Wireless Access Testbed through Visible Light and Dimming Compatible OFDM

H. Elgala, M. Rahaim, T.D.C. Little
Multimedia Communications Lab
Smart Lighting ERC
ECE Department, Boston University
Boston, USA
{helgala, mrahaim, tdcl}@bu.edu

A. Mirvakili, V. Koomson
AICS Lab, ECE Department
Tufts University
Medford, MA
{ali.mirvakili, vkoomson}@tufts.edu}

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Abstract—Visible light communications (VLC) technology has a potential to complement the RF wireless technology for indoor coverage. It promises concurrent illumination control and wireless data transmission capabilities. The potential of advanced multi-carrier modulation techniques, *i.e.* orthogonal frequency-division multiplexing (OFDM), introduces new challenges in the development of driver circuits. The reverse polarity optical OFDM (RPO-OFDM) is a recent approach to realize compatibility between the analog OFDM signal and the industry well-known pulse-width modulation (PWM) for dimming control. In this paper, we present the implementation of a wireless access test-bed through visible light and dimming compatible RPO-OFDM. A driver topology capable of driving a string of light-emitting diodes (LEDs) using a RPO-OFDM signal is proposed. The driver alleviates the nonlinearity of LEDs by proper biasing and maintaining a quasi-linear range of operation, *i.e.* minimizes the OFDM signal clipping. Using a software defined radio (SDR) platform for online modulation and demodulation, and limit for a range of un-coded quadrature amplitude modulation (QAM) constellations, the experimentally obtained measurements demonstrate linear wide-range dimming while independently maintaining a bit-error performance below the forward error correction (FEC). Error free bit-error rate (BER) performance without symbol level equalization is obtained for binary phase shift keying (BPSK) and 4-QAM.

Keywords: VLC, ACO-OFDM, Dimming, RPO-OFDM

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1. Introduction

The light-emitting diode (LED) is considered a dominant light source for future indoor as well as outdoor illumination based on the solid-state lighting (SSL) technology. Compared to conventional light bulbs, *e.g.* incandescent and fluorescent, the fast response-time of LED-based luminaires is a main reason behind the considerable interest in modulating LEDs to realize a wireless communication infrastructure using luminaires, *i.e.* based on the visible light communications (VLC) technology. For example, and from ecological and security perspectives, VLC has a number of unique advantages relative to wireless RF technologies making VLC a promising candidate to complement the conventional RF counterpart [1]. In simple and cost-effective VLC systems, the communication signal is simply modulated onto the instantaneous power of the optical carrier (no frequency or phase information) and the optical detector (a photodiode (PD)) generates a current proportional to the received instantaneous power, *i.e.* intensity modulation with direct detection (IM/DD) [2].

Orthogonal frequency-division multiplexing (OFDM) is a promising multi-carrier modulation technique for VLC systems due to, for example, its high spectral efficiency and resistance to inter-symbol interference (ISI). In OFDM-based VLC systems, and assuming a limited LED bandwidth and high-quality signal from illumination requirement, high data rates are supported through parallel transmission of high-order multilevel quadrature amplitude modulation (*M*-QAM) symbols on orthogonal sub-carriers. However, the complex-valued OFDM signal used in RF is not suitable for IM/DD as the LED driving signal must be real and positive. Therefore, real-valued OFDM optical formats suitable for IM/DD are proposed. In the optical domain, the conventional bipolar DC biased optical OFDM (DCO-OFDM) offers full spectral efficiency and low power efficiency due the DC component [3]. Half spectral efficiency and higher power efficiency are achieved using the unipolar asymmetrically clipped optical OFDM (ACO-OFDM) [4] and pulse-amplitude-modulated discrete multi-tone (PAM-DMT) [5]. However, polar OFDM (P-OFDM), spectral and energy efficient OFDM (SEE-OFDM) and hybrid ACO-OFDM (HACO-OFDM) offer full spectral efficiency as well as high power efficiency, *i.e.* same as DCO-OFDM without the need of DC-biasing [6-8].

