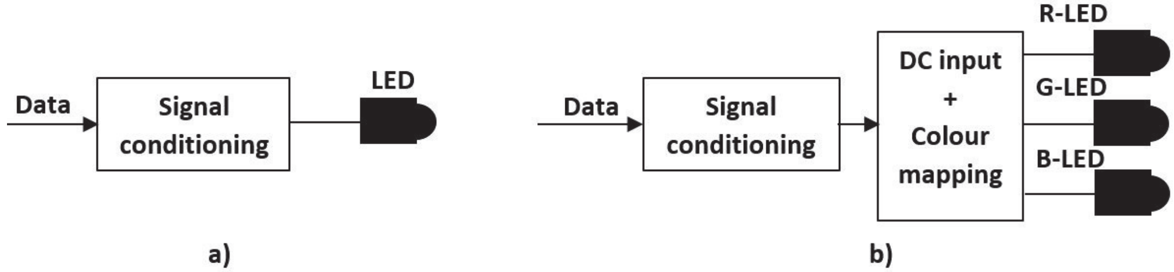

Figure 3: VLC transmitters: a) the single LED transmitter, b) a 3 channels VLC transmitter

2.2 The VLC channel

In communication, the channel represents the space between the transmitter and the receiver. It is characterised by its ability to transmit the carrier signal, and, it is influenced by many factors such as attenuation, interference and noise. In VLC technology, the channel is the space between the LED and the PD. It is mathematically represented by its transfer function $\mathbf{H}$ (see (1)). Two main types of channels are considered in VLC communication systems: the single VLC channel involving a single LED and a single PD, and the multichannel VLC systems in which the transmitter is made of multicolour LEDs. In this second case, the PD is made of more than one detector, each of them being sensitive to a colour from the transmitter.

2.2.1 A single VLC channel (single input-single output system (SISO))

In single VLC channel, one LED and one PD are used to achieve transmission. The capacity C_{SISO} of the transmission link is given by [8]

$$C_{SISO} = log_2(1 + \frac{g^2 P_t}{\sigma^2 B}), \tag{2}$$

where P_t, independent of the illumination, denotes the transmitter power, B the transmission bandwidth, σ^2 the variance of the total noise in an AWGN channel, and g the channel gain. The quantity $g^2 P_t / \sigma^2 B$ represents the SNR characterising the channel. The distribution link is organised in two different types: a line-of-sight (LOS, direct and non-direct) link, or a non-line-of-sight (NLOS) link.

- LOS VLC link

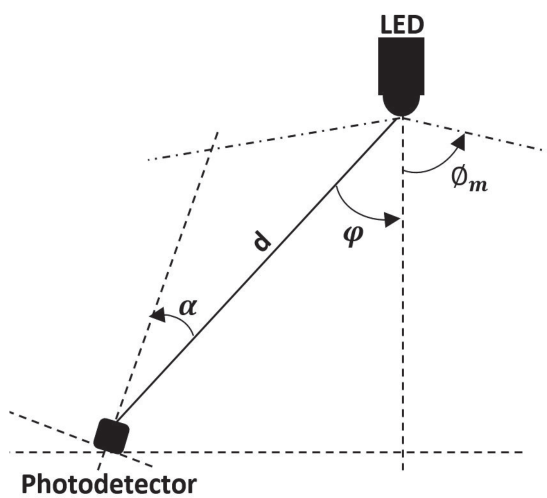

Figure 4: Non-direct line-of-sight (ndLOS) distribution of a single ray

In LOS link, there is a straight link without obstacle between the LED and the PD (see Fig. 4). We distinguish the direct LOS (dLOS) in which the LED is linked to the PD with 0^o incidence ($\varphi = 0$), and the non-direct LOS (ndLOS) in which the incidence is not null ($\varphi \neq 0$). dLOS and ndLOS links are similar in terms of model. The LOS system has been studied and more information can be found in the literature in [9], [10], [11] and [12]. In LOS VLC link, (1) becomes

$$\mathbf{r}_i = \mathbf{H}_{LOS}\mathbf{s}_i + \omega_i, \tag{3}$$

where $\mathbf{H}_{LOS}$ is the LOS channel response. This model (3) was used in [13] to describe the VLC transmission system. The diffuse link model of a LOS VLC transmission is represented in Fig. 4. The bandwidth in this situation can be determined by the summation of the LOS and diffuse component of the received signal [14]. The transmission gain $g_{(LOS)}$, studied and presented in [11], [13], [14] and [15], is given by

$$g_{(LOS)} = [\frac{(\xi + 1)A}{2\pi d^2}].cos^{\xi}(\varphi).T_f(\alpha).g(\alpha).cos(\alpha), \tag{4}$$

where the incidence angle φ is given by $0 \leq \varphi \leq \Phi_m$, $T_f(\varphi)$ is the transmission filter and $g(\alpha)$ the the concentration gain. d represents the minimum distance between the LED and the PD. It is to be noted that $g_{(LOS)}$ is null for $\varphi > \Phi_m$ [8]. In [16], the VLC channel is detailed with more distribution options and different situations is evaluated to characterise the transmission environment. A difference between the direct LOS and the non-direct LOS is underlined. The channel is modelled as proposed in [13], taking into account the direct link between the transmitter and the receiver, including the reflection paths as presented in [17], [18].

- NLOS VLC link

In NLOS VLC system, the light rays from the LED reach the PD after single or multiple reflections, this is due to an obstacle between the sender and the receiver. In a typical NLOS link between sender and receiver, the channel impulse response is seen as an infinite sum of light rays after many reflections [19], [20], and can be expressed by

$$\mathbf{H}_{NLOS} = \sum_{k=0}^{\infty} h^{(k)}, \tag{5}$$

where $h^{(k)}$ is the impulse response of rays undergoing the $k^{(th)}$ path. But this equation can be rearranged by subdividing the indoor environment into a finite number of portions. The transmission is characterised in this case by a transmission equation using the LOS transfer matrix multiplied by a coefficient ρ characterising the NLOS link [16]. For a NLOS link, (1) becomes

$$\mathbf{r}_i = \mathbf{H}_{NLOS}\mathbf{s}_i + \omega_i = \rho\mathbf{H}_{LOS}\mathbf{s}_i + \omega_i. \tag{6}$$

2.2.2 Multi-channel VLC systems

Multi-carrier communication systems can be implemented over the VLC channel by using more than one colour LED to inject the message signal to the channel. In this situation, we have finite numbers n and z of LEDs and PDs used as antenna and detectors respectively. n can be divided by the number m of groups of LEDs to obtain the number of LEDs per group. The transfer matrix in multi-carrier VLC systems is given by

$$\mathbf{H}_{multi} = \begin{bmatrix} h_{1,1} & h_{1,2} & ... & h_{1,n} \\ h_{2,1} & h_{2,2} & ... & h_{2,n} \\ . & . & ... & . \\ . & . & ... & . \\ . & . & ... & . \\ h_{z,1} & h_{z,2} & ... & h_{z,n} \end{bmatrix}, \tag{7}$$

where the entries $h_{i,i}$ represent the front-end gain between the i^{th} LED and the corresponding PD, and $h_{i,j}$ represent the crosstalk gain between the i^{th} LED and the j^{th} PD. If there is no crosstalk, $\mathbf{H}_{multi}$ becomes a diagonal matrix with $h_{i,i}$ entries. The channel capacity C_{multi} in multi-carrier VLC is given by

$$C_{multi} = \Gamma C_{CISO} \tag{8}$$

where $\Gamma = \min(n, z)$ and C_{CISO} is given in (2). RGB-LEDs being the most used multi-wavelength LEDs, the channel transfer matrix $\mathbf{H}_{3\times3}$ in the case of a single RGB-LED transmitter is given by

$$\mathbf{H}_{3\times3} = \begin{bmatrix} h_{rr} & h_{rg} & h_{rb} \\ h_{gr} & h_{gg} & h_{gb} \\ h_{br} & h_{bg} & h_{bb} \end{bmatrix}, \tag{9}$$

where the diagonal entries (h_{rr}, h_{bb}, and h_{gg}) represent the LOS link between a single LED and its corresponding PD, and the rest of entries (h_{rg}, h_{rb}, h_{gr}, h_{gb}, h_{br}, h_{bg}) represents cross-talks between channels.

