Modulation Schemes for Visible Light Communications

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***Abstract*— Visible light communication (VLC) is one of the most recent technological breakthroughs in wireless communications and it is expected to contribute significantly on future generations of mobile communications. The fundamental feature of VLC is the use of visible light spectrum to transmit data along with the traditional use for illumination. However, this requires, among others, rather fast modulation schemes of optical light sources with dimming support. In this review, we analyze the most important modulation schemes used in VLC systems and provide useful insights on their characteristics. To this end, we also investigate the data rate capabilities of each scheme along with a detailed evaluation of their pros followed by discussions and suggestions for compensating for the latter. In addition, flickering and dimming solutions based on each modulation scheme are thoroughly discussed, while new modulation techniques, such as the Asymmetric Optical Modulation, are analyzed in context with alternative highly efficient modulations schemes, such as generalized space shift keying.**

Keywords*— *visible light communication, modulations schemes, flickering, dimming, Asymmetric Optical Modulation, GSSK.

I. Introduction

Visible light communication can assist considerably conventional radio frequency communications and ensure an overall better wireless network performance, wherever short-range links are used. Such communications scenarios are largely encountered in indoor environments, such as in a home or office premise, for downlink Internet access and/or for device-to-device file transfers and video streaming. Yet, just as in the case of conventional RF communications, there are different modulation schemes that can be considered, according to the satisfaction of associated performance trade offs relating to performance, cost and complexity. However, despite the aforementioned similarity, VLC and RF technologies differ in that it is not possible to encode VLC over amplitude and phase, as in the traditional sense, since this is realized through the measurement of the light waves' intensity. Therefore, the corresponding demodulation is dependent on the data receiver's direct detection, which is also referred to as intensity modulation.

It is recalled that the radio frequency spectrum is becoming increasingly scarce due to the experienced heavy congestion in this band due to the continuously rapidly increasing demand for broadband communications and multimedia services. Based on this, the attention has been drawn towards alternative, highly efficient technologies. In this context, the exploitation of the unregulated bandwidth at the optical frequencies renders optical wireless technologies particularly attractive candidates for the future local area network. In addition, VLC systems serve a dual role in providing both illumination and wireless connectivity, which is of paramount importance due to the increased indoor wireless communications and services [1]-[5].

Nevertheless, despite the undoubtedly distinct advantages and capabilities of VLC technology, there are certain shortcomings when compared to traditional RF communication. One of the main downsides is that the achievable data rate falls sharply with increasing link distance, which limits the range of high data rate VLC use cases. Since VLC is a non-coherent form of communication, the path loss is inversely proportional to the distance [1]. Therefore, VLC technology can improve wireless network performance wherever short-range links are used, such as in a home or office for downlink Internet access and/or for device-to-device file transfers as well as video streaming. In addition to that VLC can also enable highly accurate indoor positioning of mobile devices. For example, it is predicted to achieve a functionality that is in high demand by retailers since it requires no additional hardware in mobile devices, this use case is the most promising first step in the commercialization of VLC [1].

It is recalled that in VLC systems, the optical output power of the source is simply varied according to the modulated signal. To this end, OOK (on-off keying), PWM (pulse width modulation), OFDM (Orthogonal Frequency Division Multiplexing), CSK (Color Shift Keying), GSSK (Generalised Space Shift Keying), and Optical Asymmetric Modulation are some of modulation schemes proposed in conjunction with VLC systems as they exhibit an increased performance and robust operation [2].

Motivated by the above, the present review analyzes different VLC based modulation schemes for both single-user and multi-user communication scenarios. To this end, a thorough overview of the fundamental characteristics of each scheme is provided, followed by an evaluation of the associated strengths and weaknesses .This analysis also presents the most recent contributions in VLC based modulations schemes and an insightful analysis that is useful for identifying future research on this topic.

The remainder of this paper is organized as follows: Flickering and Dimming are explained in section II, i and ii respectively. Section III revisit On-Off Keying Color Shift Keying Modulation, Orthogonal Frequency Division Modulation (OFDM). Pulse Modulation, GSSK (Generalised Space Shift Keying), and Asymmetric Optical Modulation., where each scheme is explained in context with the latest state of the art. Finally, useful discussions and insights are provided, along with some closing remarks in Section IV.

II. VLC CHARACTERSTICS

i. Flickering

Among other challenges associated with VLC systems, effective flicker mitigation of the spectrum is one of the major aims. Flicker refers to the fluctuation of the brightness level of light and can result from modulating the light source. Therefore, flicker must be effectively mitigated because it can cause noticeable, unwanted changes to humans. In order to solve this problem, the resulting changes in brightness must be kept within the maximum flickering time period (MFTP) [2]. There is no widely accepted optimal flicker frequency number, but generally a frequency greater than 200 Hz (MFTP < 5 ms) in [2] has been proven to be safe. Also, it facilitates the fluctuation of the light in the absence of perception by the human eye. Hence, the modulation process in VLC must follow the required MFTP between frames and during data frame.