In addition to a high spectral and power efficient optical OFDM formats, a major design challenge that limits the commercialization of VLC is incorporating dimming techniques widely adopted in the lighting industry while maintaining a broadband and reliable VLC links. Specifically, the challenge is the development of hybrid modulation techniques incorporating the pulse-width modulation (PWM) for dimming control and the OFDM signal for data communication. The recently proposed reverse polarity optical OFDM (RPO-OFDM) utilizes the entire PWM cycle for data transmission (data communication is taking place during the on-time as well as during the off-time of the PWM signal) [9]. Moreover, the full LED dynamic range of operation is utilized to minimize the nonlinear distortion (clipping) of the OFDM signal.

In this paper, we realized a wireless access test-bed through visible light and dimming compatible RPO-OFDM. In this real-time test-bed, the hardware components include a printed-circuit board (PCB) luminaire and a software defined radio (SDR) platform based on the Universal Software Radio Peripheral (USRP) module. A single USRP is used as a VLC transceiver. The RPO-OFDM signal is generated in Matlab and Simulink is used to interface with the USRP. The output of the USRP is applied to the PCB luminaire and the output after the optical detector is applied to the input of the USRP. The PCB luminaire provides the 50ohm input matching, amplifies the incoming RPO-OFDM signal and adds a DC level to insure quasi-linear range of operation. Targeting 10^{-3} bit-error ratio (BER), and for a range of quadrature amplitude modulation (QAM) modulation orders up to 16-QAM, a linear dimming range from 90% down to 30% is experimentally demonstrated.

The paper is organized as follows. The dimming and modulation used in VLC and specifically the RPO-OFDM are reviewed in Section II. In Section III, the design of the PCB based luminaire is introduced. In section IV the test-bed is highlighted and the obtained experimental results are shown and discussed. Finally, Section V concludes the paper.

2. Dimming and Modulation in VLC

A. *Optical Communication Constraints*

Optical communications such as VLC implement IM/DD [10]. Letting x(t) represent instantaneous optical power, or intensity of an illumination quality LED source, the constraint $x(t) \geqslant 0$ holds for all t. The illumination source also has a constraint $x(t) \leqslant P_{max}$, where P_{max} represents the maximum optical power output of the LED or luminaire. In addition, the optical conversion function is typically nonlinear near the minimum and maximum optical power levels. These constraints imply that conventional bipolar modulation schemes must be biased and conditioned in order to mitigate clipping and distortion. In the case of dual-use VLC systems, the constraint $E[x(t)] \sim P_{ave}$ must also be satisfied in order to meet requirements of the lighting system.

VLC modulation is also constrained by the resolution of the transmitter. Many commercial LED drivers are designed with 2-level outputs and dimming is controlled via PWM where the duty cycle of the pulse is varied. While discrete level modulation schemes such as On-Off keying (OOK) or pulse position modulation (PPM) are viable with two output levels, more complex modulation schemes require higher resolution. This driver resolution, or the resolution of the digital-to-analog converter (DAC) in cases where the optical converter is driven by an analog signal, constrains the potential levels of the modulated signal.

The frequency response of the VLC transmitter is often the limiting factor when considering the rate of a VLC link. The typical response time of the optical conversion (*e.g.*, LED emission or phosphorescence) leads to a 3dB frequency response in the range of 5-20MHz, hence VLC is conventionally constrained to real-valued baseband signals. Data rates of pulse-based schemes are limited by this frequency response since distortion occurs for symbols that span a wide frequency range; however OFDM techniques benefit from separation in the frequency domain and have been shown to transmit signal components beyond the 3dB bandwidth using techniques such as bit loading where higher frequency components utilize lower order modulation schemes [11].

