Impact of Lighting Requirements on VLC Systems

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MCL Technical Report No. 11-01-2013

Abstract

Advances in Solid State Lighting (SSL) are enabling Light-Emitting Diodes (LEDs) to be the dominant source for future human-made light. The adoption of LEDs is expected to significantly reduce energy consumption and facilitate precise intensity and color control of illuminated spaces. SSL also makes possible the use of Visible Light Communications (VLC), in which data are emitted from luminaires through subtle intensity variations. This article focuses on the impact of lighting requirements on VLC systems, especially as found in indoor deployment scenarios. We also consider dimming control and its impact on color quality in the context of measured versus perceived light levels.

Keywords – Solid state lighting, optical wireless communications, visible light communications, luminaires, LEDs, dimming, color intensity control, modulation, IEEE 802.15.7.

1. Introduction

Light and lighting are an integral part of the human experience. Indoor lighting or illumination is ubiquitous in the modern world and accounts for ~19% percent of global electricity consumption [1] – a value that is not expected to diminish given current socioeconomic trends and policies. Over the next 25 years experts project that global electricity consumption for lighting will rise to over 4,250 TWh, an increase of 60% overall at an average rate of 1.9% per annum [1]. However, much of the world's artificial illumination continues to be produced by inefficient light sources such as incandescent lamps. Moreover, a lack of modern lighting control, a failure to harness natural daylight, and an unawareness of over-provisioned lighting levels contribute to unrealized energy savings. Fortunately, significant reductions in energy consumption and productivity gains are possible by installing LEDs and adopting "smart" lighting control of illumination intensity and color [2].

In an apparently disparate context, the rapid growth in adoption of wireless mobile devices is driving the need for increased wireless capacity for delivery of rich-media and cloud-based services. As these devices continue their expansion into the marketplace, the resulting rise in traffic has placed enormous strain on conventional radio frequency (RF) wireless communications capacity. Congestion results from the finite size of the allocated RF spectrum. In simple terms, we are running out of available radio waves to carry data traffic.
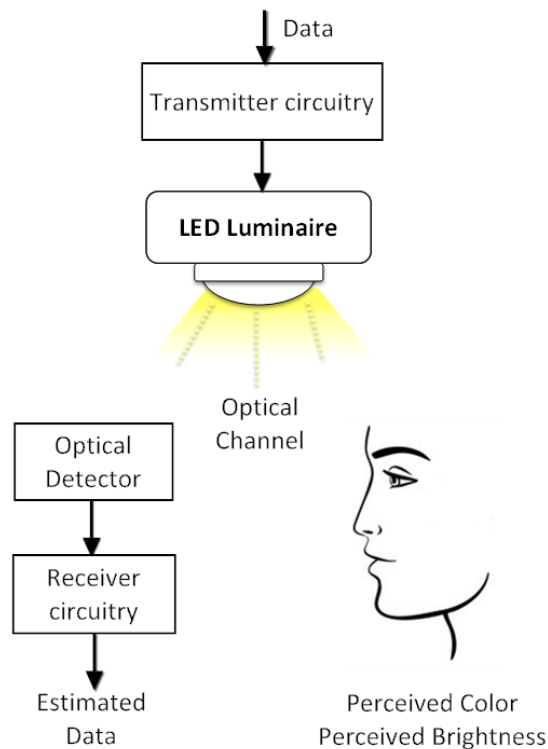
Fig. 1: Due to the dual functionality of VLC (communication and lighting), one must consider the optical detector as well as the human eye. The optical detector followed by the receiver circuitry estimates the transmitted data, while the human visual system constructs an image, necessarily perceiving color and brightness of the incident light.

The upheaval in the lighting paradigm driven by the demand for energy efficiency and light quality has created a unique opportunity to re-engineer the function of indoor lighting *and* to address the wireless capacity challenge. We, and many others, have recognized the possibility of leveraging the visible spectrum provided by indoor lighting to deliver new wireless data capacity in Visible Light Communications (VLC). [Footnote: henceforth in this article we imply that VLC is used for both lighting and communication; not just the latter.]

VLC is motivated by several benefits including a huge, unregulated bandwidth (THz), license-free operation, low-cost electronics, no interference with RF systems, and no health concerns. A data waveform can be modulated onto the instantaneous power of the optical carrier and the optical detector generates a current proportional to the received instantaneous power, i.e., intensity modulation with direct detection (IM/DD). Due to the potential synergy of lighting and communication, it is unsurprising that VLC has been a subject of increasing interest and development. Nonetheless, there are a number of practical challenges to be addressed before its widespread acceptance [3].