It is also recalled that the occurrence of flickering is associated with the long streams of ones and zeros, which minimize the frequency at which the intensity of light is changing. The result is a harming fluctuation; thus, balancing the sequence has been guaranteed through the utilization of unique codes referred to as the Run Length Limited (RLL) codes. There, data symbols are taken in random at input and guarantee DC balance with equal 1s and 0s at the output for every symbol. In addition, various RLL line codes such as Manchester, 4B6B, and 8B10B are defined in the standard [2], and provide tradeoffs between coding overhead and ease of implementation. Each PHY mode contains mechanisms for modulating the light source, run length limited (RLL) line coding, and channel coding for forward error correction (FEC).

It is also noted that three physical (PHY) types for VLC are offered by the associated IEEE 802.15.7 standard. PHY I operate from 11.67 to 266.6 kb/s, whereas PHY II operates from 1.25 to 96 Mb/s. Finally, PHY III operates between 12 and 96 Mb/s. Each PHY modulation mode has an associated optical clock rate which is "divided down" by the various coding schemes to obtain the final resulting data rates, as depicted in Tables 1 - 3. For PHY I the optical clock rate is chosen to be ≤ 400 kHz, in PHY II the rate is chosen to be ≤ 120 MHz, and in PHY III the clock rate is ≤ 24 MHz for reasons mentioned in [2]. This standard also supports the use of different clock rates with the same device for transmitting and receiving data since the transmitter (LED) and receiver (PD) are independent circuits. The infrastructure could be transmitting at a lower clock rate using slower but brighter LEDs while receiving at a higher clock rate from a portable device that has faster but weaker LEDs. [3] In the proposed PDSM a pulse changes modestly in order to make the flicker less noticeable than in PPM and PWM. It also can be applied to an extremely low light intensity. In the same context, [3] has proposed a detection scheme at the receiver in PDSM, which has a simple structure. On the contrary, the method in[4] exhibits an almost half flicker, where VLO is filtered by a 3kHz lowpass filter.

ii. Dimming

In addition to effective and robust flickering control, it is required that the communication level between the users is maintained as the brightness of the light is reduced or minimized. Naturally, when the brightness of the light is lowered, the human eye reacts by enlarging paving the way for more light into the eye. Dimming support is an important consideration when dealing with VLC, providing higher power savings and energy efficiency. It is also vital to maintain communication activities while a user casually dims the light source, since the light is fundamentally both for illumination and data transmission. Enlarging the pupil is the human's eye natural respond to a lower light level; hence, communication support needs to be maintained when the light source is dimmed over a large range, typically between 0.1–100 percent as shown in Figure 1 [2] and below:

$$Preceived\ Light\ (\%) = 100\ \times \sqrt{\frac{Measured\ Light(\%)}{100}} \quad (1)$$

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

Table 1: PHY I operating modes

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

*Table 2:*PHY II operating modes

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

Table 3: PHY III operating modes

IEEE 802.15.7 standard allows a pattern to be inserted between the data frames for light dimming. Where there is an idle pattern, the duty cycle can be changed to provide brightness variation. This pattern can either be in-band or out of band. In-band idle pattern does not require any change in the clock and can be seen by the receiver. Conversely, an out-of-band idle pattern is typically sent at a much lower optical clock and is not seen by the receiver. This standard also allows for compensation time to be inserted into either the idle pattern or into the data frame to either reduce the average brightness of the illumination source or increase it [3]. In this context, [5] proposed a simple method to suppress the interference after discussing the illumination interference caused by PWM dimming for VLC channels. A data transmission scheme using visible light LEDs with color and dimming control is introduced in [6]. PWM and VPPM coding schemes are used for the control of color and dimming, respectively [6]. Another scheme is introduced where LEDs are separated for the functions of dimming control and data transmission respectively in [7], where an experiment of a 2.5Mbit/s VLC system demonstrated that the dimming controlling and data transmission can be observed simultaneously. Meanwhile, the diming control function has no interference to data signal transmission.

III. VLC Modulation Schemes

There are different schemes through which VLC is modulated. These include: Color Shift Keying Modulation, Orthogonal Frequency Division Modulation (OFDM), Pulse Modulation, Asymmetric Optical Modulation, GSSK (Generalized Space Shift Keying) and On-Off Keying. In what follows, we provide a thorough evaluation of the main advantages and disadvantages of each scheme.

A. On-Off Keying

On and off keying modulation is represented using 1 and 0, which represent on and off, respectively. Even though the OFF mode may be set, it does not imply that LED has been turned off completely. This is one of the simplest and easily implementable modulation schemes, and this is the reason why it is commonly considered in VLC systems.