B. *Modulation Schemes*

Various modulation schemes have been proposed for use in VLC. Pulse-based schemes such as pulse amplitude modulation (PAM) and PPM offer relatively simplistic processing techniques for encoding / decoding. Modifications to these schemes have also been proposed in order to incorporate dimming capabilities. Varying the DC bias of a PAM or PPM signal will alter the average optical output power; however the dynamic range must be conditioned to minimize clipping. Dynamic range affects the received signal and, accordingly, the signal-to-noise ratio (SNR) performance of the link. Variable PPM (VPPM) sets the duty cycle of a PPM pulse in order to meet average optical power requirements and has been proposed in the IEEE 802.15.7 standard [12]; however varying the pulse width also changes the Euclidean distance between symbols and, accordingly, link performance.

The multi-carrier OFDM technique offer a distinct advantage over pulsed schemes in regards to the use of individual frequency bins. This mitigates signal distortion from the nonlinear frequency response by utilizing many subcarriers such that the modulated signal on each subcarrier has a relatively linear response. This allows the OFDM signal to utilize frequency components beyond the 3dB bandwidth without severe distortion of the signal components from any individual subcarrier. In optical communications, techniques such as DCO-OFDM and ACO-OFDM [3,4] have been developed to satisfy many of the optical communications constraints; however additional modifications are required to dynamically adapt to average optical power constraints. RPO-OFDM is a proposed technique that combines ACO-OFDM with PWM in order to satisfy both the channel and illumination constraints of a dual-use VLC link.

C. *Reverse Polarity Optical OFDM*

RPO-OFDM is proposed to combine the fast optical OFDM communication signal with the relatively slow PWM dimming signal, where both signals contribute to the effective LED brightness. The building blocks and the method of deriving this RPO-OFDM are explained in details in [9]. The basic idea is superimposing the OFDM signal on top of the PWM dimming signal. For example, and assuming an ACO-OFDM signal and a known dimming set point, convenital ACO-OFDM symbols are superimposed during the off-time of the PWM signal and flipped (reverse polarity) ACO-OFDM symbols are added during the on-time of the PWM signal.

RPO-OFDM can be applied to any optical OFDM signal including the bipolar DCO-OFDM. The same modulation-demodulation sequence is valid for a DCO-OFDM signal. However, and compared to ACO-OFDM symbols, two consecutive PWM periods are required to transmit the DCO-OFDM symbols, *i.e.* in order to include the positive as well as the negative time-domain samples of the DCO-OFDM symbols. While maintaining positive synchronization signals suitable for IM/DD, conventional fine and course synchronization techniques used in RF can be adapted and applied for frame/symbol synchronization. Figure 1 shows the RPO-OFDM for two different dimming ratios of 70% and 20% duty-cycles of the PWM period.

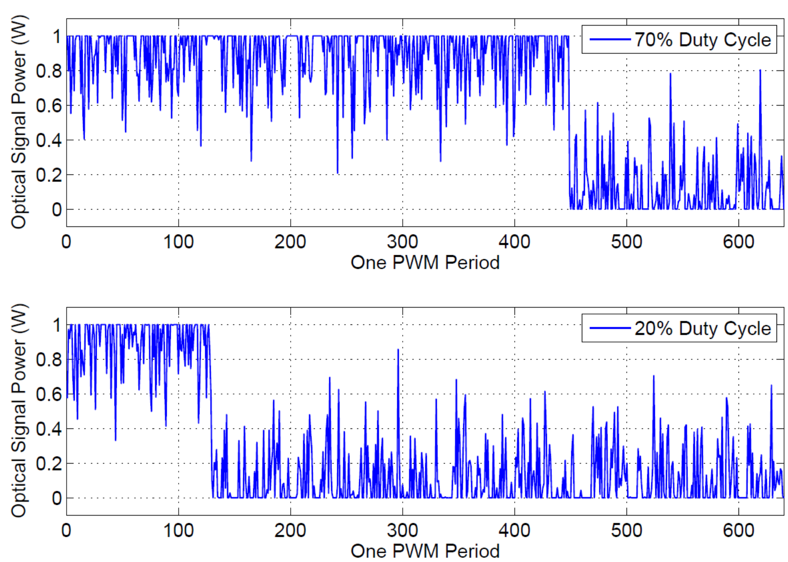

Fig. 1. Optical RPO-OFDM signal waveform based on ACO-OFDM at 70% (upper) and 20% (lower) duty-cycles