2.3 The VLC receiver

The main element in the VLC receiver is the photo-detector used to collect the light radiation [14]. Two main types of photodetectors are used in VLC receivers: the photo-diode and the phototransistors. The digital camera, consisting of an array of photo transistor is a good device for receiving VLC signal in smart devices such as smart phones and laptops [21]. As described in [13], a complete receiver system made of components such as the concentrator, the optical filter, the amplifier and the equaliser, necessary to capture the maximum light needed to convert the received signal into message. The rays pass through the concentrator and the optical filter before they reach the proper detector core. The architecture of a VLC receiver is presented in Fig. 5.

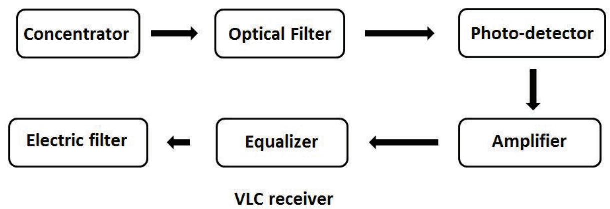

Figure 5: Architecture of a VLC receiver

2.3.1 Optical received power

Considering the instantaneous power of the LED, $p_{LED}(t)$, the average optical power produced by a single LED is given by [16], [19]

$$P_{LED} = \lim_{T\to\infty} \frac{1}{2T}[\int_{-T}^{T} p_{LED}(t)dt]. \tag{10}$$

The received power P_{PD} is calculated using the transmission gain (g). In the case of a LOS VLC communication system, P_{PD} is given by [21]

$$P_{PD} = P_{LED} \times g_{(LOS)}, \tag{11}$$

where $g_{(LOS)}$ is the transmission gain defined in (4). This power depends on the wavelength as depicted in [13]. But three other factors are also taken into account: the filter gain $T_f(\varphi)$, the concentration gains $g(\alpha)$ and the Lambertian distribution order (ξ) (see equation 4).

2.3.2 Distribution of Light from LEDs

With the rapid development of solid state lighting technologies, LEDs are designed to generate 10-120 lumen each with very good efficiency. Indoor illumination demands about 400 to 1200 luxes in a single room. A single LED is not enough, meaning an array of LEDs is required, which is an advantage for the uniformity of the illumination required for a comfortable visual impression. The ideal LED optical model is a perfect Lambertian, meaning that the intensity of the propagation is proportional to the cosine of the viewing angle. But in the real world, some LEDs can be represented by an imperfect Lambertian. We distinguish the far field illumination areas, in which the LED illumination range is about 5 times larger than its maximum size. The scattering produced by many light sources increases the number of paths in the VLC channel. As the number of packages (p_a) increases, the number (β) of resolvable paths increases according to the relation $\beta = \alpha^{p_a}$, where α is the number of LEDs per group. Hence, increasing the number of LEDs enhances the uniformity of the illumination an makes the implementation more complex in indoor environment. In this case, an efficient equalization technique is required to overcome the effects of delay spread owing to the multipath effects. Generally, they are all manufactured with the Lambertian emission principle. The link transmitter-receiver in VLC is then based on this principle. Fig. 6 shows the distribution of light from LED. A Lambertian distribution is characterised by its Lambertian order (ξ). This distribution confers to the VLC channel a multipath environment. The Lambertian order ξ is given by [17]

$$\xi = -\frac{ln2}{ln(\Theta_{0.5})}, \tag{12}$$

where $\Theta_{0.5}$ represents the semi-angle corresponding to half the received optical power ($P_r/2$). An important characteristic of this distribution is the radiant intensity $\kappa(\varphi)$ of the Lambertian transmitter. It is used to define the channel gain given in (4). $\kappa(\varphi)$ is given for a SISO channels by [8]

$$\kappa(\varphi) = \frac{\xi+1}{2\pi} cos^{\xi}(\varphi). \tag{13}$$

In [22], a multiple inputs - single output system (MISO) version of the radiant intesity of the Lambertian transmitter related to the number n of inputs is studied, taking into account the number of transmitting antennas. This extends the VLC link proposed for a single user to a multi-user scenario.

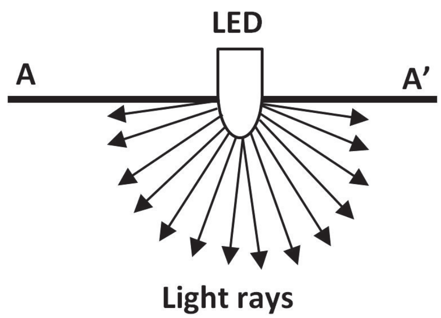

Figure 6: Scattering of the light from LEDs (Lambertian distribution); ($\mathbf{A} - \mathbf{A}'$) represents the Lambertian surface in the profile view

2.3.3 Other parameters affecting the received signal

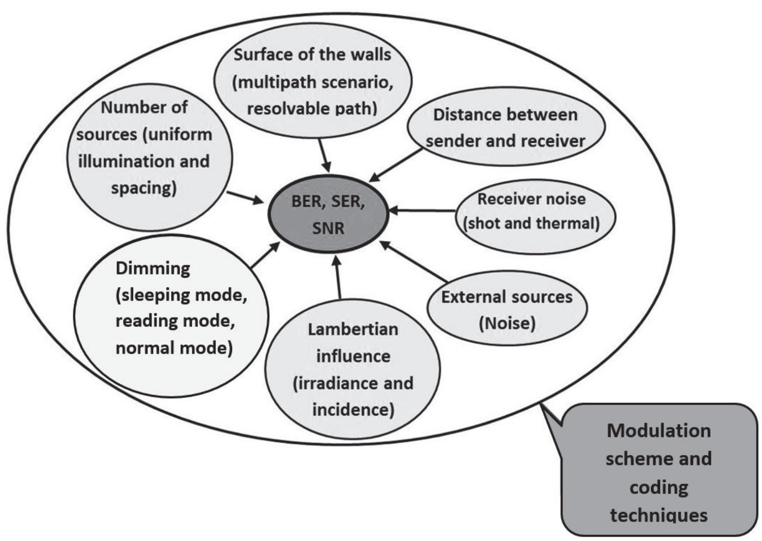

Figure 7: Factors influencing the VLC transmission link

In the design of the light distribution by LEDs, some other parameters to be thoroughly analysed are: the luminous spatial intensity distribution, the optical power and the spectral density. In addition to the influence of the type of distribution, many parameters are likely to affect the communication link. These are: the illumination related to the current intensity flowing in the LEDs, the number of sources in the LEDs array (uniform illumination and spacing between sources), the external sources of light (interference), the order of the Lamtertian emission ξ, and the nature of the wall surface (multi path scenario and resolvable path) [18]. Hence, the bit error rate (BER), the symbol error rate (SER) and the signal to noise ratio (SNR) are functions of these parameters. This has previously been analysed by the authors and summarised in Fig. 7.

2.4 Noise and SNR in VLC systems

2.4.1 Noise

In VLC systems, the noise sources include sunlight, incandescent and fluorescent light in indoor or outdoor environments [9]. But in addition to the noise present in the environment, the receiver in its operation produces noise. This is due to the impact of the photons on the surface of the receiver. Two main types of noise source are inventoried: shot and thermal noise. Thermal noise is an energy equilibrium fluctuation phenomenon and shot noise produced by current fluctuations, refers to the random nature of photon absorption and electron hole recombination. It can be modelled using Poisson distribution and it is white noise [23]. Additionally to the current generated from the photons of the light, there is a component called dark current, which influences the variance of the shot noise ($\sigma^2_{shot} = \sigma^2_{light} + \sigma^2_{dark}$). It is proved that the variance of the shot noise has two components related to the direct and the ambient light. This is detailed in [24] where the variance of shot noise is defined as a function of the electronic charge (q), the received average optical power ($\mathbf{P}_r$), the noise bandwidth ($\mathbf{B}$), the background current (I_{bg}), the responsivity $\mathbf{R}_r$ of the photo receiver and a factor related to the noise bandwidth (ζ). The thermal noise is also defined as depending on factors such as the Boltzmann constant ($\mathbf{K}$), the absolute temperature (T_k), the detector area (A), the open loop voltage gain (G) and the field effect transistor channel noise factor (η). But the fluctuations in a current across a semi-conductor due to shot noise can be distributed using Fourier transform as [25]

$$I_n(t) = \sum_{k=1} i_k(t), \quad k \in \mathbb{N} \tag{14}$$

Practically, it is very difficult to separate shot noise and thermal noise. But the variance σ^2_n of the total noise is equal to the sum of the variances (σ^2_{shot}) of the shot noise and (σ^2_{th}) of the thermal noise (15).