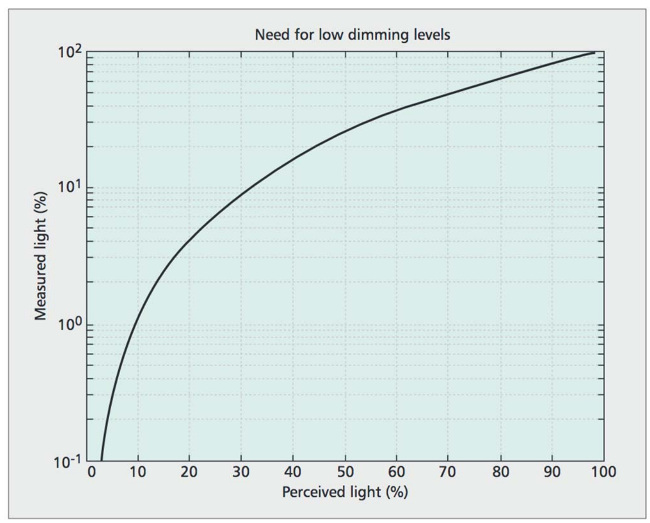

Figure 1: Human eye shows nonlinear sensitivity to dimming , motivating the need for high-resolution dimming support [2].

The simplest direct method for transmitting information is by generating light pulses and turning ON and OFF the HB-LEDs at high speed (i.e., pulse-based modulation schemes). Unlike other types of LEDs, the white LEDs exhibit less response time. To construct an RGB white LED, it is essential to note that three independent driving circuits are required which are used by the white light. A proposed two-phase synchronous buck converter for VLC transmitters is able to reproduce single-carrier digital modulation schemes and to fulfill the lighting functionality [8].

Once information bits enter through the upper layers, they pass through the Manchester RLL code where their data is embedded with a clock; the logical zero in an OOK symbol is written as “01” and a logical one in an OOK written as “10”, to balance the code. Yet, two key considerations are required when OOK modulation scheme is considered. The first one is to redefine ON and OFF levels. For the maximum or optimal level of dimming to be attained, it is important to allocate the different levels of intensity of light to both the OFF and the ON levels. One merit of this concept is that it is possible to acquire the desired levels of dimming without necessarily increasing the corresponding overhead. Since OOK modulation is always sent with a symmetric Manchester symbol, the second required consideration is compensating the period to adjust the average intensity of the perceived source. If additional compensation is created maintaining the ON and OFF modulation levels, it can help to solve the problems associated with dimming. This process breaks the frame into subframes and each subframe can be preceded by a resync field that aids in readjusting the data clock after the compensation time [3]. Determining the duration of compensation depends on the preferred level of dimming. Finally, data frame is fragmented into subframes of the appropriate length after the FCS (frame check sequence) has been calculated and FEC (forward error correction) has been applied.

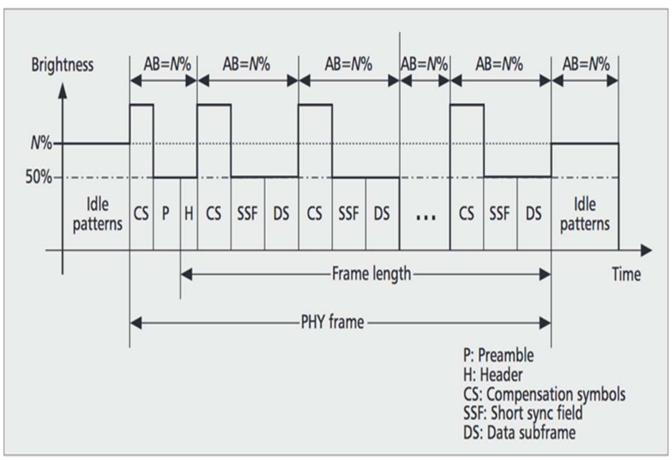

Figure 2: Dimming support using OOK modulation. The figure shows the use of idle patterns (when there is no data) and the use of compensation symbols (in the presence of data using OOK) to maintain an average brightness (AB) of N percent [2]

i. Pros and Cons of OOK

One of the pros of OOK is that it is one of the simplest modulation schemes that exist and one that requires simple mechanisms of operations to work [2]. One of the cons of OOK is that it provides lower data rates when different dimming values are maintained. As a result of this challenge, most of the alternative schemes of modulation are created using pulse position as well as width posision, as explained below [2]. The second merit of the OOK modulation scheme is that it is associated with minimal efficiency, which decreases as the dimming process is conducted. Thirdly, the intensity of the ON/OFF modulations does not change, which affects the communication process as it ultimately renders it unchanged.