3. PCB based luminaire

The emergence of modern illumination applications for LEDs and the complex modulation techniques used for data transmission in the VLC systems, introduces new challenges in the development of driver circuits. The digital modulation schemes such as OOK are compatible with standard PWM diming technique, and the data-dimming combination can be implemented in the circuit level design [13, 14]. Similar design can be applied to the analog modulation schemes as well. As mentioned earlier, the combination of data signal with the PWM dimming signal, *i.e.* RPO-OFDM, is done in the Matlab and the output is transferred into the USRP platform using

Simulink. USRP is the peripheral device that generates an electrical signal from the digital signal produced in Matlab. For the implementation and proof-of-concept of RPO-OFDM, a linear LED driver for concurrent data transmission and dimming control is presented in this section. The schematic of this proposed LED driver and the PCB luminaire are depicted in Fig. 2 and Fig. 3, respectively. Most of the commercially available LEDs, which are considered as the load of driver, have a nonlinear I-V curve for all given input voltages; this makes it hard for the driver to achieve a linear response. The linear portion of the curve is defined from the turn-on voltage to the start of its saturation region where the ramp of the I-V curve is constant. This driver makes it possible to provide the appropriate voltages across the quasi-linear range of LEDs such that the output light intensity which is proportional to the LED current, varies linearly with the input voltage.

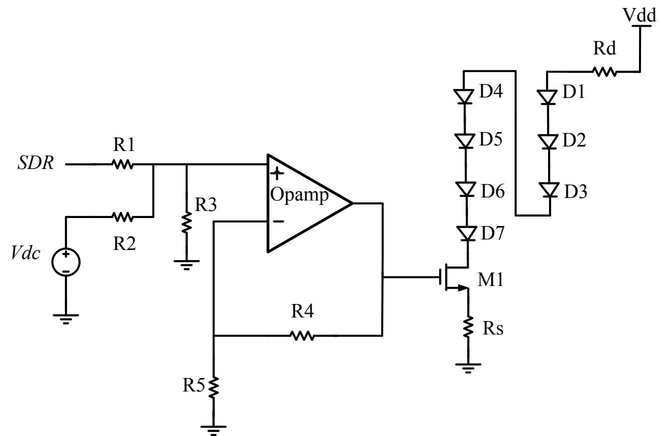

Fig. 2. The schematic diagram of proposed LED driver

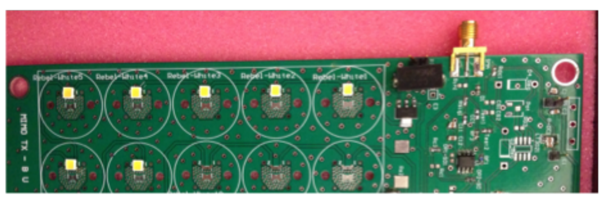

Fig. 3. The PCB luminaire

The electrical signal generated by the USRP will be the input of this LED driver. According to the Fig. 2, this signal will be shaped by the network of R1, R2 and R3 resistors and then will be amplified by the gain of $(1 + R4/R5)$. Voltage gain from input to the output of Op-amp is given by (1):

$$\frac{(R2||R3)}{R1+ R2||R3}\left(1+\frac{R4}{R5}\right) \tag{1}$$

The DC voltage Vdc will be shaped by the network of R1, R2 and R3 as well and after amplification its value will be superimposed by that of signal coming from USRP. The voltage gain for this DC voltage is given in (2).

$$\frac{(R1||R3)}{R2+ R1||R3}\left(1+\frac{R4}{R5}\right) \tag{2}$$

To keep operation in the linear region, the minimum level of signal at the output of Op-amp should be higher than the threshold voltage of MOSFET M1. Also for the 50ohm input matching, the values of this resistive network at the input of driver should be set as to have the equivalent input impedance of 50ohms. The input impedance is given by (3).

$$(R1 + R2||R3) \tag{3}$$

By optimization of these three equations, the design parameters are derived.