Paramount to the practical implementation of VLC in lighting is ensuring high-integrity color quality that is satisfactory to humans. VLC is unique compared to most other communication technologies due to its dual functionality – communication *and* ambient lighting. As shown in Fig. 1, beside the optical detector VLC transmission must be cognizant of a second type of signal receiver – the human eye. Thus, a consumer VLC system is limited by critical color quality and brightness constraints, which are necessary to meet functional and aesthetic requirements of lighting. Most VLC research to date has primarily focused on achieving increasingly high data rates. Recent experimental setups have demonstrated VLC links above 1 Gbps [4]. Yet, the laboratory conditions for these demonstrations are usually limited to near-field communications instead of conventional home or office spaces and do not address lighting quality issues. Dealing with color-quality and energy consumption constraints while achieving high data rates is a clear objective to make ubiquitous VLC systems viable. Industry standards for light quality and human factors will play an important role in defining modulation techniques which address the challenge of incorporating broadband VLC with high-quality illumination and lighting state control.

In the remainder of this article we focus on the properties at the intersection these two themes. In section II we review the nature of VLC signals; in section III the perceptual, technical, and commercial nature of dimming is explored. Section IV considers the nature of color. Section V considers the impact of data modulation on color quality and dimming. Section VI concludes the paper.

2. Features of VLC Signals

The VLC transmission signal chain includes the LED source and a modulation technique suitable for the optical channel. An LED is a p-n junction-based semiconductor diode that emits a narrow spectrum light in response to an electric current, a phenomenon known as electroluminescence. As shown in Fig. 2, the dominant wavelength of the LED, corresponding to the color, is a product of the semiconductor materials used and the "energy gap" between them. There are two primary methods used to produce the white light. The cheapest and most popular is phosphor conversion, in which a blue LED is coated with a yellow phosphor to emit broad-spectrum white light. The second approach combines monochromatic LEDs of different colors to produce white. This method also offers color-tunable lighting by varying the intensity of individual colors.
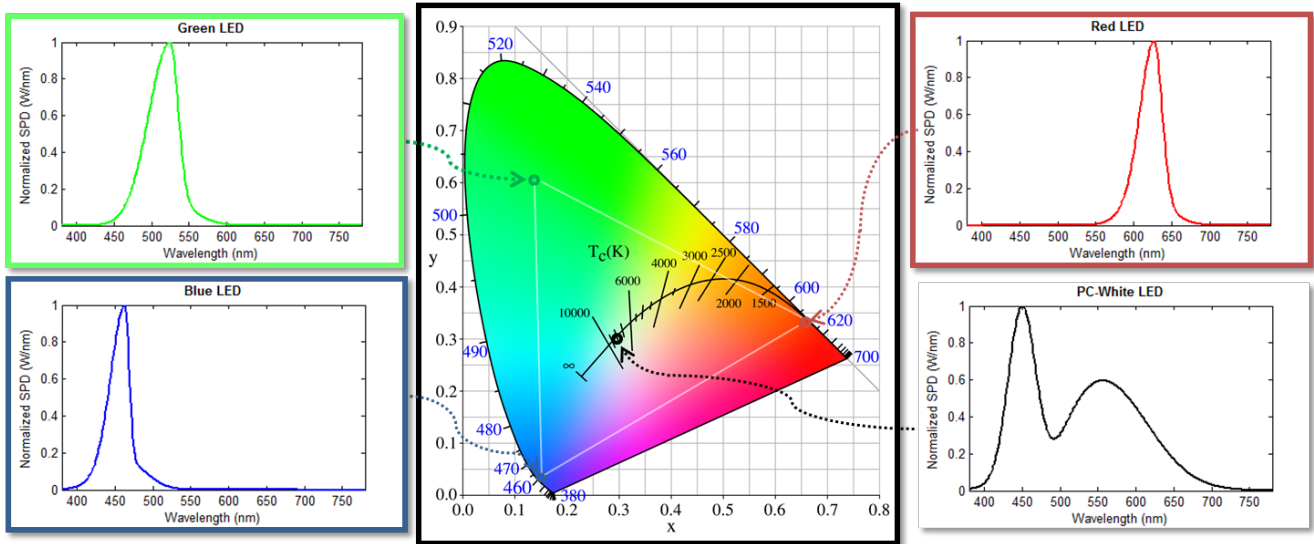
Fig. 2. The power distribution as a function of wavelength for phosphor-converted (PC) white LED and monochromatic LEDs. The x-y chromaticity values are marked on the CIE 1931 chromaticity diagram. A weighted mixture of the green, red, and blue LEDs can yield any chromaticity point within the white triangle gamut. The PC white LED has a CCT near 8000 K on the black body (Planckian) locus, indicating that this LED would emit a bluish-white light.