$$\sigma^2_n = \sigma^2_{shot} + \sigma^2_{th} \tag{15}$$

σ^2_{shot} and σ^2_{th} are defined in [24], [26] as

$$\sigma^2_{shot} = \mathbf{B}[2qI_{bg}\zeta + 2qP_r\gamma\mathbf{R}_r] \tag{16}$$

and

$$\sigma^2_{th} = \frac{8\pi\mathbf{K}T_k}{G}\eta A\zeta\mathbf{B}^2 + \frac{16\pi\mathbf{K}T_k\Gamma}{g_m}\eta^2 A^2\zeta_{th}\mathbf{B}^3. \tag{17}$$

2.4.2 Signal to noise ratio

The SNR is a parameter defining the strength of the signal carrying the information and comparing it to that of unwanted signal. In VLC system, since the noise vector appears as a composition of the shot and the thermal noise, in most research, it is assumed that the total noise is dominated by the white Gaussian component [24]. Hence, the SNR is defined by [9]

$$SNR = \frac{\mathbf{R}_r^2\mathbf{P}_r^2}{\sigma^2_{shot} + \sigma^2_{th}}, \tag{18}$$

But considering the case of a system with inter-symbol interference (ISI) from multi-path propagation, the received noise power due to ISI will affect the SNR. Under the same condition for which (18) is given, the SNR in ISI systems is also given by [27]

$$SNR = \frac{\mathbf{R}_r^2\mathbf{P}_r^2}{\sigma^2_{shot} + \sigma^2_{th} + \mathbf{R}_r^2\mathbf{P}^2_{r,ISI}}. \tag{19}$$

2.4.3 Optical interference noise

One cannot study noise over the VLC channel without mentioning the optical interference that occurs on the optical link between the LEDs and the PD. It is to be noted that in the environment of the transmission, there is a background noise sourced by the sunlight. This background noise can be accompanied by the incandescent and the fluorescent noise. This will induce a background current in the PD. But that background current was taken into account when formulating the variance of the shot noise given in (16).

3 Standardisation of VLC

To regulate transmission in VLC technology, the Institute of Electrical and Electronics Engineers (IEEE) working group IEEE 802.15.7, proposes schemes and techniques. The IEEE 802.15.7' standard devises the physical layer (PHY) of VLC technology in three parts: PHY I, PHY II and PHY III [3], [28]. Specific modulation schemes and coding techniques are dedicated to each of these layers. PHY I operates from 11.67 kb/s to 266.6 kb/s, PHY II operates from 1.25 Mb/s to 96 Mb/s, and PHY III operates from 12 Mb/s to 96 Mb/s [28]. PHY III, dedicated to multiple optical sources using CSK, was developed and presented in [29]. PHY I and PHY II use schemes such as OOK and VPPM. Other standardisation organisations do exist in VLC. In Japan, the visible light communication consortium (VLCC) provides a collaborative platform for researchers, universities and industries, for improving the VLC technology. The VLCC membership includes the following: Nippon Electric Company (NEC) corporation, Panasonic, Toshiba corporation, Samsung Electronics, Casio Computer, Nakagawa Laboratories, and Sharp corporation. The activities of the VLCC consortium are to develop standards for VLC technology. VLCC proposes to use VPPM to implement communication systems in VLC technology. In Europe, the Wireless World Research Forum (WWRF) also works on VLC technology. Its working group 5 is in charge of investigating the VLC environment. Other organisations such as the Telecommunications Technology Association in South Korea also looks at VLC technology.

4 Modulations methods

The deployment of a modulation technique depends on the application of the system to be designed. Throughput, received signal quality, and the required channel capacity are the main parameters influencing the choice of a modulation technique. Various modulation techniques are available to be deployed over the VLC channel [30], [31], [32]. They are organised regarding the number of channels (carriers). For example, CSK works with more than one carrier. OFDM and sub-carrier index modulation (SIM-OFDM) can work with single or multiple LEDs [33], [34]. Dual-header pulse interval modulation (DH-PIM) and sub-carrier PSK intensity modulation are also suitable modulation techniques for VLC system implementation. From a standardization point of view, VLCC recommends the sub-carrier pulse position modulation (SC-PPM) because of its robustness in avoiding DC [35]. OOK, VPPM CSK are proposed in IEEE 802.15.7 [30],[28].
In this section, some modulation schemes are briefly studied, including OOK, VPPM. Some complex modulations (CSK, OFDM, Spatial diversity) are also mentioned.

4.1 Pulse Position Modulation (PPM)

PPM is a scheme in which the position of the pulse, relative to its unmodulated time of occurrence, is varied in accordance to the message signal. It was designed to reduce the energy waste occurring during transmission in pulse duration modulation (PDM) or pulse width modulation (PWM). In these modulation schemes (PDM), (PWM) and PPM, samples of message signals are used to vary the duration of the individual pulse.

4.1.1 VPPM

In the literature [13], many variants of the PPM are mentioned, including level pulse-position modulation (LPPM), differential PPM (DPPM), and variable PPM (VPPM). VPPM is needed in VLC technology because it simultaneously supports illumination, dimming control and communication. In a multipath dispersion channel, the VPPM signal can be written as [36]

$$l_{vppm}(t) = \sum_{i=-\infty}^{+\infty} \mathbf{s}_{ppm}(t - iT_s), \tag{20}$$

where T_s is the total duration of a symbol transmission including the LOS duration and the duration of the extra time caused by the NLOS path. $\mathbf{s}_{ppm}(t)$ is defined as the modulated signal depending on the bit value {0,1} and is used for controlling the LED illumination. It is expressed as

$$\mathbf{s}_{ppm}(t) = f_i(t)\sqrt{E_b \varrho}, \tag{21}$$

where i={0,1} and $f_i(t)$ is the basic function providing dimming control of the LEDs. ϱ represents the dimming level and is defined in a percentage between 0 and 100 ($0 \leq \varrho \leq 100$ %). To insure constant balanced lighting between ones and zeros, a 50 percent duty cycle is applied for both ones and zeros [30]. Let $l'(t)$ be the light emitted by the LEDs, $l'(t)$ depends on the electrical signal $l_{vppm}(t)$. $l'(t)$ is subject to the convolution by the optical response of the channel $\mathbf{h_o}(t)$. Then the transmission equation is expressed as

$$\mathbf{r}_e(t) = l'(t) * \mathbf{h_o}(t) + \omega_e(t), \tag{22}$$

where $l'(t)$ is related to $l_{vppm}(t)$ by $l'(t) = \Upsilon l_{vppm}(t)$, Υ being the total electrical to optical conversion factor. ω_e represents the electrical AWGN at the output of the photodetector and $\mathbf{r}_e$ represents the electrical received signal from the photodetector. $\mathbf{h_e}(t)$ is rearranged from (5) taking into account the effects of multipath dispersion. $\mathbf{h_e}(t)$ is given by

$$\mathbf{h_e}(t) = \sum_{i=1}^{M-1} \Delta_i e^{(-\tau_i(t-d_i))}, \tag{23}$$

where M is the number of single clusters, d_i represents the delay in the i^{th} path, and Δ_i and τ_i are the channel gain and the time constant of the i^{th} cluster respectively. In terms of performance of the VPPM, the correlation factor between AWGN noise over the bits 0 and 1 requires careful handling because it affects the error probability of the received symbol.

4.2 On-Off Keying (OOK)

OOK is a very low complexity modulation scheme. It is a special case of amplitude shift keying (ASK) employing two voltage levels where the second one is zero. The carrier signal in OOK is given by [37], [38]:

$$l_{ook}(t) = \sum_{i=-\infty}^{+\infty} v[i]\mathbf{s}_{ook}(t - iT_b) \tag{24}$$

In case of consecutive ones or zeros, OOK suffers from unbalanced intensity provided to the LED. Two methods are available to solve the unbalance. The first method consists of redefining the voltage level by keeping them identical and playing with the duration of the pulse. This method gives constant data rate as the light changes, even though in the case of colour LEDs, the shifting of the colours is expected [30]. It also wastes energy since the control is now based on the variation of the width of the pulse. The second technique is base on introducing a compensation time into the wave form. In this case, the data rate is automatically reduced because of dimming.