The comparison of different OOK modulation in the form of analytical and simulating graphs (BER vs SNR) for OOK Return-To-Zero (RZ-OOK), Non-Return-To-Zero OOK (NRZ-OOK), are illustrated in [9]. A VLC system was successfully implemented in [10] by using an ac–dc single stage buck–boost PFC converter operating in the DCM condition with a dimmable capability varying from 10% to 90% for OOK-M-FSK modulation, with a proven robustness for the VLC system applications, with 1.11 Mb/s achieved transmission rate over a distance up to 20 m while under the influence of external lighting sources. Researchers in [11] established visible light communication for indoor application using NRZ OOK with data rate of 10kb/s and distance up to 10m. Likewise, [12] reports a visible light communication system which transmits data with a speed of 115.2 kbps over a distance of 1 meter using OOK modulation with MATLAB as an interface. Moreover [13] used a combination of PWM with OOK with an adaptive LED receiver achieving a data rate of 1 Kbps with 33% higher range compared to the non-adaptive VLC counterpart.

B. *Pulse Width Modulation*

In this modulation scheme, there is a balance among the width of the pulses depending on the expected levels of dimming while the pulses make digital pulses that are used in taking the signal of modulation. When the LED brightness is highest, the transmission of data occurs. Notably, it is possible to adjust as well as accommodate the rate of data depending on the dimming requirement. According to researchers, a dimming level between 0% and 100% is achievable with the PWM frequency modulation technique. Below is an indication of how the amplitude modulation scheme is implemented.

i. *Pros and Cons of PWM*

One of the merits of this scheme is that it can achieve the highest dimming level without alteration to the intensity of the light; implying that it does not require the definition of on and off levels. One of the demerits of PWM is that the data rates are limited to 4.8kbps [2].

The authors in [14] proposed pulse width modulated VLC (PWM-VLC) by using DMD projector for the voice information guidance. To this effect, the system was able to transmit four different fundamental waves which are sine, square, triangular and sawtooth wave to each different direction at the same time using the PWM-VLC technique at high speed with simple receiver design. In addition, in [15], the implications of PWM dimming on the performance of a DMT-based VLC system was quantified and was proven by simulations that reliable communication is only possible when the PWM samples the DMT waveform at a rate at least twice of the highest subcarrier frequency of DMT. In [16], the authors evaluated the accuracy of PWM, while measurements were taken based on different parameters such as PWM frequency, transmitter-receiver distance, and the receiver’s angle of view.

It was shown that 920 bps data transfer rate and 10^{-4} bit error rate (BER) resulted without affecting the lighting function.

A. *Pulse Position Modulation (PPM)*

In the PPM modulation technique, the symbol time is partitioned into equal slots of time. In one of the slots, the pulse position is used to recognize the transmitted pulse. This modulation technique suffers from low spectral efficiency as well as low data rate or a single pulse per duration of a symbol. As a result, it is possible to suggest a varying position of the pulse-based modulation. Below is an indication of the overlap PPM (OPPM), which allows for the transmission of more symbol duration in the form of a single pulse.

As opposed to the PPM, the OPPM has one merit, which is that it has both a higher spectral efficiency and its dimming values have a wide range. This ultimately assists in the attainment of higher rates of data. Studies have shown that the OPPM symbols pulse width is wider and independent of dimming levels. This requires fixed and small bandwidth for the detection at the receiver at different dimming levels, unlike VPM which requires variable pulse width for dimming [17].

Other than the OPPM, there is the Multiple-Pulse PPM (MPPM) which can acquire more spectral efficiency relative to the OPPM. MPPM is more attractive than VOOK and VPPM, due to the fact that it can achieve a higher spectral efficiency with less optical power as the code-word length increases [18].

The third type of PPM is the variable pulse-position modulation (VPPM) which alters the optical symbol's duty cycles to encode bits. However, it is important to note that the VPPM can change the duty cycle over time as the dimming level also changes. To distinguish VPPM optical symbols, the position of the pulse is used. Since the bit rate does not change irrespective of the dimming level, the range is minimized as the brightness of the light is reduced. The figure below is an indication of how the VPPM technique is carried out.

i. *Pros and Cons of PPM*

One of the benefits of VPPM, which can help is achieve optimal resolution, is that it has the capacity to multiplex with varying levels of dimming in a given frame [18]. One of the demerits of VPPM is that it faces the challenge of attaining optimal duty cycles. One of the challenges and constraints of single carrier modulation is that it encounters high ISI. This results from the fact that it is non-linear regarding the response to the frequency of the channels that use visible light for communication [18]. In [19] it demonstrated the performance of VLC system based on offset-PPM by using single white LED and a new code scheme, a speed of 11 Mbps over 1 m was reported. The authors in [20] introduced a PPSM scheme where it combines both pulse position and pulse shape modulation in order to increase the transmission rates in VLC communications, which allowed more transmission at a better rate. A dicode pulse position modulation (DiPPM) technique has been successfully implemented for an indoor visible light communication (VLC) based system in [21] with a data rate of 13 Mbps.