The VLC channel has a number of unique features: (1) the optical carrier modulation is only achieved through intensity modulation, i.e., no frequency or phase information, (2) the transmitted waveform is modulated onto the instantaneous power, resulting in a real and positive waveform, (3) the average transmitted power is the mean of the input power signal rather than the mean square of the signal amplitude as in RF transmission, and (4) the magnitude of the transmitted power is constrained to a prescribed value. This last item (4) is due to eye safety considerations, power consumption constraints, and LED dynamic range limitations. Signal degradation arises from the combined effects of the proportionality of the signal-to-noise ratio (SNR) to the square of the average received optical signal power (path-loss), ambient shot noise, sunlight and artificial illumination, thermal shot noise within the receiver electronics, and inter-symbol interference (ISI) from multipath propagation.

Channel conditions of VLC systems are a function of the environment and/or illumination settings. Settings may be manually defined (e.g., using a dimmer switch on a wall or wireless devices), or automatically actuated by a smart lighting control system. This is in contrast to RF wireless communication systems, in which end-users have little effect on the channel conditions besides influencing the location of mobile devices. Whereas an RF system is primarily concerned with communications performance, a lighting system equipped with VLC must arbitrate the needs of both communication and lighting quality.

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3. Dimming – Perception and Implementation

3.1 Building Automation Perspective

Lighting controls can increase the value of commercial buildings by making them more productive, comfortable, and energy-efficient [2]. This is often a product of dimming functionality, which can be application specific. For instance, settings such as conference rooms, restaurants, or examination rooms, can require light levels as low as 1 percent of maximum illumination for aesthetic and comfort purposes. For office tasks, an illuminance level of 300 lux (lumen/meter^2) is recommended for reading and writing tasks whereas 30 lux is sufficient for computer tasks. However, for spaces in which saving energy is the primary goal, dimming requirements are less stringent. For instance, critical performance is secondary in environments such as corridors, stairwells, or utility rooms. In these settings, dimming is primarily for energy management and/or security and can be limited to a value such as 20% of full light output before it is more economical to shut the lights off completely. Diming can also yield energy savings by reducing heat production and in turn reducing HVAC cooling loads.

A VLC enabled lighting design must carefully consider these unique qualities and services of individual spaces and applications.

3.2 Electronics Perspective

The brightness of an LED is adjusted by controlling the forward current through the LED. There are three primary methods to dim LEDs: (1) analog dimming, (2) digital dimming, and (3) hybrid dimming. Analog dimming, also known as amplitude modulation (AM) or continuous current reduction, is the simplest type of dimming control. This technique lessens the current amplitude linearly to adjust the radiated optical flux. Unfortunately, AM is prone to inducing a noticeable change in color ("color shift"), which is discussed in more detail in Section IV [6].

In digital dimming, the average duty cycle or signal density represents the equivalent analog dimming level, i.e., a digitally modulated pulse train yields the same average LED drive current as achieved using the analog technique. Pulse-width modulation (PWM) is the simplest example of digital dimming modulation. The time period of the PWM signal is fixed, whereas the duty cycle varies proportionally to the required dimming percentage. The classic case switches between an 'on' (high) and an 'off' (low) state. PWM is preferred in the industry due to its simplicity and inherent linearly as compared to AM; and its reduced susceptibility to chromaticity shift. Combinations of both AM and PWM in hybrid techniques have been proposed for even further reduction of perceived chromaticity shifts [6].

