Optimization of an OFDM-Modulated Visible Light Communication Link based on Experimental Approach

David Esteban Farfán-Guillén, Paulo de Tarso Neves Junior and Alexandre de Almeida Prado Pohl

***Abstract*— Visible Light Communication (VLC) allows the use of the existing lighting infrastructure to transmit data, however, the limited bandwidth of commercial LEDs prevents high data rate systems from being achieved. In this work, an experimental procedure was employed to improve the data transmission rate of an OFDM-modulated link. The results show that by optimizing the system parameters, a bandwidth greater than the LED 3-dB bandwidth can be utilized, while maintaining the illumination at a minimum of 300 lux. Based on the optimized configuration, a data rate of 96 Mbps using a 16-QAM constellation was achieved for a BER $\leq 10^{-3}$ at a distance of 2m.**

***Keywords*— LED, Optical OFDM, Visible Light Communication, Photodetector**

I. Introduction

Visible Light Communication (VLC) is a technology that transmits data at high speeds through pulses of light [1-2]. In indoor environments (rooms or offices), white LEDs are used to implement the VLC link while illuminating the environment with the required levels (300-700 lx) [3-4]. However, commercial LEDs used for illumination typically exhibit low bandwidth, limiting the data rates [5]. This limitation can be overcome to a certain degree by the use of high spectral efficiency techniques, such as the orthogonal frequency division multiplexing (OFDM) [6]. This technique has been increasingly employed in VLC due to reduced inter-symbol interference (ISI) and improved performance when compared to other modulation types, such as on-off keying (OOK) and pulse position modulation (PPM) [7]. For instance, in [8] the physical layer of an OFDM-based VLC system is implemented and a hardware prototype for transmission using a white LED lamp is developed. In [9], a communication rate of 3 Gb/s is achieved for a VLC system that implements a 50 μm gallium nitride LED and is capable of using a modulation bandwidth of at least 60 MHz. In [10], the peak-to-average power ratio (PAPR) affecting the OFDM modulation is minimized using the spatial summation concept, where the broadband signal is divided into several narrow-band signals with low PAPR and transmitted by different LEDs.

However, in most articles the relationship between the illuminance level and the data rate for optimized operation is not approached. In this way, the main contribution of this work is to maximize the use of the commercial LED bandwidth to obtain the best bit transmission rate with an OFDM modulation while maintaining the illumination within the recommended light levels. This work focuses on the experimental part since several works focus on simulations; however, experimental studies have not been addressed with the same urgency. Based on the optimization, a VLC transmission link has been achieved with a rate of 96 Mbps with a lighting level of 300 lux and for a line of sight distance of 2 m between the transmitter and the receiver. BER $\leq 10^{-3}$ has been maintained and 16 QAM modulation has been used.

The article is structured as follows. Section II provides a theoretical description about lighting and OFDM modulation and its variant is implemented for this DCO-OFDM project. Section III describes the experimental configuration and section IV shows the different experiments carried out to optimize the system. Section V shows the results of the experimental optimization. Finally, section VI details the conclusions of this work.

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II. Lighting and optical communication

A. Lighting in VLC

In VLC, the transmitter is made up of a current driver and an LED light source [11]. Light sources have some properties, such as luminous flux, which is measured in lumen (lm) and represents the amount of brightness that the source delivers; and illuminance, expressed in lux (lx), which represents the luminous flux or light density incident on a surface [12].

Since LED lighting follows a Lambertian radiation pattern [13], the existing illuminance at a point on the receiver surface is expressed as a function of the luminous flux through [14-15]:

$$E_h = \frac{(m+1)\cos^m(\phi) cos(\psi)}{2\pi r^2}\Phi_{lum} \quad [lx], \tag{1}$$

where ϕ is the irradiation angle with respect to the normal axis of the transmitting surface, ψ is the incidence angle with respect to the normal axis of the receiving surface, r is the distance between the LED luminaire and the illuminated surface, m represents the directivity of the source beam with the half-power angle, and Φ_{lum} represents the luminous flux.

For indoor spaces, there are different standards that regulate lighting recommendations, including the European Standard [16], which recommends an illuminance varying from 300 to 700 lux for offices.

In this work, a single white LED from the Golden Dragon LW W5SM [17] was used, with a mean power angle of 55 degrees. As the luminous flux of a single LED is limited to a small area, in order to illuminate larger surfaces, a greater number of LEDs arranged in a luminaire is required.