4.3 Frequency Shift Keying (FSK)

FSK-VLC is non-standardised scheme. This is due to the non-negative aspect of the VLC technology. The introduction of a DC offset (see Fig. 2) automatically solves the problem. However, FSK-VLC is still to be properly investigated. In FSK, symbols are mapped to frequencies. The authors initiated the analysis of the FSK transmission principle for VLC technology (the analysis is still under-way). They look at the conditions to perform a communication under a constant average transmit optical power.

The intention being to keep the illumination constant during transmission. By definition, the average transmitted electric power over a symbol period T_s is given by:

$$\mathbf{P}_{avg} = \frac{1}{T_s}\int_0^{T_s} \mathbf{p}(t)dt = D\mathbf{P}_{max} + (1-D)\mathbf{P}_{min} \tag{25}$$

where D is the duty-cycle, of the PWM, $\mathbf{P}_{max}$ and $\mathbf{P}_{min}$ correspond to the power during *on* and off times respectively. Then, the average value of the power over the i^{th} symbol depends on the duty cycle D, and on $\mathbf{P}_{max}$ and $\mathbf{P}_{min}$, not on the i^{th} frequency f_i. Transmitting the symbols S_i and $S_{(i+1)}$ at the same average power (see Fig. 8) brings up two scenarios:

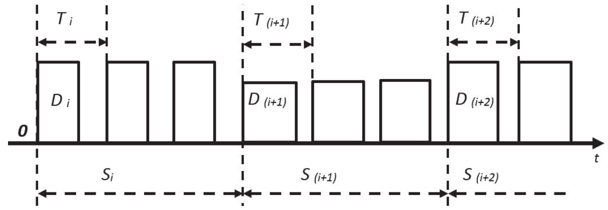

Figure 8: LED's control signal in frequency shift keying (FSK) for VLC systems

- $D_i = D_{(i+1)}$

In the case of identical duty cycles between the signals over the i^{th} and the $(i+1)^{th}$ symbols, the signals $s_i(t)$ and $s_{i+1}(t)$ must be defined with the same maximum and minimum values ($\mathbf{P}_{i,max} = \mathbf{P}_{(i+1),max}$ and $\mathbf{P}_{i,min} = \mathbf{P}_{(i+1),min}$).

- $D_i \neq D_{(i+1)}$

In this case, the loss on the duty cycle during the transmission of the i^{th} symbol will be compensated by changing the maximum and/or the minimum power during the transmission of the $(i+1)$ symbol as shown in Fig. 8. The equations for compensation are given in (29) and (30).

$$\mathbf{P}_{i,max} = \frac{D_i}{D_{i+1}}\mathbf{P}_{(i+1),max} \tag{26}$$

$$\mathbf{P}_{i,min} = \frac{1-D_i}{1-D_{i+1}}\mathbf{P}_{(i+1),min} \tag{27}$$

4.4 Complex modulations

4.4.1 Colour Shift Keying

CSK is a scheme mapping data stream symbols to colours. The colours are produced by the tritimulus principle using the three basic colours red-green-blue. Consequently, RGB-LEDs are used in CSK modulation.

- CSK constellation design

Let $\mathbf{S}_i$=$\{S_1, S_2, ..., S_N\}$ and $\mathbf{C}_i$=$\{C_1, C_2, ..., C_N\}$ be the incoming symbol set and the colour constellation respectively, N being the constellation size. $\mathbf{S}_i$ is mapped into $\mathbf{C}_i$ and the light colour produced by the RGB-LEDs changes by sequence of the data symbols. $\mathbf{C}_i$ fits in a triangle delimited by the primary colours red, green and blue (see Fig 9). Some design examples for CSK constellation are provided in the literature in [39], [40] and [41]. Each C_k, $k = \{1, 2, ..., N\}$ represents one point on the constellation triangle shown in Fig 9. C_k is represented in the RGB colour space by its coordinates R_k, G_k and B_k. R_k, G_k and B_k, the sum of which is 1, give the current intensities to be apply to the red, green and blue LEDs for producing the colour C_k [39] [40] and [41].

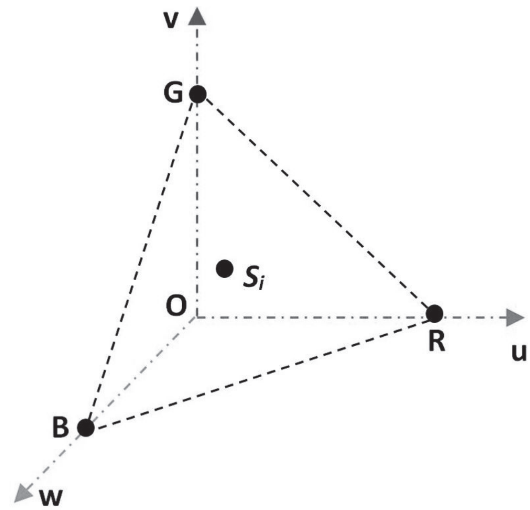

Figure 9: RGB plan and constellation triangle

Nevertheless, C_k can also be represented in the chromaticity plan by its xy coordinates given by

$$\begin{cases} x_k = R_k x_r + G_k x_g + B_k x_b \quad \text{(a)}, \\ y_k = R_k y_r + G_k y_g + B_k y_b \quad \text{(a)}, \end{cases} \tag{28}$$

where x_r, x_g, x_b and y_r, y_g, y_b are the xy coordinates of the primary colours red, green and blue. Fig. 10 shows the CSK transmission system using a single RGB-LED. Its channel matrix is given in (9) and the transmission is governed by

$$r_k = (\mathbf{H}_{3\times3})s_k + \omega, \tag{29}$$

where r_k=$[R'_k\ G'_k\ B'_k]^T$, s_k=$[R_k\ G_k\ B_k]^T$ and ω=$[\omega_r\ \omega_g\ \omega_b]^T$ respectively.

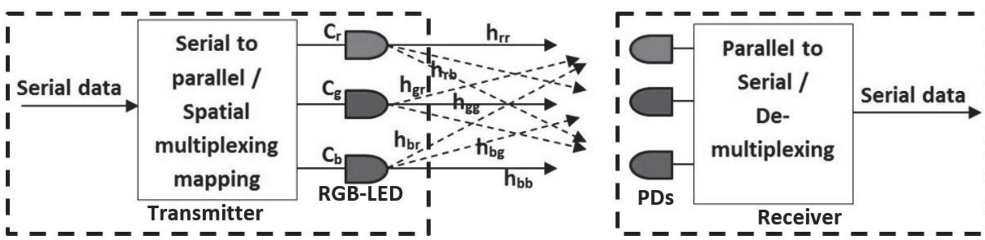

Figure 10: A colour shift keying (CSK) transmission system

- Design constraints

The CSK constellation design has two main constraints. The first constraint is related to the lighting while the second touches on the communication efficiency. The average power over the N transmitted symbols and the average colour must remain constant. This has been extensively studied in [1] and [41]. The average power and colour are given by

$$\mathbf{P}_{avg} = \frac{1}{N}\sum_{i=0}^{N-1} p_i \tag{30}$$

and

$$C_{avg} = \sum_{i=1}^{N} \gamma_i S_i. \tag{31}$$

where p_i represents the power allocated to the i^{th} symbol and γ_i the weight of the the i^{th} symbol. The communication efficiency is determined in the design objective: under the conditions of average power and colour, the system should maximise the minimum Euclidean distance between S_i and S_k (S_i, S_k $\in \mathbf{S}_i$). This is achieved by applying the maximum a posteriori probability (MAP) detection rule ($\varpi = arg\,max$ probability $\{received|sent\}$). When the transmission is dominated by AWGN, the optimum receiver has to minimize the squared Euclidean distance metric between two points of the constellation. Hence, the objective is given by

$$\varpi = min\{\|\mathbf{H}_{3\times 3}(S_i - S_k)\|^2\} \tag{32}$$

- Average energy

The average energy E_{avg} is an important characteristic of the constellation $\mathbf{S}_i$. It is generally given by

$$E_{avg}(\mathbf{S}_i) = \frac{1}{N}\sum_{i=0}^{N-1}\|\mathbf{S}_i\|^2, \tag{33}$$

where $\mathbf{S}_i$ is mapped to $\mathbf{C}_i$, and $\mathbf{C}_i$ is set of 3-tuple signal point having the sub-sets $\mathbf{S}_{i,r} = \{S_{1,r}, S_{2,r}, \dots, S_{N,r}\}$, $\mathbf{S}_{ig}$, $\mathbf{S}_{g,r} = \{S_{1,g}, S_{2,g}, \dots, S_{N,g}\}$, and $\mathbf{S}_{i,b} = \{S_{1,b}, S_{2,b}, \dots, S_{N,b}\}$ as sets of coordinates on the three axis u, v and w respectively (see Fir 9).