3.3 Perceived Brightness

There is a nonlinear relationship between human-perceived brightness and quantified luminance achieved by dimming. This property is described by the Weber-Fechner law, whereby the perceived brightness is proportional to the logarithm of the luminance, or the model of Stevens, in which the perceived brightness is proportional to the square root of the luminance (or another root depending on light source properties). These approximations reveal how the eye adapts well to low-light conditions. For example, a luminaire that decreases its luminance, or optical power, from maximum by 50% results

in a perceived brightness reduction of only 30% according to the model of Stevens. However, because a receiver's signal strength is proportional to luminance, this phenomenon is unfavorable from a VLC perspective – signal strength decreases to a lower percentage than that of perceived brightness.

4. Illumination Color

Conventional incandescent lighting produces "white" light across a broad visible spectrum. SSL using LEDs, in contrast, synthesizes "white" light by either phosphor-converted blue LEDs or by composition of light from narrow-spectrum LEDs with different wavelengths. In this context, "dimming" must be redefined to encompass the intensity of individual wavelengths which may be known as "color intensity control." In the following, we address color models, color quality evaluation, and opportunities to exploit the differences between perceived light and what can be detected with electronics.

4.1 Color Metrics

The distinguishing characteristics of today's LED luminaires include the emission pattern, luminous flux, lamp color, and color rendering ability. While the emission pattern is highly dependent on the optical packaging and luminaire enclosure, the remaining properties can be derived from the spectral power distribution (SPD). The SPD is mathematically defined to be the derivative of the luminous flux with respect to wavelength. It provides information about the light's spectral composition – its output intensity at different wavelengths.

In integrating the SPD with so-called color matching functions, the numerical coordinates that represent a particular hue perceived by the human eye can be determined. The coordinates and color matching functions are specified with respect to a color space. CIE 1931 (Fig. 2), CIE 1976 [L*, u*, v*] (CIELUV), and CIE 1976 [L*, a*, b*] (CIELAB), defined by the International Commission on Illumination (CIE), are today some of the most popular color spaces. However, a less exact color measurement, known as the correlated color temperature (CCT), is more frequently specified for white LEDs in the marketplace. The CCT assigns temperatures to a color scale of "warm," reddish hues to "cool," bluish hues of white light (Fig. 2). They correspond to the temperatures of an ideal blackbody radiator emitting like colors.

In addition to the perceived hue of an LED, its ability to render the colors of illuminated objects with high fidelity is of prime importance. For a white light source, we seek to match the light qualities of the Sun. The most common measure of color rendering ability in industry is the color rendering index (CRI). The CRI is based on color difference measurements between specified color samples illuminated by a luminaire under testing and the same samples illuminated by a reference light source. This value can be calculated provided the reflectance distributions of the samples and the SPD of the luminaire. Other metrics, such as the National Institute of Standards and Technologies' color quality scale (CQS), and statistical methods, have been designed to mitigate the shortcomings of the CRI, which does not always measure color rendering performance accurately [5].

4.2 VLC and Color Quality Evaluation

Given the importance of hue and color rendering in producing quality illumination, knowledge of the SPD of a light source is critical. In the context of VLC, a prominent feature of the SPD is its deviation as

a function of LED drive current. A shifting SPD can induce a perceptible chromaticity shift and affect color rendering properties [6]. Similarly, particular VLC modulation techniques are more resilient to color quality degradation than others.

One approach to evaluate the color effects of VLC modulation schemes is by using SPD models to measure the SPD deviations as a function of the drive current [7, 8]. However, the models can have a cumbersome number of fitting parameters available only through significant empirical testing of the LEDs. Furthermore, using SPD models to characterize color effects of VLC has a number of other pitfalls. Such models are designed assuming relatively static conditions, and, therefore, do not account for the high-frequency current fluctuations of VLC. Finally, it is challenging to fit one SPD model to the wide variety of LED types each with unique characteristics. This is especially true when one attempts to account for the extra effects of phosphor material utilized in phosphor-converted LEDs.

Another approach to LED characterization is by means of experimentation under VLC operating conditions. Preferably, LED manufacturers would provide more extensive color data (SPD at best, or chromaticity coordinates and CRI at least) for varying drive currents and modulation frequencies for their high brightness LED products. Until a greater amount of data is readily available, researchers will need to continue to rely on laboratory characterization of candidate LEDs.