B. Communication in VLC

The DC-OFDM modulation was implemented in Matlab for the communication system. Figure 1 shows the OFDM modulation scheme. The input data block, consisting of bits (0, 1), is defined first. To estimate the channel at the receiver, pilot bits with a defined position are added. This allows for data recovery through equalization at the reception. The data bits are then mapped using an M-QAM constellation. In this work, we used a 4-QAM, 16-QAM, 64-QAM constellation. Since the communication is optical, the values must be real, positive, and unipolar. Therefore, the Hermitian symmetry property is applied to convert the complex values of an OFDM signal into real values. This results in the loss of half of the OFDM subcarriers, but a real signal is obtained. The QAM modulator generates complex symbols of the form (±a ±*j*b). The Inverse Fast Fourier Transform (IFFT) block passes the signal from the frequency domain to the time domain and allows real bipolar values to be obtained. To convert the values into a unipolar signal, the DCO-OFDM variant is applied. In the DCO-OFDM technique, an appropriate DC polarization is added to the signal, which clips any signals with negative peaks to zero, leaving only positive and real values. A cyclic prefix (CP) is then added, which generates a guard interval in which a portion of the end of the signal is copied and placed at the beginning of the signal to minimize ISI. The generated data is transformed from a parallel to serial (P/S) sequence. The signal is then intensity modulated by the luminaire.

The inverse process is used to recover the data on the receiver. The Fast Fourier transform (FFT) is used to return the values to the frequency domain. The receiver directly captures the signal through the photodetector. To evaluate the BER of an OFDM signal, the following equation is used [18]:

$$BER_{OFDM} = \frac{4}{\log_2 M} \cdot (1 - \frac{1}{\sqrt{M}}) \cdot Q(\sqrt{\frac{3\log_2 M}{M-1} SNR}). \qquad (2)$$

where Q(.) is the Q-function.

Since conventional OFDM signals, such as DCO-OFDM, have a very high peak-to-average power ratio (PAPR) [10], they are sensitive to nonlinear distortions of the LEDs. To compensate for the nonlinearity problem, the LED is operated in a current range where it exhibits sufficiently linear behavior. Laboratory experiments are performed to establish such limit.

III. Experimental Setup

In Figure 2, the setup is presented. On the transmitter (Tx) side, a Mini Circuits ZFBT-6GW-FT+ bias-tee is used, which couples a DC signal that polarizes the LED with an OFDM data signal previously loaded on an arbitrary waveform generator (AWG). The output of the bias-tee is connected to the LED. On the receiver (Rx) side, a module consisting

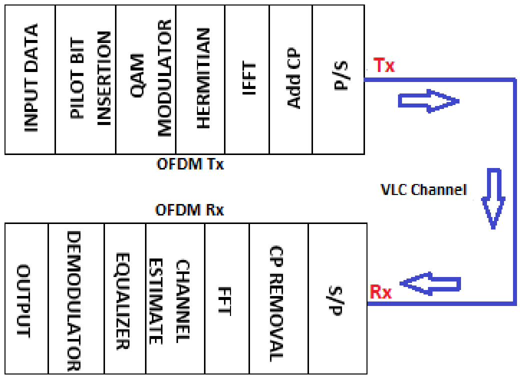

Fig. 1. OFDM Scheme.

of an APD photodetector with an active area of 3.0 mm is used. The white light emitted by the LED is captured by the photodetector, which operates in the range of 350 to 1100 nm and has a maximum responsivity (R) of 15 A/W at 800 nm. Optical lenses were used at the Tx and Rx sides to increase the range of the signal. The received data were acquired on an oscilloscope and processed offline.

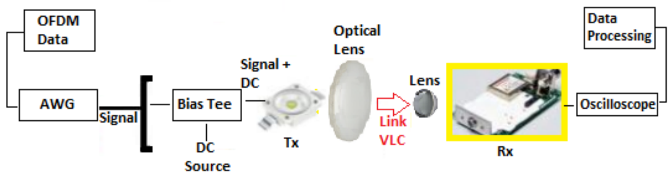

Fig. 2. Experimental VLC Setup.

Figure 3 shows the measurements performed to establish the baseline scenario on which the communication measurements is carried out. The level of illuminance was measured using a luxmeter (Figure 3.a). The distance at which appropriate illumination between the transmitter and the receiver is guaranteed was determined to be 20 cm (300 lx), as described in [19]. Lenses were used on each side to extend the Tx-Rx distance up to 2 m (Figure 3.b) while maintaining constant illumination. The lenses are designed to focus the light at a specific point, which is beneficial for improving the link distance, however it can limit the system's capacity to provide uniform illumination.