4.4.2 Orthogonal Frequency Division Multiplexing

OFDM is a multi-symbol modulation. It is one of those schemes where the form of the carrier wave must be sinusoidal. Over the VLC channel, OFDM is performed using a single LED and a single photodetector as shown in (Fig. 11). In the transmitter, the original data is converted to symbol data using inverse fast Fourier transform (IFFT). The symbol data of all sub-carriers are superimposed to produce the baseband signal expressed by:

$$l_{ofdm} = \sum_{i=0}^{N-1}\mathbf{B}_i e^{j(2\pi i\frac{k}{N})}. \tag{34}$$

$l_{ofdm}(t)$ is then used to modulate the LED. Considering the square matrix a^2 of the LED array in multiple LED transmission, and taking into account the multipath effect and the delay of the i^{th} propagation path Δt, the output of the PD can be given by [42], [43]:

$$\mathbf{r}(t) = \sum_{j=0}^{a^2}\sum_{i}\Omega_{ji}\nu_i(t-\Delta t) + \omega(t), \tag{35}$$

where Ω_{ji} represents a weighting factor characterised by the number of LEDs per array and the number of arrays, and $\nu(t)$ is the amplified signal from the PD. The reverse operation in the receiver uses fast Fourier transform (FFT) to recover the transmitted data expressed by:

$$\mathbf{B}_i = \sum_{i=0}^{N-1} l_{ofdm} e^{-j(2\pi i\frac{k}{N})}. \tag{36}$$

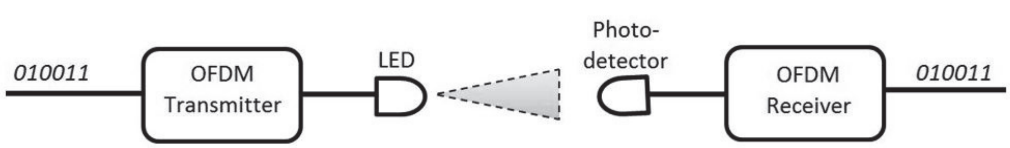

Figure 11: Basic principle of an orthogonal frequency division multiplexing (OFDM) for VLC systems

- Sub-carrier index OFDM (SIM-OFDM)

Sub-carrier index modulation OFDM exploits the sub-carrier orthogonality to add a new dimension to the complex two dimensions signal plan used in the normal OFDM [33], [42] and [43]. SIM-OFDM may increase power per sub-carrier, and will also increase the throughput and give better spectral efficiency in respect to the normal OFDM.

4.4.3 Multiple inputs multiple outputs

The use of multiple LEDs or multiple arrays of LEDs offers the potential for parallel transmissions across the VLC channel. The channel matrix given in (7) is suitable for a MIMO channel. It considers n and z transmitting and receiving antennas respectively. The principle diagram of a MIMO-VLC system is depicted in Fig. 12.

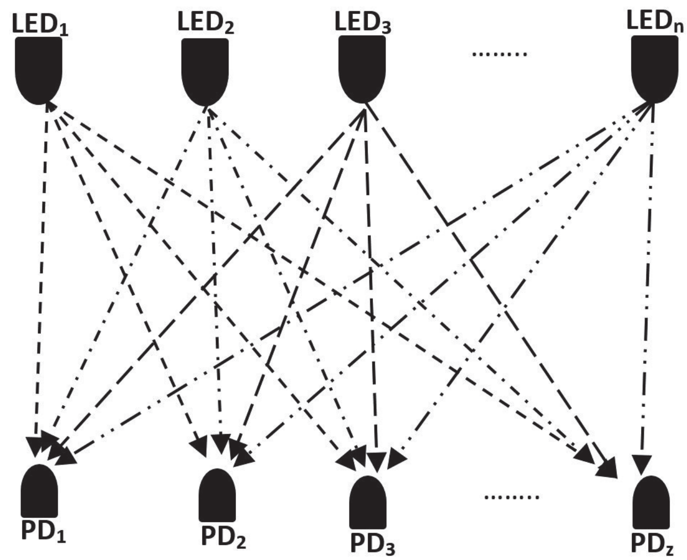

Figure 12: Basic principle of an $n \times z$ MIMO-VLC system

Indoor MIMO was reviewed in the literature and more information can be found in [44] and [45]. The incoming symbols are redistributed for a parallel transmission using the total number of LEDs or group of LEDs. This technique is characterised by a very hight channel capacity. In fact the capacity of a MIMO system is the capacity of a SISO system multiplied by the scalar number Γ (see (8)).

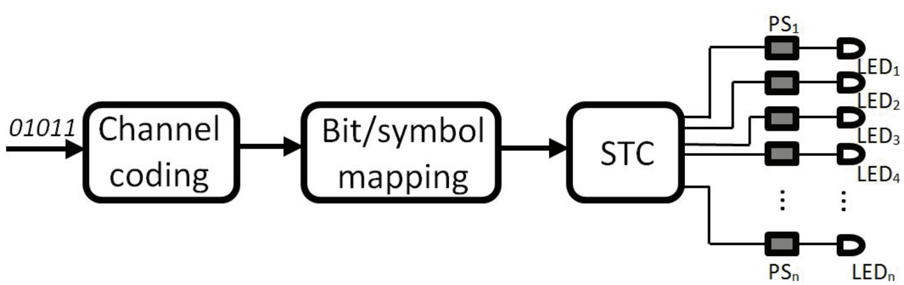

Figure 13: Basic principle diagram of a space-time-coding (STC) for VLC systems

In MIMO-VLC system implementation, it is very important to distribute the redundancy in space and time in an appropriate manner in the transmitter. This is achieved by applying the space-time-coding (STC) technique [44], [46]. The aim here is to seek better coding and diversity gains. STC provides very good signal quality at the receiver, thus, good SNR. A basic representation of the STC and spatial multiplexing transmitter is given in Fig. 13. The received symbols set is given by the relation in (1), where the channel response $\mathbf{H}$ is replace by the $n \times z$ impulse response ($\mathbf{H}_{multi}$) given in (7). In fact, $\mathbf{H}_{multi}$ is seen as a composed matrix having three components: two unitary rotation matrices $\mathbf{U}$ and $\mathbf{V}$, and a diagonal matrix Λ, hence, $\mathbf{H}_{multi}$ is given by [8]

$$\mathbf{H}_{multi} = \mathbf{U}\Lambda\mathbf{V}^* \tag{37}$$

(1) becomes

$$\mathbf{R} = (\mathbf{U}\Lambda\mathbf{V}^*)\mathbf{S} + \mathbf{W}, \tag{38}$$

where $\mathbf{S}$ is a n-dimensional transmitted vector, $\mathbf{R}$ and $\mathbf{W}$, are z-dimensional receiving and noise vectors respectively. A geometry rotation is applied to (38), Afterwards,the parameters $\mathbf{S}$, $\mathbf{R}$ and $\mathbf{W}$ are given by their representation $\mathbf{S}'$, $\mathbf{R}'$ and $\mathbf{W}'$ respectively, such that

$$\mathbf{R}' = \Lambda\mathbf{S}' + \mathbf{W}', \tag{39}$$

where $\mathbf{S}' = \mathbf{V}^*\mathbf{S}$, $\mathbf{R}' = \mathbf{U}^*\mathbf{R}$ and $\mathbf{W}' = \mathbf{U}^*\mathbf{W}$. The corresponding analogue baseband signal $y_j(t)$ measured at the j^{th} PD can be expressed by [47]

$$y_j(t) = \frac{1}{nT}\sum_{i=1}^{nT} h_{ji}S^i(t) + W_j(t),\ \ 0 \leq t \leq T_s,\ \ 1 \leq j \leq z, \tag{40}$$

where W_j is the noise components at the j^{th} PD.