4.3 Perceived Light

In the analysis of LED spectral data for various VLC schemes, human ocular properties and limitations play a crucial role (Fig. 3). On a fundamental level, VLC relies on the low-pass nature of the human visual system to filter the embedded high-frequency data modulation. Also due to our physiology, VLC signal strength losses are greater than those of perceived brightness in dimming. Yet, by exploiting illumination color, there are potential gains to be realized in the dimming scenario. For instance, it is known that the human eye is less sensitive to color in dim settings than bright settings due to the use of different retinal cells for different light levels – cone cells for well-lit settings and rod cells for dim settings. Thus, a high data rate scheme which could be rejected at high brightness due to color quality effects could potentially be utilized in darker settings using adaptive techniques. Future work entails measuring the gains of such an approach for VLC transmitters that apply different spectral power distributions at different dimming regimes.

The eye's limited SPD distinguishability is an additional feature that may be exploited for VLC. Since the eye only has three types of color-receptive cone cells, it is possible that light sources with differing SPDs can appear to be the same color. This property is known as metamerism. A modulation technique known as color shift keying (CSK) varies the relative intensities of red, green, and blue LEDs of a white luminaire in an order dependent on the transmitted bit sequence [9]. The rapidly changing colors will appear white to a human due to the eye's relatively long integration time, but each color channel can be individually detected by properly filtered receivers. Metameric modulation, another approach, encodes data sequences to combinations of LEDs which are all metamerically equivalent, but having differing SPDs that are distinguishable at the receiver. Due to metamerism, the instantaneous color is always the same. Thus, metameric modulation has the potential to eliminate color flicker effects that could be present for CSK [10].
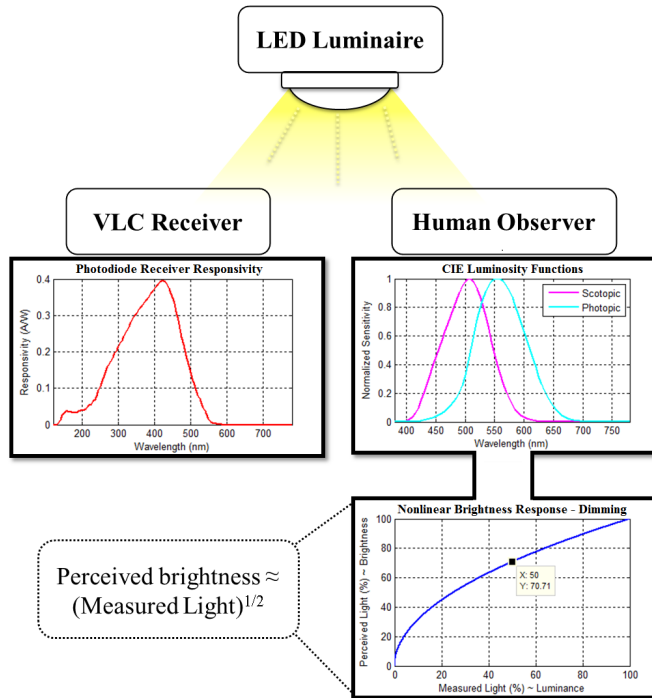
Fig. 3. The sensitivities with respect to wavelength are depicted with the responsivity and luminosity curves. For the human eye, the luminosity curve varies appreciably as a function of brightness. Dimly lit scenes correspond to scotopic vision, whereas bright scenes correspond to photopic vision. The range between these two extremes is named mesoptic vision, which occurs approximately at luminances between 0.003 candela per meter squared (cd/m^2) and 3 cd/m^2. VLC would occur in the brighter two regimes. An approximation of the nonlinear response of the eye to light intensity is shown according to the model of Stevens.

The concept of color mixing for illumination has also been explored with lasers as the source. Reference [11] describes experiments in which the combination of red, green, blue, and yellow lasers can produce white light with high quality color-rendering properties. This is somewhat counterintuitive as one would expect that the "spiky spectra" of a laser luminaire would behave much differently than an incandescent source (the gold standard in color-rendering) with a smoother SPD. However, since the reflectance distribution of nearly all everyday objects is "broad, smooth, and continuous," the effect of reflected laser light is similar to that of reflected full-spectrum white light [11]. Future adoption of laser-produced illumination, if cost effective, could enable significant performance gains in VLC systems due to the high-frequency modulation capabilities of lasers. In the meantime, we focus on how LEDs, with lower modulation bandwidths, can be applied in meeting both missions.

5. Dimming and Communication

By its very nature, dimming reduces the average signal strength and places an extra constraint on modulation schemes in order to enable both data transmission and light intensity adjustment. A variety of intensity control approaches, described below, are being developed to optimize data and bit error rates without sacrificing illumination quality.