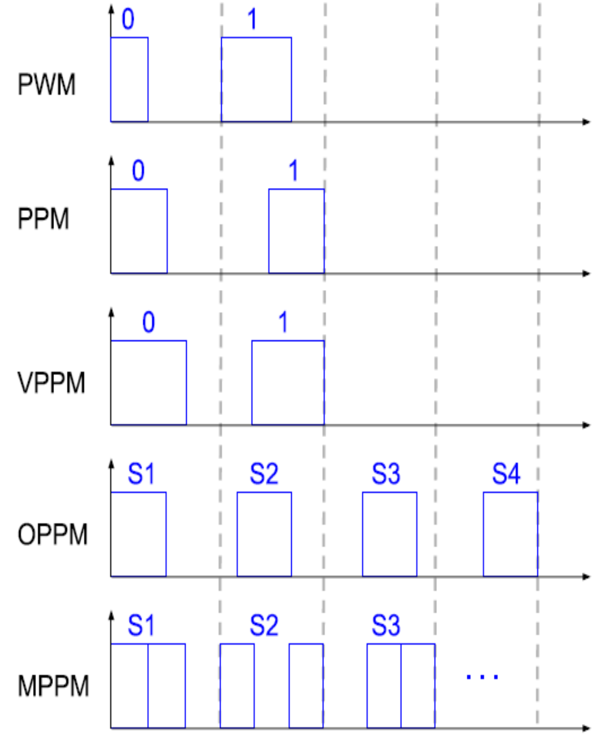

Figure 2: Single pulse modulation illustration [39]

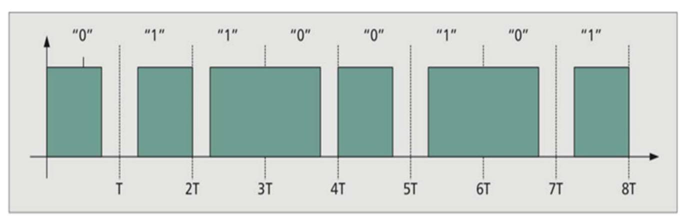

Figure 3: An indication of how the VPPM technique is carried out

Researchers in [22] studied duobinary PPM (DuoPPM) and experiments resulted to a data rate of 14 Mbit/s. In addition, they analyzed the robustness of DuoPPM.

C. *Orthogonal Frequency Division Multiplexing*

This is one of the modulation techniques that is generally accepted because it has the capacity to mitigate against conflicting interference of symbols as well as fading of the multipath. It is also a multiple carrier modulation technique relative to the others. The initial proposition of the OFDM was meant to be used for visible light communication [18]. OFDM operates in such a way that the bandwidth is divided into multiple subcarriers which carry the data in parallel form. Each of the sub-carrier ferries the data in the form of a sub-stream which are modulated using the subcarriers. As opposed to using complex frequency equalization techniques, the OFDM is used to reduce the relevance of the equalizers as well as reduce the interference between symbols. However, many challenges are encountered in realizing this reduction. OFDM is of two types, and they depend on the manner in which the bipolar symbols are converted.

The first one is the Asymmetrically-Clipped Optical OFDM (ACO-OFDM) which only modulates the odd subcarriers leading to a signal that is automatically symmetric in its domain. In this scheme, the negative signals are clipped to zero during transmission. The second type of the OFDM is the DC-biased Optical OFDM (DCO-OFDM), which modulates all the subcarriers using an additional positive direct current where DC bias is added to the normal OFDM symbol to reduce the amount of signal distortion and noise induced by negative clipping. In this regard, the positive direct current is meant to make the signal unipolar [23].

i. *Pros and Cons of OFDM*

One of the pros of this modulation scheme is that it has the ability to mitigate against interferences from multipath fading. The second advantage is that it reduces the complexity of the bipolar signals which require conversion into real signals [18]. Research has shown that OFDM/OQAM can also tame the multipath generated IS and ICI as well as increase the bandwidth. Compared with single carrier-based VLC systems, such as on-off keying, pulse width modulation and pulse position modulation, OFDM/OQAM VLC systems offer higher spectral efficiency and high immunity against multipath distortion [24].

One of the challenges that affect OFDM is that there is a non-linear relationship between the light produced and the current. Its high peak-to-average power ratio (PAPR) is a major drawback of OFDM based modulation, which causes clipping distortion, that results into abasement of systems' performance. In addition, a high PAPR reduces the illumination to communication conversion efficiency and lifetime of the LED. This problem is solvable by Double pre-coded OFDM resolves this problem along with constant envelope GMSK pulse shaping further improves the performance [25], although compared with QAM-DMT explained in [26] it is slightly lower the difference is that OFDM is real. OFDM/OQAM scheme for the VLC system was introduced, OFDM/OQAM can increase the bandwidth efficiency and overcome multipath induced IS and ICI. When compared with single carrier-based VLC systems, such as on-off keying, pulse width modulation and pulse position modulation, OFDM/OQAM VLC systems offer higher spectral efficiency and high tolerance against multipath distortion [24]. The authors in [27] used spectral-efficient orthogonal frequency division multiplexing (OFDM) in addition to bit-loading algorithm and they successfully achieved a high transmission rate over 0.6 m of >1 Gbit/s. Asymmetrically clipped DC biased AADO-OFDM is proposed in [28].