- Optical spacial modulation (OSM)

OSM is a combination of the spacial multiplexing and the pulse position modulation. This technique is studied and presented in [48]. In terms of performance, a 4×4 OSM achieves the same BER performance as OOK, even though at the double data rate.

5 Challenges of VLC practical implementation

Implementing a VLC communication system requires in-depth knowledge of both communication and electronic systems. The communication perspective demands a good definition of the modulation scheme which depends on the application of the communication system and should meet the communication objectives. This aspect also requires us to know if it is necessary or not to use a coding technique. The practical implementation of the design requires one to have good knowledge of electronic circuit design, in this case, accuracy of the design, quality of the schematic diagram and quality of the selected components are very important. The responsivity of all the elements appearing in the design is to be taken into consideration. The complexity of the design depends on the complexity of the modulation technique. So, modulation schemes such as OOK are easier to implement when compared to complex schemes such as CSK. In this aspect, the type of waveform is also very important. Schemes demanding pulses provide less complexity in design compared to those demanding sine waves. This section of the article details a few techniques that may be used in the practical implementation of a VLC system. The aims are to comply with the illumination constraints of the VLC technology. Before we go in-depth into the development, let us start by presenting the LED control and dimming.

5.1 LED control and dimming

LEDs are semi-conductors with two modes of operation: the forward and reverse biased modes. In forward biased mode, the electrons are able to recombine with holes within the device, releasing energy in the form of photons, producing the forward current I_F. I_F defines the brightness of the LED and therefore requires to be limited. The main elements used to control I_F are: a series resistor and a current source used to produce a stable current. Here, LEDs is a combination of a finite number α of identical light emitting diodes in series and in β branches. The current limiting resistor is then given by

$$R = \frac{V_s - \Delta_v - \alpha V_F}{\beta I_F}. \tag{41}$$

In practice, the value of V_F for on-shelf LEDs is between 1.2V and 2.5V for a current I_F of about 60 mA. The combination to be used depends on the number of lumens required in the room. A PWM control method is used to control the duty cycle and the dimming of the LEDs. This module will be accompanied by the communication module grouping the modulator and many other components. The output power of the LED is given by $P_d = V_F I_F$. P_d is also given as a function of the duty cycle as expressed in (25). The basic diagram of LED's control is given in Fig. 14.

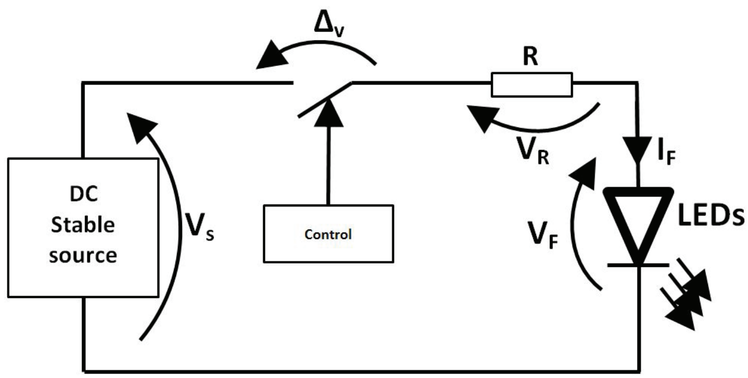

Figure 14: Basic diagram of LED's control

5.1.1 Controlling the Brightness of LEDs

Dimming and illumination of LEDs are controlled by the brightness. Many methods can be used to control the brightness of the LEDs. These include pulse frequency modulation (PFM), bit angle modulation (BAM) and PWM. PWM is the most used method. It is based on the variation of the duty cycle of the pulses, through varying the duration of the on-time t_{on}. Fig. 15 shows brightness control using the PWM method. The percentage of the duty cycle corresponds to the percentage of the brightness needed for a specific illumination and a specific value of P_d.

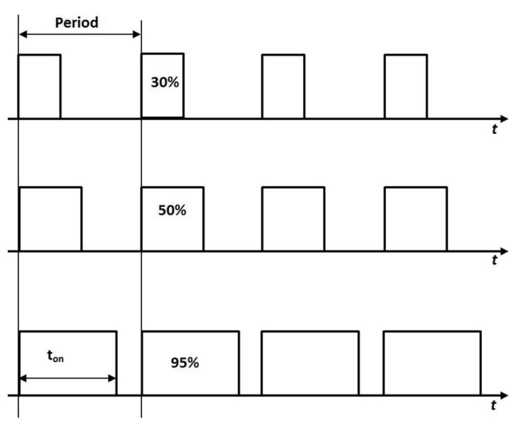

Figure 15: Brightness control of LEDs using a pulse width modulation (PWM) signal

5.2 LED control for OOK systems

On-off-keying is possibly the simplest modulation that can be implemented over the VLC channel. After the signal conditioning, channel coding, interleaving and bit mapping; the signal message generates a PWM that will control the switching system. This is performed through a driver to match the voltage and current level between the PWM source and the control pin of the switch. The baseband signal in OOK is produced to control the LEDs, resulting in the carrier signal (Fig. 16).

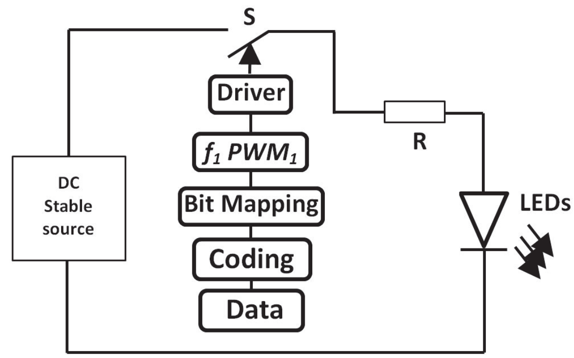

Figure 16: Basic diagram for on-off keying (OOK) modulation and LED control

5.3 LED control for frequency shift keying (FSK) transmission systems

Fig. 17 shows an example of FSK modulation technique over VLC. It includes a module treating the message to be sent. Channel coding and interleaving if necessary, and a function to map symbols to different circuits is produced. The circuit corresponds to a specific PWM generator with its specific frequency, a switching system and a driver. Then the LED will be lighting at variable frequencies according to the input data stream. It is to be emphasised that, this system works with a DC offset injected in the circuit.

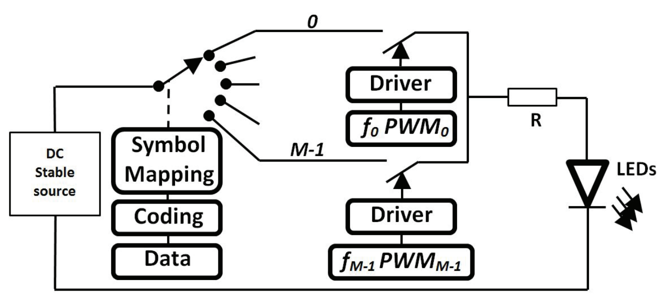

Figure 17: Basic diagram for frequency shift keying (FSK) modulation and LED control

5.4 LED control for colour shift keying (CSK) systems

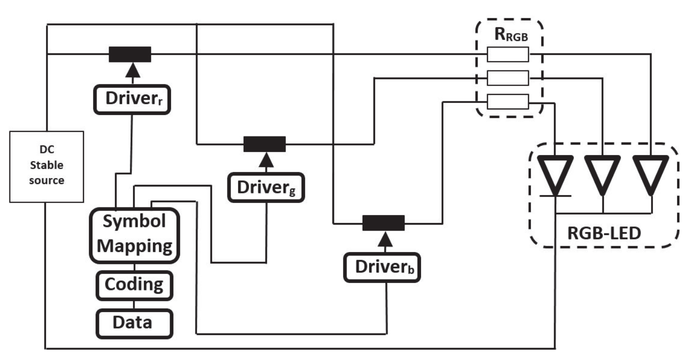

Figure 18: Principle diagram for colour shift keying (CSK) modulation and control of the RGB-LED

The complexity of the mapping module makes difficult the implementation of a CSK system. In CSK, symbols are mapped in turn to colours. This can be done practically using the diagram presented in Fig. 18. The symbol mapping processor executes an algorithm that is more complex than that used in

OOK. The RGB-LED circuit is made of three single colour LEDs in series with the current limiter. In this modulation scheme, there is no flickering, meaning that there is no light interruption during transmission. To achieve this, to each symbol is allocated three forward currents with different intensities in such a way that the output of the RGB-LED produces a constant optical power. Considering that the three intensities are I_R, I_G and I_B, and the average power produced by a single LED is given in (11). Applying (11) to each LED, an algorithm that meets the power envelop constraint of CSK can be developed.