The resistor Rd is placed in series with LEDs as to limit the current through LEDs. The resistor network as well as the gain stage can be considered a linear circuit as long as the frequency of interest lies under the 3dB bandwidth of the system. It is worth mentioning that the degenerated common source configuration composed of M1 and Rs not only converts the voltage at the gate of M1 into the current signal, but also helps to extend the linearity of the circuit. Placing Rs in series with the MOSFET changes the equivalent trans-conductance of the circuit from g_m to G_m where g_m is the trans-conductance of M1 and G_m is defined as (4).

$$G_m = \frac{1}{Rs+1/g_m} \tag{4}$$

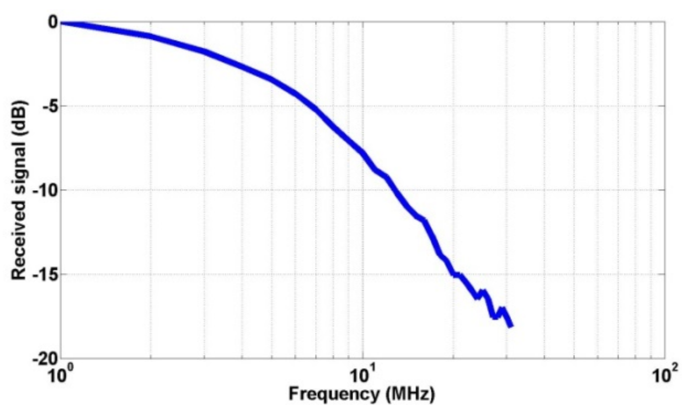

Fig. 4. The frequency response of LED driver

Based on this equation, the equivalent trans-conductance is no longer changing directly by g_m, which is process, temperature and DC current dependent. The equivalent or effective trans-conductance in this case is controlled by the value of Rs especially for the large values of g_m, and it helps to increase the linearity. To increase the linear range of operation, the LEDs are biased properly by setting the DC voltage of Vdc shown in Fig. 2. The frequency response of this driver is shown in Fig. 4. In obtaining this frequency response, a photodetector (PDA10A) is used. Based on this frequency response, the 3dB bandwidth of this circuit is 5MHz which is well beyond the bandwidth needed for transmission of the electrical signal that is sampled at 400KSps and used as the input to the PCB luminaire in this implementation. As depicted in Fig. 2, seven series of Cree XLamp ML-B LEDs are used which are operated under the DC supply (Vdd) of 25V. The MOSFET used in this implementation, M1, is BSP110, and the Op-amp is AD8009. The intensity of light over the wide dimming range varies linearly which is explained more in detail in the next section.

4. Measurement Results

The software defined radio (SDR) concept is a broadly adopted technique where the signal processing, *i.e.* the complete modulation and demodulation chains, is moved from the analog domain to the digital domain in order to provide implementation flexibility [15]. The block diagram of the proof-of-concept test-bed for dynamic adaptation of lighting conditions (to fulfil illumination requirements) is shown in Fig. 5. Matlab is used to build the RPO-OFDM system model, while Simulink is used to interface with the USRP from Ettus Research. We generate a random series of data and the corresponding digital RPO-OFDM samples in Matlab. We use the USRP Hardware Driver (UHD) interface within Simulink (this requires the USRP support package for the communications system toolbox) to repeatedly transmit the digital signals to the USRP. In this implementation, and within the USRP, we utilize the low frequency transmitter (LFTX) daughter card to generate the baseband electrical signal at 400KSps that acts as the input to our PCB luminaire introduced in Section III. The USRP is equipped with the LFRX daughter board also operating at 400KSps. In this setup, 8 ACO-OFDM symbols per PWM period, 64 subcarriers per symbol and 17dBm average electrical power per ACO-OFDM symbol are considered. A sinusoidal wave at the beginning of every PWM period is transmitted and used to realize a coarse Tx-Rx synchronization, *i.e.* the receiver searches for this sinusoidal wave (correlation process) to determine the start of a PWM period (see Fig. 7).