D. Color Shift Keying

It is possible to produce white LED lights using a combination of different colors. This process of combination can be carried out using two methods. The first one is through the combination of the yellow phosphor with blue LEDs. However, one setback of this combination is that yellow phosphor is associated with the slowing down of the white LEDs' response. The second method of attaining the white color is through the combination of blue, green, and red LEDs which leads to the faster realization of the white color and speedy communication [2]. CSK modulation is attained through the use of multiple color LEDs.

Frequency Shift Key modulation and Color Shift Key modulation have a similarity in that both of them depend on color encoding or the combination of wavelengths. IEEE 802.15.7 has broken down the spectrum into seven colors which are supportive of the multiple color LED choices during communication. Based on the figure below, it is an indication of the center of the seven color bands on a Cartesian plane based on the definition of CIE 1931 color coordinates [2]. In the figure, it is possible to obtain the shite color through a combination of three colors which generate the CSK signal. The center of the wavelength determines the CSK constellation on the x-y coordinates. A single rule is used to define the CSK communication using the 4-CSk symbol points. A new CSK system that uses multiple full-color LEDs is proposed for realizing non-variable LED current control [29].

i. *Pros of CSK*

First, the color coordinates guarantee the final output color. Secondly, although different light sources have different output power, there is a constant power output of the CSK light source. This constant total power is guaranteed through the dimming of the CSK. Thirdly, both the digital and analog converters are supported in terms of their amplitude changes by the CSK.

Observing Fig.8 it can be realized that Non-Return-to-zero On-Off Keying (NRZ-OOK) has the lowest performance and Binary Phase Shifted Keying (BPSK) has the best performance. In the same context, the authors in [9] also compared it to BPSK, CSK, and PPM see Table 4. The factors of interference are including sunlight, incandescent, fluorescent, and other background light which cause the additive white Gaussian noise (AWGN). Thus, AWGN is assumed to be the channel noise in this paper. Table 4 shows that Pulse Position Modulation (PPM) exhibits the highest data rate. Yet, it is recommended that more factors are needed to make a safe decision on which one is efficient and thus, further investigations are necessary.

E. Generalised Space Shift Keying

An additional degree of freedom can be added by using the concept of spatial position of transmitters. Therefore, all transmitters are active during a symbol transmission, which results highly excaustive computations.

Usually in VLC more than one LED is needed for illumination, and since the same LEDs are used for communication MIMO techniques are required. $N\tau$ bits transmit per symbol each period T. Using the pathloss power to identify the indices of transmitting LEDs at the receiver was a challenge. Nt LED system is used instead where return to zero pulse pattern with a peak power of Pt for each active LED (1s) with a duration of τT [30]. Zero is idle when transmitted with 1s, however when all transmitted bits are zeros, the pattern sent is orthogonal to all ones data pattern as shown Fig.7.

The optimal symbol set selection in a generalized space shift keying (GSSK) is presented and validated through hardware test-bed experiments. There the VLC system uses an array of LEDs as a transmitter and a digital camera receiver. This study maximizes the inter-symbol Euclidean distances and minimizes the number of corresponding neighbors [31]. Apart from the constraints imposed on the average power, as well as on the peak power relying on non-negative signaling, the input signals of GSSK-VLC systems are discrete [32].

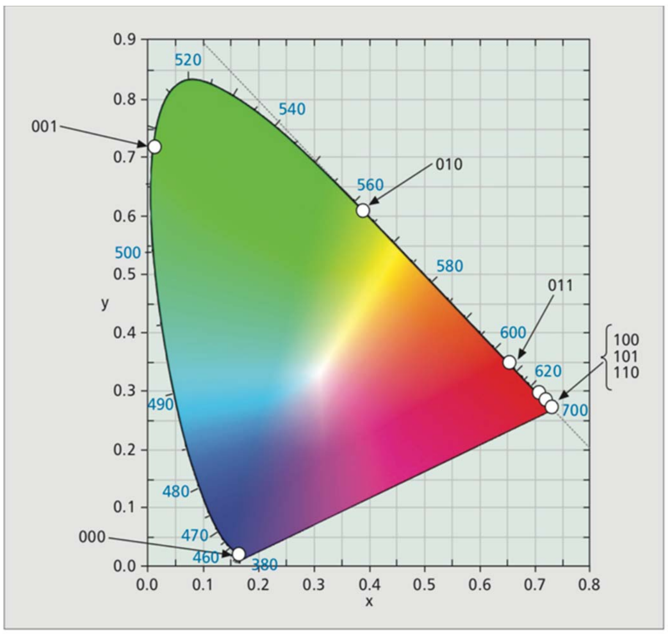

Figure 4: Illustration of the center of all seven color bands on a xy color coordinates