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5.1 Single Carrier Pulsed Techniques

The IEEE 802.15.7 Visible Light Communications Task Group completed a physical and media access control (MAC) standard for VLC which incorporates two-level dimming schemes. The standard's physical I and II types support on-off keying (OOK) with dimming by the insertion of compensation time (CT), and variable pulse-position modulation (VPPM) [9]. In OOK with CT, a subframe containing information bits is followed by a CT subframe which is either completely 'on' or 'off' and of the correct duration to achieve the target dimming percentage. VPPM is a variant of 2-PPM, wherein a symbol period is constant and has two possible slots. A pulse in the first slot denotes a 0-bit, and similarly a pulse in the second slot denotes a 1-bit. VPPM increases or decreases the pulse width in accordance with the required dimming level. The ease of implementation of OOK with CT and VPPM is an important quality of these communication/dimming techniques (Fig. 4).

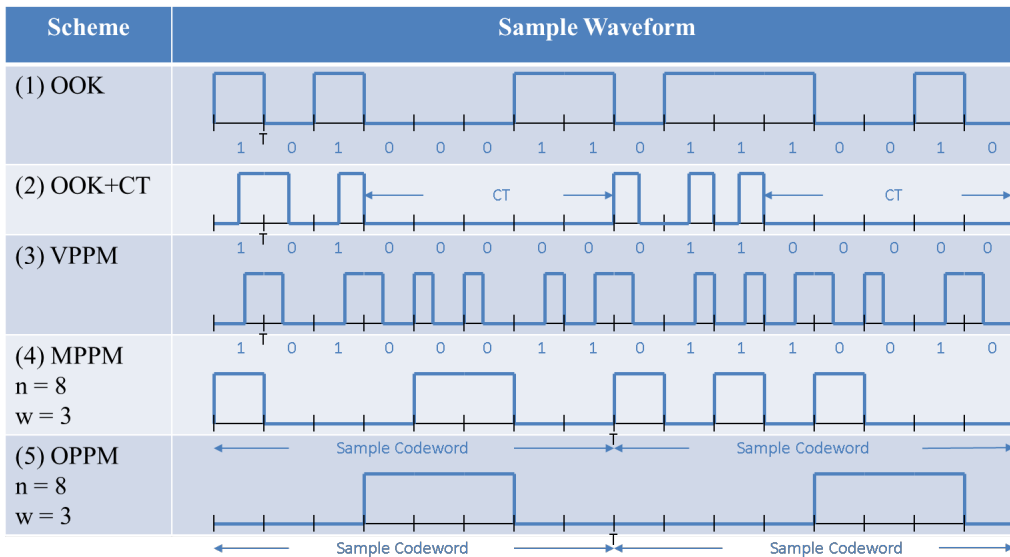| Scheme	Sample Waveform
(1) OOK	
(2) OOK+CT	
(3) VPPM	
(4) MPPM n = 8 w = 3	
(5) OPPM n = 8 w = 3	

Fig. 4. Two-level modulation plus dimming schemes to demonstrate 62.5% dimming. (1) OOK: reference 50% dimming, (2) OOK+CT: a 0-bit is a high-low transition and a 1-bit is a low-high transition (Manchester line coding), (3) VPPM: pulse width of conventional 2-PPM is reduced from 1/2 to 3/8, (4) MPPM: 56 possible codewords, and (5) OPPM: 6 possible codewords.

With more advanced modulation, but increased implementation complexity, it is possible to gain improved data rates with comparable dimming functionality. Multiple pulse-position modulation (MPPM) is one such example. Lee and Park present MPPM in their review on dimming schemes [12]. In this case, a symbol is divided up into a predetermined number of slots, also called "chips." Assume n chips. In any n chip block, there are 2^n possible codewords, or distinct sequences of ones and zeros. Yet, if we restrict codewords to have a weight w, where w is the number of ones in a codeword, then

$\binom{n}{w} = L$ codewords exist. This will result in $log_2(L)$ bits per symbol. When w is adjustable, MPPM

functions as a dimming scheme. The fraction w/n is the percent of maximum illumination. Clearly, if $w=o$ (all zeros), or $w=n$ (all ones), no data are transmitted. A larger number of chips increases the extent and resolution of the dimming. The ones can also be constrained to be consecutive in what is known as

overlapping PPM (OPPM) (Fig. 4). Although this reduces the possible number of codewords *(L=n-w+1)*, OPPM has better spectral efficiency as compared to MPPM [13].