At the receiver, we utilize the off-the-shelf transimpedance amplifying photodetector PDA10A from Thorlabs with a concentrating lens (no blue filtering). The received electrical signal is input to the low frequency LFRX daughter card receiver of the USRP. The received digital signals are processed in real-time using Matlab/Simulink in order to calculate the BER performance. For measurements, the optical detector and a Lux meter are located directly on top of the PCB luminaire. A LodeStar Lux meter is used to evaluate the linear change brightness at different dimming levels. Figure 6 shows the measurement setup, where 8-QAM modulation with a 50% duty cycle is used and displayed on the oscilloscope display. A single USRP is used as a VLC transceiver.

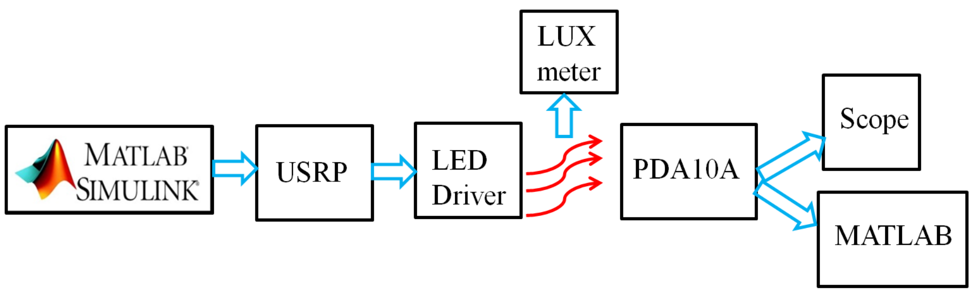

Fig. 5. Block diagram of the testbed

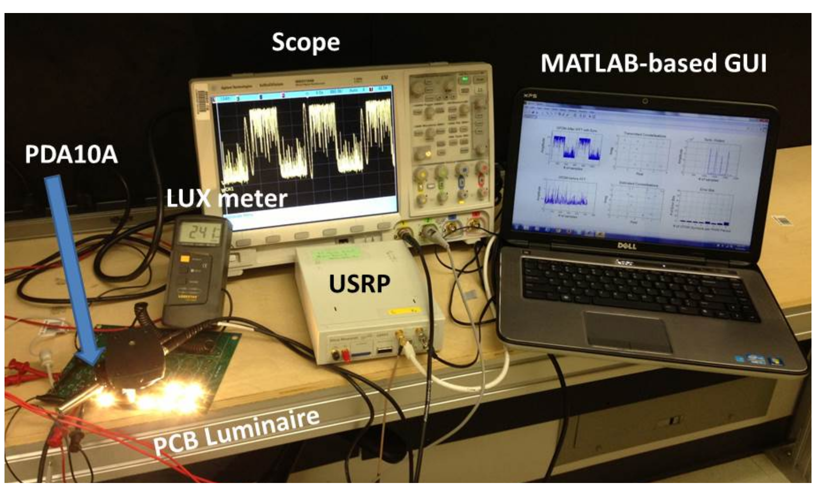

Fig. 6. The measurement setup

We realized a real-time implementation, where the Matlab-based graphical user interface (GUI) shows, for example, the number of bits in error per OFDM symbol and the estimated complex constellations (see Fig. 7). Figure 8 shows the linear change of dimming for modulation schemes of BPSK, 4-QAM, 8-QAM and 16-QAM. Also for several modulation schemes BPSK, 4-QAM, 8-QAM and 16-QAM the measured BER curves as a function of the PWM duty cycle are shown on Fig. 9. It is experimentally confirmed that at a fixed average of power of a RPO-OFDM symbol (17dBm), the obtained BER is maintained independent on the dimming level within the supported dimming range. Error free BER is obtained for BPSK and 4-QAM. The supported dimming range covers as low as 30%. It is also noticed that at around 50%, the QAM modulation order has no effect on the dimming level. The reported BER in the order of 10^{-3} is obtained without channel estimation and symbol equalization, *i.e.* no pilot symbols are transmitted to estimate the channel for frequency-domain equalization (raw estimated bits without symbol equalizations are used to calculate the BER). In addition, error free BER performance using BPSK and 4-QAM is obtained.