i. *Pros and Cons of GSSK*

This is an efficient and relatively low complexity modulation scheme. In addition, it offers a good power efficiency and higher spectral efficiency. Dimming support is achieved by changing the duty cycle of the transmitted pulse. With an array of Nt white LEDs, the scheme is able to deliver Nt bits/symbol by utilizing the natural differences in the channel gains of the spatially separated LED array. However, the error performance of GSSK mainly depends on having dissimilar channel gain values. This requirement represents a fundamental limitation of the technique. Thus, GSSK is most suitable for applications that require fixed configuration or limited receiver mobility [33].

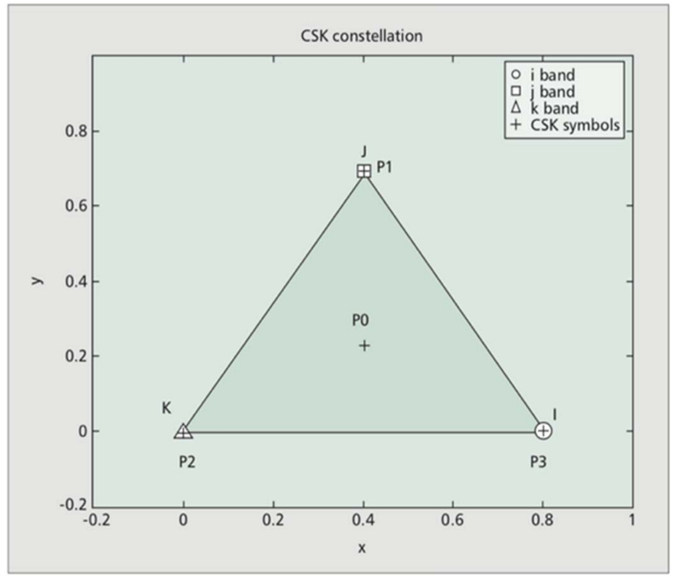

Figure 5: The design rule defining the 4-CSK symbols

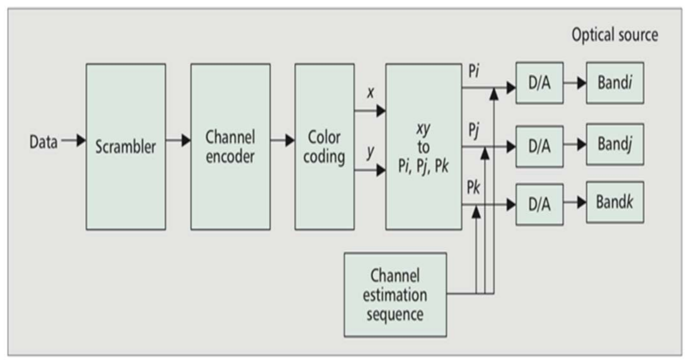

Figure 6: Illustration of the CSK system configuration for PHY III together with three color light sources

The authors in [34] compared multiple space shift keying (SSK-MIMO) techniques such as generalized space shift keying (GSSK), hamming code aided space shift keying (HSSK) and variable generalized space shift keying (VGSSK) for visible light communication (VLC) systems. The performance gain of 1dB is observed for VGSSK over HSSK steadily. Thus, it is concluded that VGSSK-MIMO provides the most advantages.

Presented in [35] is the error performance analysis of GSSK which has a lower complexity signaling technique for short range indoor visible light communications, where an analytical expression for the SER has also been presented and it is also validated by simulations, for SER $\leq 10^{-1}$ which is the region where any meaningful communication can be established.