5.5 LED control for VLC-OFDM systems

Implementing OFDM over the VLC channel is more complex when compared to other modulation schemes. This is because the implementation needs to produce a signal similar to the graph shown in Fig. 19. The OFDM signal is added to a DC power in such a way that the average value V_{avg} over the symbol period remains constant. V^{avg} is then used to control the RGB-LED.

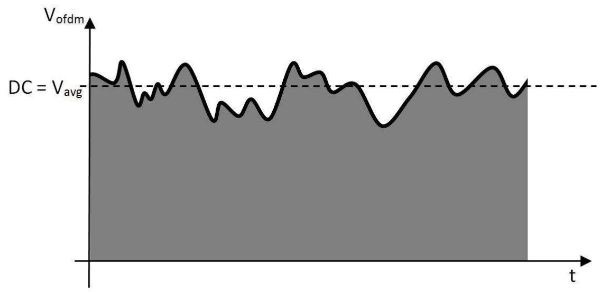

Figure 19: Typical wave form in VLC-OFDM

6 Applications of VLC

By modulating the fluorescent light, the VLC technology can transmit signals at 10kb/s. But LEDs can provide up to 500 Mbps. From 1.2 Mbps, the system is said to be high data rate transmission [3]. The potential applications of VLC technology can be grouped (see Table 1 and 2) in two main sets: Low data VLC applications and applications for high data transmission.

6.1 Low data VLC

In general nowadays, low data rate communication systems are intended for control. VLC technology can also be implemented in such applications. Table 1 presents a few of them.

Table 1: Application field of low data VLC technology

Application fields	**Comments**
General positioning	VLC technology provides the possibility to uniquely identify each VLC transmitter in an indoor environment
Vehicle and transportation	VLC technology also allows inter-vehicle communication in using the front light as transmitter and the back red light as receiver thus prevent accidents [49]. This property is also used by engineers to design advanced traffic-light systems that can, for example, give passage to a vehicle under control of the red light when there is no vehicle travelling in the green light direction
Smart lighting	The intensity and the switching of a light can always be controlled remotely thus providing users comfort in utilising the light. This quality is advantageous because of its energy saving property

6.2 High data VLC

The applications of high data rate VLC are beyong the scope of this paper. Table 2 highlights the most promising applications of VLC that demand high data rate techniques.

Table 2: Application field of high data VLC technology

Application fields	**Comments**
Mobile connectivity	Firstly, by enabling light fidelity (Li-Fi), VLC can be used to relieve the wireless radio frequency (RF) spectrum. The light bulbs become the base station for millions of users. Secondly, it enables secure communication between two smart devices at a very high speed data link.
Hospitals and healthcare	RF is undesirable in some parts of hospitals, especially around scanners and in operating theatres. VLC technology consequently is the promising technology that can be used in hospitals owing to the fact that the VLC spectrum does not interfere with the RF spectrum.
Aviation	To reduce the risk of interference, LiFi may be used to replace WiFi in aircraft cabins. Additionally, VLC can be used to provide air-passengers with continuous communication services. This will impact the cost in aircraft manufacturer.
Underwater communications	The propagation of RF signals is not efficient in underwater environments. This is due to the quick attenuation of the transmitted signal [50]. The propagation of visible light enhances the quality of underwater data transmission.
Defence, security, and hazardous environments	The VLC signal cannot pass through walls. This technology is well suited for application where security is of great importance. In hazardous environments such as a petrol-chemical plan or a mining environment, there is a high risk of explosion when the RF signal is used. RF signal can produce a spark of such intensity that it could ignite a vapour air mix, which could lead to an explosion [51]. VLC is an excellent technology that can be used in these settings

6.3 Other applications

There are probably many other applications of VLC not dealt with in this paper. The technology can also be used in applications such as smart learning and teaching, smart grid-friendly appliances, asset analyses, resource tracking, and smart networking, from an endless list.

7 Challenges of VLC commercialisation

The utilisation of LEDs for lighting provides many advantages such as in cost and comfort. Increasingly, it is becoming unavoidable to light without using LEDs in light bulbs. In general, manufacturers exploit the potential offered by the emerging technologies to meet the needs of the population. For a large scale deployment of VLC technology, a number of challenges and issues relating to its commercialisation needs to be addressed. Hence, highlights the regulation and market factors. Firstly, the VLC spectrum needs to be organised. To date, the standardisation of VLC technology has received relatively little attention. In IEEE, however, the working group IEEE 802.15.7 provides rules and regulations for VLC technology. In Japan, the consortium VLCC has also developed a few working standards. The Japan Electronics and Information Technology Industries Association (JEITA) has standards focusing on visible light identification systems (see Section 3). Though these standards could be enough to allow the deployment of VLC technology, there are still issues to be addressed when its comes to commercialising the technology. Other communication technologies, such as wireless RF technology, could see VLC as a very strong competitor, but this may not happen if the manufacturers are the same for both technologies. With new technologies, new companies must come to the fore, but looking at the types of technology (short range versus long range), the applications and advantages provided by each, VLC technology may never supersede RF wireless technology. Many other barriers are emerging down the mass production of VLC transceivers.

Duplex transmission techniques are very difficult to implement, as driving LEDs at high speed demands very accurate electronic calculations. The line of sight characteristic of light works best over very short mobility distance. VLC has seamless interoperability with other networks. LEDs can not be used as network product due to the disruptive nature of the lighting.

8 Advances in VLC technologies and field trials

Against the background knowledge that VLC technology is still in its infancy, we must highlight the increasing volume work that has been done. Researchers, universities and companies are working to see this technology deployed. In the United Kingdom, the first Li-Fi application is installed in a classroom in the Business Academy Bexley, a school in South London [52]. The installed system provides access to internet at 5 Mbps for both uplink and downlink. In Japan there have been many cases of field trials. A 100 Mbps full-duplex multiple-access VLC system is in used. It is a multiple access system using a carrier sense multiple access with collision detection (CSMA/CD) method to transmit at a distance of 3 meters [53]. Also developed in Japan is a high-speed parallel wireless VLC system using 2D image sensor and LEDs on the Transmitter side. The transmitter is composed of an array of 8×8 LEDs, each transmitting different data. The photodetector is composed of a high speed image sensor including an array of photo transistors. Another Japanese achievements is a three-dimensional position measuring system with an accurate position detection of a transmitter or a receiver. In this last example, the LED lights send position data, and an image sensor of a robot receives the data as well as the image. The signal processing is performed inside the robot to calculate its position. Some cases of hybrid system including VLC and other communication technologies such as power line communication (PLC) technology are reported [9]: this example presents the implementation of a hybrid system involving PLC and VLC. Another example using spread FSK (S-FSK) modulation on the PLC side and OOK technique on the VLC side is presented. In this case, the behaviour of the visible light channel corrupted by background noise due to sunlight including the fluorescent light was investigated. Earlier in this paper, the communication system is based on the spread orthogonal continuous phase binary frequency shift keying (SOCPBFSK) and OOK. It is a bridge between PLC and VLC channels to relay communication for low data rate purposes [38]. Some characteristics of the interface are presented and the error rate is presented. It is reported from this work that the transmission over the VLC channel is affected by PLC noise and the background light over the transmission environment.

9 Unsolved problems and future directions

Let us recall that an effective implementation of the VLC technology depends on the existence of appropriate regulations. From this angle, standards are lacking to regulate VLC. Likewise, VLC faces both practical implementation and commercialisation challenges as discussed in Section 5 and Section 7 respectively. Thus further research needs to be done both sectors. Most of this will be based on subjects such as Li-Fi, MIMO, multi-user VLC, hybrid system combining PLC and VLC technology or RF and the visible spectrum to name only few.