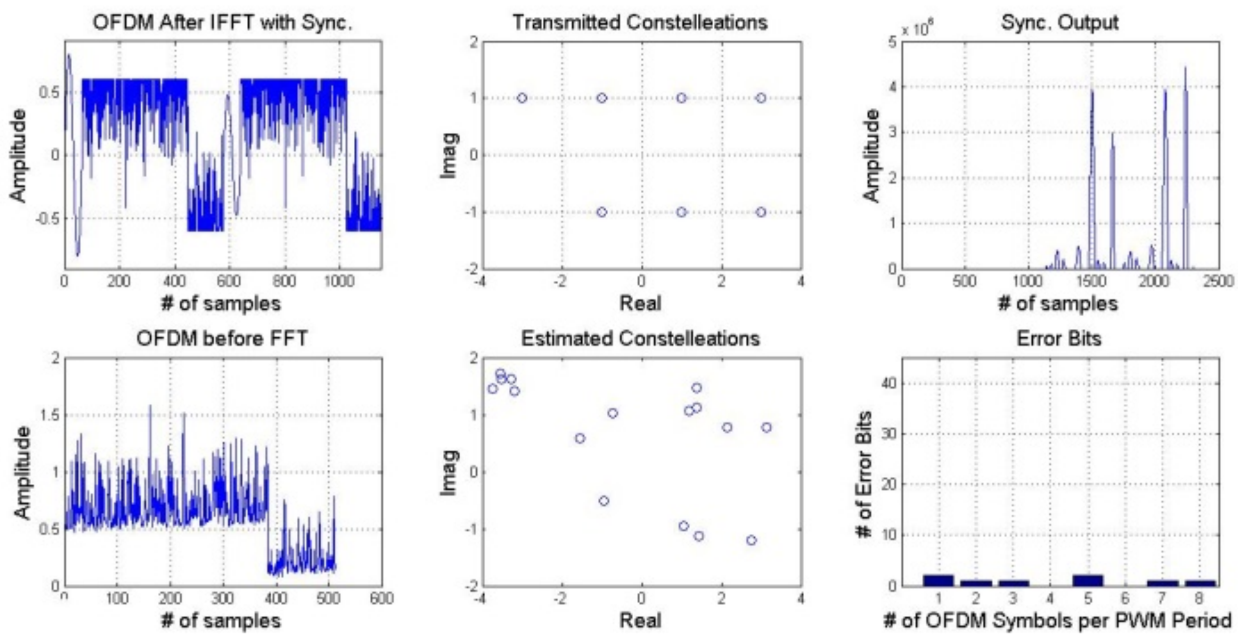

Fig. 7.The MATLAB GUI showing the generated RPO-OFDM signal (using 8-QAM) (upper left), the ideal QAM constellations (upper middle), the peaks of the correlation process to realize frame synchronization (upper right), the received RPO-OFDM after extracting the RPO-OFDM from the PWM signal (lower left), the estimated constellations (lower middle) and the number of bits in error per OFDM symbol where 8 symbols are used within a PWM period (lower right)