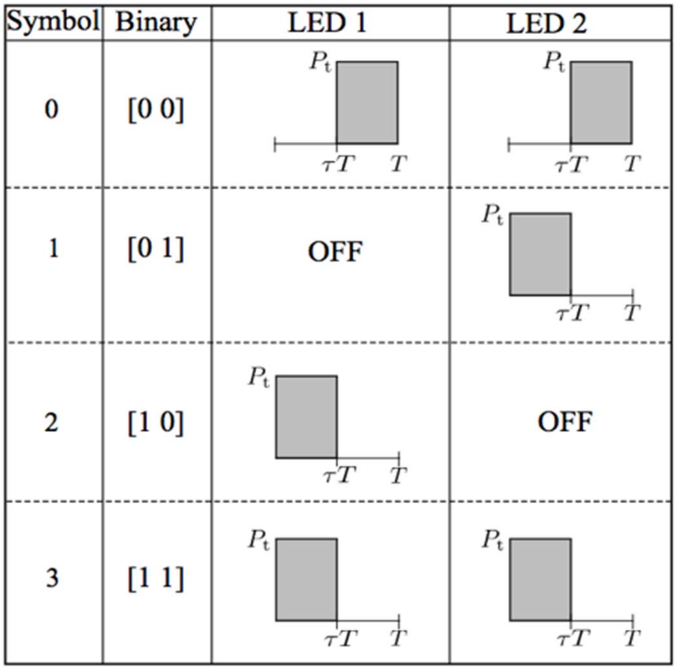

Figure 7: GSSK description for Nt = 2

The authors in [33] demonstrate the advantages and disadvantages of a low complexity, multiple transmitter generalized space shift keying (GSSK) signaling method applied for short range indoor visible light communications. GSSK is most suitable for applications that require fixed configuration or limited receiver mobility, The reason being is that the error performance of GSSK strongly depends on having different channel gain values, where this requirement limits GSSK technique to fixed configuration, the results show that a data rate of up to 20 Mbaud (40 Mbits/s) is achievable. An approach that maximizes the inter-symbol Euclidean distances as well as the number of corresponding neighbors. The symbol search space is significantly reduced using a novel clustering property of GSSK VLC symbols benefits of search space reduction and local tree search are demonstrated in [31]. In addition, a modified generalized spatial modulation (MGSM) scheme with dimming support is proposed in [36] and analyzed for indoor optical wireless communication applications. The error performance of MGSM is derived analytically using the union bound method investigating the effects of channel correlation and imperfect channel estimation on the performance of MGSM with higher spectral efficiencies.

Likewise, the authors in [37] provided the performance analysis of a PLS-aided GSSK-VLC system where four major contributions has been proposed. The input signal characteristics and channels of the proposed GSSK-VLC system, the secrecy performance was analyzed, when the input signals are assumed to have finite discrete distributions subject to specific amplitude and power constraints

F. *Optical Asymmetric Modulation*

In OAM each transmission (M-ary) represents individual symbols by a sum of different trigonometric functions, where those functions entail predefined angles. It follows the robustness applied to the highly correlated VLC system where the subchannels are highly correlated. This modulation scheme represents each symbol of the M symbol scheme and represents it in the constellation diagram as the sum of cos and sin of the angle that was predefined. After that it superimposea the signals in the power domain and they are sent simultaneously [38].

i. Pros of OAM

The OAM modulation scheme provides a more improved performance with lower hardware complexity compared to the other schemes. It has high capability of enabling high data-rates. Compared with GSSK it has higher robustness. It also deals with the high correlation nature of the environment VLC is used to. This is largely indoor environment, due to the fact that mostly more than one LED is used for illumination and since the same LEDs are used for data transmission correlation is a very important aspect of it.

Table 4: THE COMPARING TABLE FOR EACH MODULATION

Comparison	Colour index	Data rate	Flickering	Simplicity
OOK	Not required	96Mb/s [1]	N/A	Simple
CSK	Required	96Mb/s [1]	N/A	Complex
PPM	Not required	600Mb/s [3]	Low [1]	Normal
PWM	Not required	N/A	N/A	Normal
OFDM	Not required	220Mb/s [2]	Medium [1]	Complex

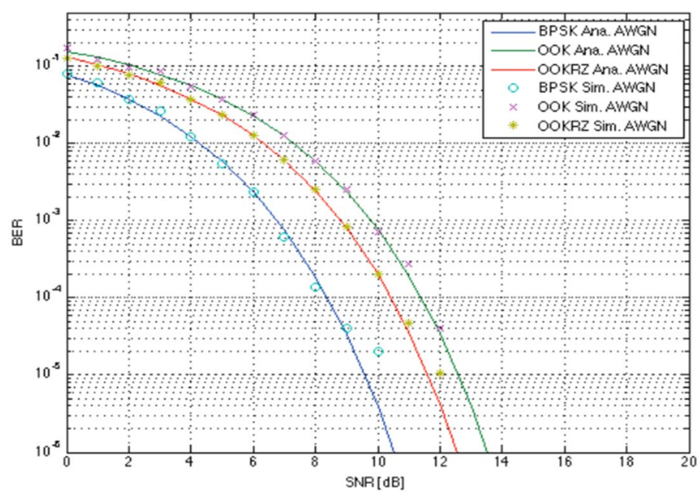

Figure 8: The comparing graph between the analytical and the simulation graph [9]

IV. Conclusion

This article reviews the different modulation schemes used in Visible Light Communication. An overview of the state of the art on the system design is provided, which includes the major advantages and disadvantages for each scheme. It was shown that the great advantages of the extremely high bandwidth provided by VLC is limited by the modulation scheme used. While each scheme had decent response, we believe that with a good sum-rate and overall high bit-rate, VLC systems can considerably contribute toward meeting the capacity demands expected in future 5G networks and beyond.

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