List of Abbreviations

AWGN: Additive white Gaussian noise

BAM: Bit angle modulation

BER: Bit error rate

CICTR: Center for information communication technology research

CSK: Colour shift keying

CSMA/CD: Carrier sense multiple access / Collision detection

DC: Direct current

DH:	Dual-header
dLOS:	Direct line-of-sight
DPPM:	Differential pulse position modulation
(I)FFT:	(Inverse) Fast Fourier transform
IEEE:	Institute of Electrical and Electronics Engineers
ISI:	Inter-symbol interference
JEITA:	Japan Electronics and Information Technology Industries Association
LASER:	Light amplification by stimulated emission of radiation
LED:	Light emitting diode
LiFi:	Light fidelity
(N)LOS:	(Non) Line-of-sight
(L)(V)PPM:	(Level)(Variable) Pulse position modulation
MAP:	Maximum a posteriori probability
MIMO:	Multiple input - multiple output
MISO:	Multiple input - single output
ndLOS:	Non-direct line-of-sight
NEC:	Nippon Electric Company
OFDM:	Orthogonal frequency division multiplexing
OOK:	On-off keying
OSM:	Optical spacial modulation
OWC:	Optical wireless communications
PD:	Photodetector
PDM:	Pulse duration modulation
PFM:	Pulse frequency modulation
PHY:	Physical layer
PIM:	Pulse interval modulation
PLC:	Power line communications
PSK:	Phase shift keying
PWM:	Pulse width modulation
RF:	Radio frequency
RGB:	Red - green - blue
SDO:	Standardisation organisation
SER:	Symbol error rate

(S)FSK: (Spread) Frequency shift keying

SIM: Sub-carrier index modulation

SISO: Single input - single output

SNR: Signal-to-noise ratio

SOCPBFSK: Spread orthogonal continuous phase binary frequency shift keying

STC: Space-time-coding

VLC: Visible light communications

VLCC: Visible light communications consortium

WiFi: Wireless fidelity

WWRF: Wireless World Research Forum

References

[1] R. J. Drost and B. M. Sadler *IEEE Transactions on Communications*, vol. 62, pp. 1995–2005, 2014.

[2] K. Lee and H. Park *Photonics Technology Letters, IEEE*, vol. 23, pp. 1136–1138, 2011.

[3] IEEE *IEEE P802.15.7/D8, April 2011*, pp. 1–306, 2011.

[4] M. Nakagawa, "Visible light communications," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, 2007.

[5] A. P. S. Louvros and D. Fuschelberger, "Vlc technology for indoor lte planning," in *System-Level Design Methodologies for Telecommunication*, pp. 21–41, Springer, 2014.

[6] M. Biagi, A. Vegni, and T. D. C. Little, "Lat indoor mimo-vlc localize, access and transmit," in *Optical Wireless Communications (IWOW), 2012 International Workshop on*, pp. 1–3, Oct 2012.

[7] Y. Hong, J. Chen, Z. Wang, and C. Yu *Photonics Journal, IEEE*, vol. 5, pp. 7800211–7800211, 2013.

[8] P. M. Butala, H. Elgala, and T. D. Little, "Svd-vlc: A novel capacity maximizing vlc mimo system architecture under illumination constraints," in *Globecom Workshops (GC Wkshps), 2013 IEEE*, pp. 1087–1092, IEEE, 2013.

[9] T. Komine and M. Nakagawa *Consumer Electronics, IEEE Transactions on*, vol. 49, pp. 71–79, 2003.

[10] Z. Wu, J. Chau, and T. Little, "Modeling and designing of a new indoor free space visible light communication system," in *Networks and Optical Communications (NOC), 2011 16th European Conference on*, pp. 72–75, IEEE, 2011.

[11] K. Lee, H. Park, and J. Barry *Communications Letters, IEEE*, vol. 15, pp. 217–219, February 2011.

[12] J. Barry, J. Kahn, W. Krause, E. Lee, and D. Messerschmitt *Selected Areas in Communications, IEEE Journal on*, vol. 11, pp. 367–379, Apr 1993.

[13] M. Saadi, L. Wattisuttikulkij, Y. Zhao, and P. Sangwongngam *International Journal of Electronics & Informatics*, vol. 2, 2013.

[14] S. il Choi, "Analysis of vlc channel based on the shapes of white-light led lighting," in *Ubiquitous and Future Networks (ICUFN), 2012 Fourth International Conference on*, pp. 1–5, July 2012.

[15] R. Roberts and Z. Xu, "Update on vlc link budget work," in *IEEE 802.15. 7 VLC Standard Meeting*, 2009.

[16] M. Biagi, T. Borogovac, and T. D. Little *Journal of Lightwave Technology*, vol. 31, pp. 3676–3686, 2013.

[17] H. Yang, J. W. Bergmans, T. C. Schenk, J.-P. M. Linnartz, and R. Rietman *Optics express*, vol. 16, pp. 21641–21646, 2008.

[18] J. Tan, K. Yang, M. Xia, and Y. Yang *Opt. Appl*, vol. 41, pp. 507–517, 2011.

[19] J. M. Kahn and J. R. Barry *Proceedings of the IEEE*, vol. 85, pp. 265–298, 1997.

[20] X. Zhang, K. Cui, M. Yao, H. Zhang, and Z. Xu, "Experimental characterization of indoor visible light communication channels," in *Communication Systems, Networks & Digital Signal Processing (CSNDSP), 2012 8th International Symposium on*, pp. 1–5, IEEE, 2012.

[21] F. Porikli, "Inter-camera color calibration by correlation model function," in *Image Processing, 2003. ICIP 2003. Proceedings. 2003 International Conference on*, vol. 2, pp. II–133, IEEE, 2003.

[22] Z. Yu, R. J. Baxley, and G. T. Zhou, "Multi-user miso broadcasting for indoor visible light communication," in *Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on*, pp. 4849–4853, IEEE, 2013.

[23] J. R. Janesick, "Photon transfer," SPIE, 2007.

[24] K. Cui, G. Chen, Z. Xu, and R. D. Roberts, "Line-of-sight visible light communication system design and demonstration," in *Communication Systems Networks and Digital Signal Processing (CSNDSP), 2010 7th International Symposium on*, pp. 621–625, IEEE, 2010.

[25] M. Zhang and Z. Zhang, "Fractionally spaced equalization in visible light communication," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 4282–4287, IEEE, 2013.

[26] P. S. Venkataram. Web information. Available at `http://web.mit.edu/pshanth/www/johnsonshot_psv1.pdf`. Accessed: 2014-09-14.

[27] T.-H. Do and M. Yoo, "Received power and snr optimization for visible light communication system," in *Ubiquitous and Future Networks (ICUFN), 2012 Fourth International Conference on*, pp. 6–7, July 2012.

[28] R. D. Roberts, S. Rajagopal, and S.-K. Lim, "Ieee 802.15. 7 physical layer summary," in *GLOBECOM Workshops (GC Wkshps), 2011 IEEE*, pp. 772–776, IEEE, 2011.

[29] A. Yokoi *IEEE P802*, vol. 15, 2008.

[30] S. Rajagopal, R. Roberts, and S.-K. Lim *Communications Magazine, IEEE*, vol. 50, pp. 72–82, 2012.

[31] K. Wong, T. O'Farrell, and M. Kiatweerasakul *International Journal of Communication Systems*, vol. 13, pp. 551–576, 2000.

[32] S. Teramoto and T. Ohtsuki *IEICE transactions on communications*, vol. 87, pp. 3385–3388, 2004.

[33] R. Abu-Alhiga and H. Haas in *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, pp. 177–181, IEEE, 2009.

[34] D. Tsonev, S. Sinanovic, and H. Haas, "Enhanced subcarrier index modulation (sim) ofdm," in *GLOBECOM Workshops (GC Wkshps), 2011 IEEE*, pp. 728–732, IEEE, 2011.

[35] L. Hanzo, M. Münster, B. Choi, and T. Keller, *OFDM and MC-CDMA*. Wiley, March, 2004.

[36] J.-H. Yoo and S.-Y. Jung *EURASIP Journal on Wireless Communications and Networking*, vol. 2013, pp. 1–6, 2013.