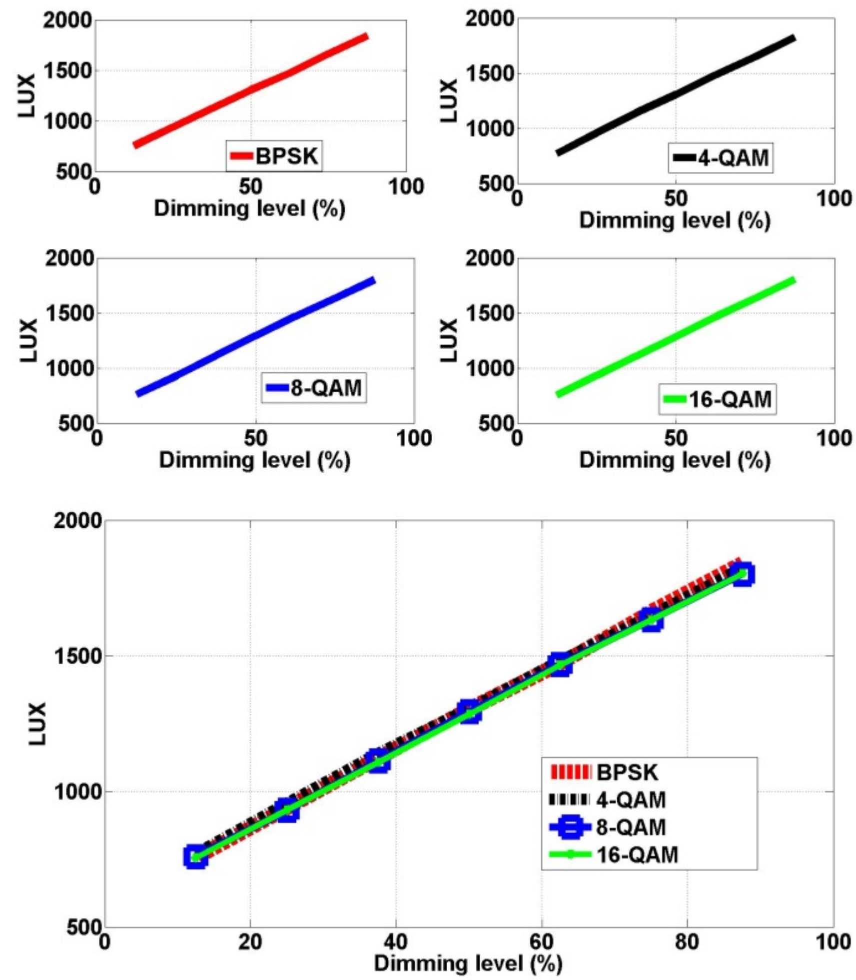

Fig. 8. Linear change of dimming for different modulation schemes

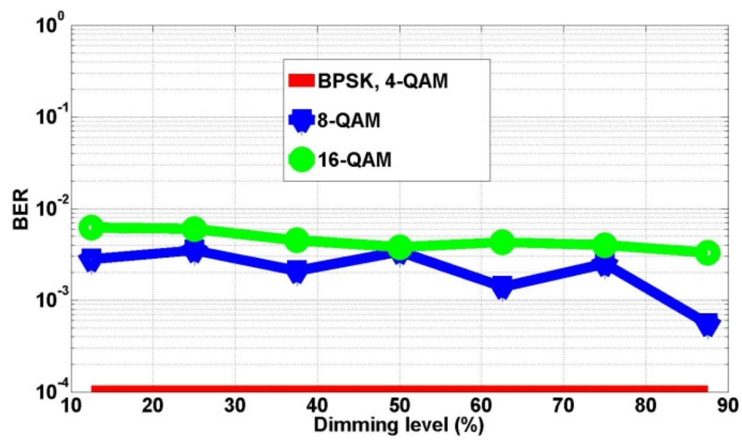

Fig. 9. BER vs dimming level for different modulation schems. Error free BER is obtained for BPSK and 4-QAM.

5. Conclusion

The developed PCB luminaire is successfully used in a real-time test-bed to demonstrate VLC transmission using RPO-OFDM to achieve dimming compatibility with the industry-standard PWM signal. Error free BER performance using un-coded BPSK and 4-QAM and without symbol equalization is obtained. Using the same setup parameters, A BER performance in the order of 10^{-3} is achieved for 8-QAM, and 16-QAM modulations over a wide-range of dimming levels. A linear control of the brightness is confirmed while maintaining the target data rate.

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