Just as wireless RF has adopted adaptive communication schemes in numerous systems, VLC can benefit from an adaptive framework. The adaptive technique adjusts the modulation based on factors such as realistic transmitted power, modulation bandwidth, noise and interference limitations as well as closed-loop feedback control. This is especially feasible due to the development of software defined cognitive radios, where communication operating parameters are simply altered through software (as opposed to hardware) based on knowledge of the environment. Indeed, software defined VLC (SDVLC) is already a reality [14]. As shown in Fig. 5, VLC adaptive systems will incorporate the lighting state into communication decisions.
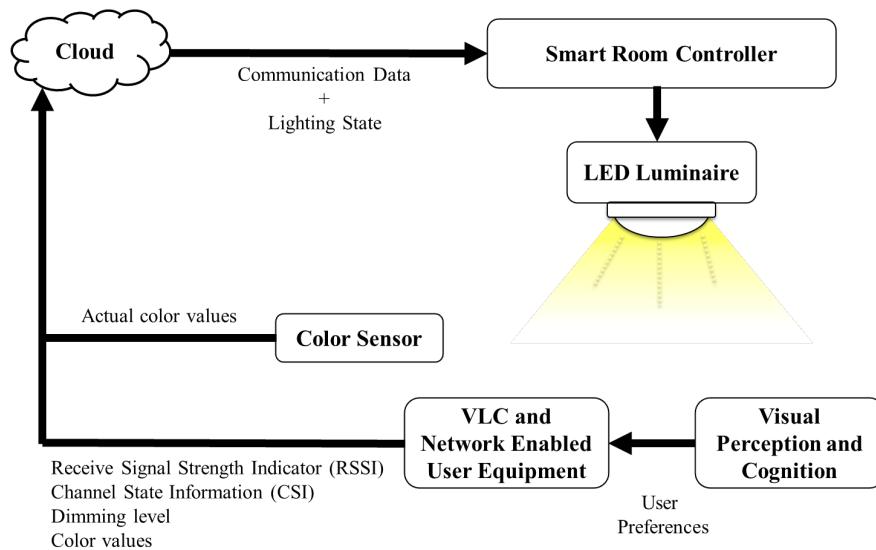

Fig. 5. Feedback controlled VLC adaptive system.

A particular opportunity for adaptive schemes occurs in high noise regimes. Here the shot noise can be relatively large compared to signal strength (low SNR) depending on the environmental conditions such as dimming settings imposed by the user, natural sunlight from a window, or light from other luminaires. Yet, most analyses assume a high SNR regime in which bandwidth is the limiting factor, not noise. A scheme such as OPPM can yield higher data rates compared to MPPM due to its higher spectral efficiency in this operating regime. However, when the environmental conditions change to a high noise regime, other schemes will be more effective, such as MPPM. An adaptive VLC system could automatically switch schemes in such an example by monitoring the channel state.

5.2 Multi Subcarrier Techniques

Orthogonal Frequency Division Multiplexing (OFDM) can be applied to VLC to improve spectral efficiency of the modulated signal. However, as a modulation strategy for dimming it is not acceptable by itself, but can be combined with other dimming techniques. As shown in Fig. 6, two conventional

schemes are used to realize a real-valued OFDM signal suitable for IM/DD, namely DC biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM).