The lens on the Tx side is a plano-convex spherical lens with a diameter of 90 mm, and it operates in the range of 400-1100 nm. The lens on the Rx side is a plano-convex spherical N-BK7 lens with a diameter of 12.7 mm, also operating in the range of 400-1100 nm for focal distances between 15 mm and 2500 mm.

IV. Measured Parameters for Optimization of VLC Link

The main components in VLC are the LED (Tx) and the photodetector (Rx). In this section, the characteristics of the LW W5SM LED are measured in terms of non-linear behaviour, frequency response and of the photodetector module

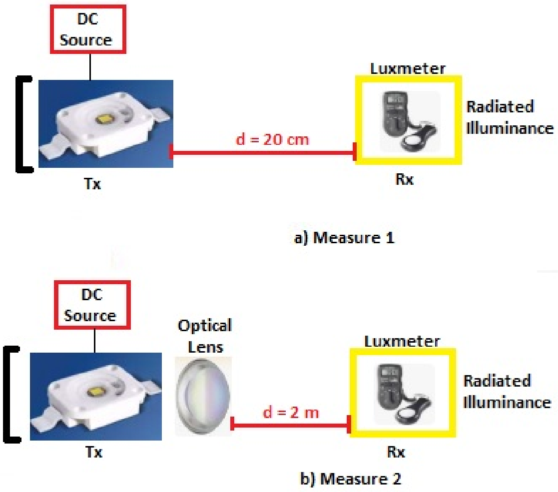

Fig. 3. Baseline Scenario. a) Tx-Rx distance is determined while maintaining the illumination above 300 lux. b. Lenses are placed in Tx and Rx to increase the distance while maintaining illumination above 300 lux.

in terms of optical power. The LED has a relative spectral emission of 400 - 780 nm with a peak at 560 nm, which corresponds to yellow light. As detailed in the previous point, the distance between Tx-Rx is 2 m for an indoor environment in line of sight.

A. *LED Non-linearity*

Non-linearity refers to distortion in the LED's response to the applied electrical signal, which can result in distortion of the data signal transmitted by the light. Modulation techniques can be used to reduce non-linearity in the LED. In addition, reception distortion correction techniques, such as equalization, can be used to improve the quality of the received signal [13]. Another way of approaching the problem of non-linearity in LEDs used in VLC is by determining a linear zone in their performance, for which experiments are carried out in the laboratory. LEDs require direct current bias to emit light. Generally, manufacturers usually indicate the appropriate operating values in their data sheets [17]. For the LW W5SM LED, the typical value is 350 mA. Figure 4 shows the relationship between the illuminance radiated by the LED, the received optical power and the polarization current applied to the LW W5SM LED. It is observed that as the polarization current increases, the illumination emitted by the LED and the optical power received by the photodetector also increase in a non-linear way, which leads to distortions in the signal amplitude [20].

To reduce the effect of non-linearity, the LED is made to operate in a dynamic range where it exhibits a linear behavior. To determine the best point of operation, a Tx-Rx transmission was performed configuring an OFDM signal with an IFFT size of 256 and 88 data subcarriers. The signal was configured with different amplitudes and the LED was polarized with different DC currents. Figure 5 shows the BER of the OFDM signal for different combinations of amplitude and polarization. The best operation point occurs for a signal with an amplitude of 200 mV and a polarization current of 120 mA. At this current

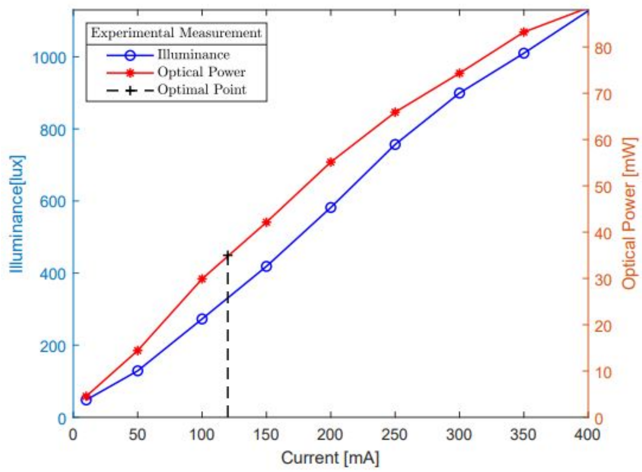

Fig. 4. Optical power and illumination measurements against the polarization current.

the illuminance is within the range of adequate illumination, as seen in the curves of Figure 4.