An OFDM signal can be cast onto the PWM dimming-controlled signal during the 'on' period (Fig. 6). However, this limits data throughput to the relatively low PWM line rate of commercial LED drivers (tens of KHz). Achieving high-speed links with this approach is only feasible when the PWM dimming signal is at least twice the frequency assigned to the largest subcarrier frequency of the OFDM signal to avoid subcarrier interference. However, this constraint is not practical for commercial LEDs with limited modulation bandwidth and limits the opportunity to use conventional LED drivers.
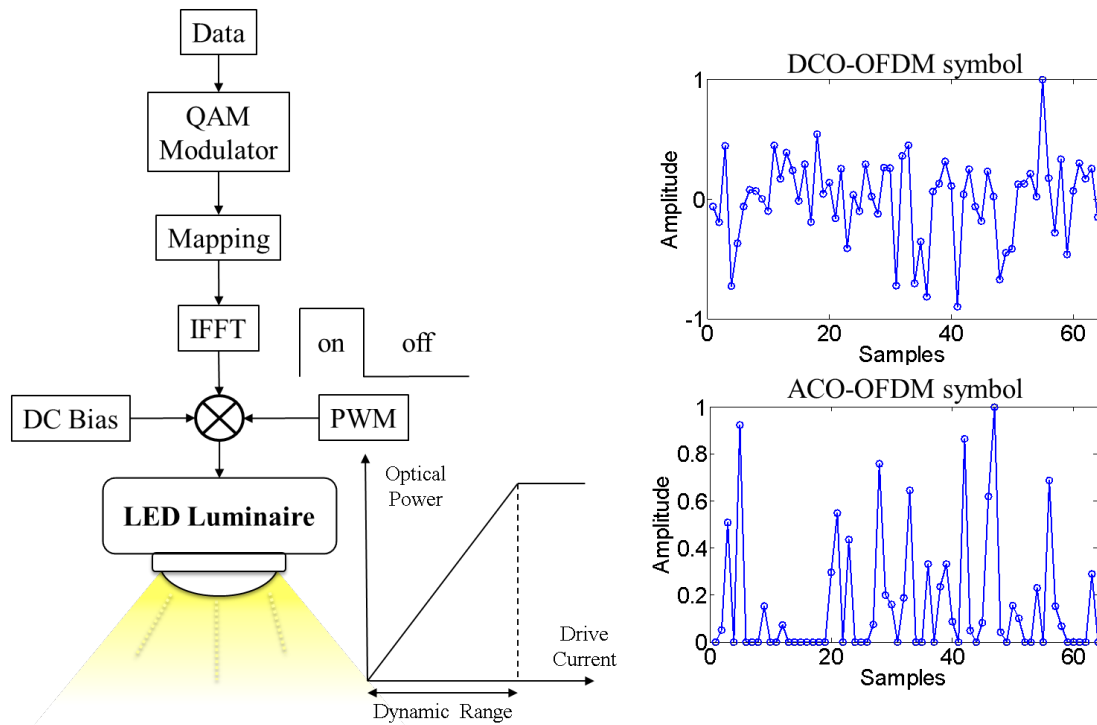

Fig. 6. Building blocks of a VLC OFDM modulator with dimming and LED dynamic range constraint. The serial data bits are grouped into symbols and modulated using a quadrature amplitude modulation (QAM) modulator. The mapper assigns the QAM symbols to the inverse fast Fourier transform (IFFT) operation input bins (OFDM subcarriers). The OFDM time-domain symbols are available after the IFFT operation. Different OFDM schemes for VLC (real-valued OFDM symbol) are realized based on how the QAM symbols are assigned to the subcarriers (Mapping). The bipolar DCO-OFDM symbol is used to modulate the optical carrier intensity after setting a proper DC operating point. In ACO-OFDM, the generated bipolar symbol is converted to unipolar through clipping of all negative values at zero.

Therefore, OFDM schemes with dimming are being developed to consider existing LED and driver technologies. For instance, the proposed approach in reference [15] utilizes the entire period of a PWM signal for OFDM signal transmission, maintaining the data rate for a wide dimming range independent of the PWM frequency. This approach also maintains the signal within the dynamic range constraint of the LED. Also, for an OFDM signal superimposed on a DC bias level (analog dimming), the signal must be adaptively scaled to control the effective brightness and to minimize the induced noise due to signal clipping.

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Although OFDM continually gains in popularity due to its attractive communication performance, additional research focus is necessary to examine its effect on light quality in practical scenarios. If such schemes coupled with intensity and color control techniques prove to be acceptable to the human eye, OFDM stands to be a forefront contender in the future of practically adoptable VLC systems that satisfy lighting requirements.

6. Conclusion

The revolution in lighting with the adoption of LED devices has created an opportunity to exploit the visible spectrum for wireless communications. Energy-efficient dimming, or color intensity control, remains a key challenge in achieving the need for efficient and high-speed data modulation while supporting human illumination requirements. In this article we have reviewed the challenges to achieving this 'dual use,' with an eye towards identifying strategies that will lead to successful commercial adoption in the lighting industry. With the continuing efforts on global energy use reduction and the rapid adoption of mobile devices, it appears that both the demand for localized wireless capacity and energy-efficient lighting will continue unabated.

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