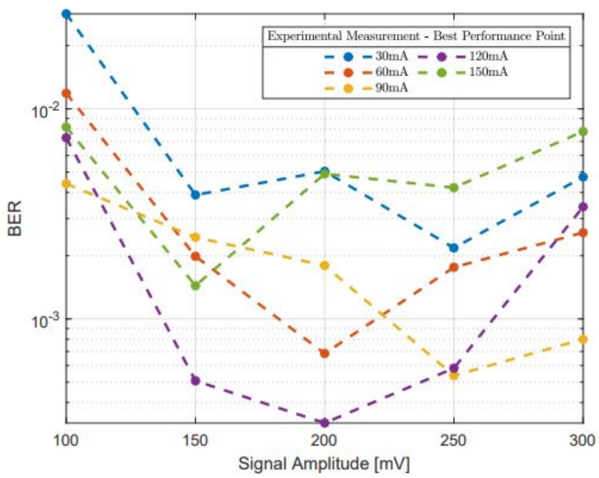

Fig. 5. Determination of the operation point based on the BER performance while varying the amplitude of the signal and the polarization current.

B. *LED Frequency response*

The LED frequency response indicates the possible bandwidth that can be used to transmit the data signal. Figure 6 shows the LED response in dB for different frequencies (up to 50 MHz) and polarization currents with measurements done using a network analyzer. In this work, we employed the 120 mA value, according to the previous results, as a reference. For this particular current, the LED frequency response curve lies between the red and yellow curves. This result helps us visualize that at frequencies higher than the -3dB cutoff frequency, the LED can still be used for transmission, as verified in the following Figures.

V. Results of the Experimental Optimization.

In this section, the influence of bandwidth and the number of subcarriers and the system transmission rate for a BER $\leq$

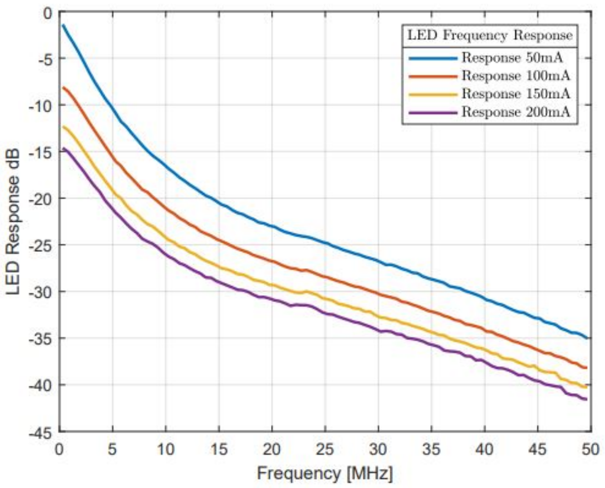

Fig. 6. LED Frequency response at different currents.

10^{-3} is analyzed. The OFDM code is generated in Matlab and loaded into the AWG. The signal is configured with the parameters listed in Table I.

TABELA I
PARAMETERS OF THE OFDM SIGNAL

Parameters	Values
Carriers	256
Data Carriers	100:128
Cyclic prefix	16
Number of pilot carriers	8
Number of symbols	592
Modulation	[4 16 64]-QAM
Interactions	20

A. *Optimization of the number of subcarriers*

First, we estimate the optimal number of subcarriers that provides a BER $\leq 10^{-3}$. We configure different OFDM signals with different numbers of subcarriers, noting that only half of the generated subcarriers are loaded with data due to the use of Hermitian symmetry, taking 256 subcarriers as the upper limit. As seen in Figure 7, by using 123 subcarriers carrying data, we can guarantee a BER $\leq 10^{-3}$. Therefore, N=123 subcarriers is considered as the optimal value of the OFDM code in this experiment.

B. *Optimization of modulated bandwidth*

As the next step, the bandwidth of the OFDM signal was varied. Figure 8 shows that a BER $\leq 10^{-3}$ can be kept up to a bandwidth of 50 MHz. Based on the results shown in Figure 6, it is observed that the useful bandwidth is larger than the -3dB bandwidth in agreement with results described in [20].

C. *Optimization of the transmission rate*

Finally, to determine the maximum data rate, the OFDM signal was configured with different bandwidths and with different QAM constellations. Figure 9 shows that for a 16-QAM signal with a 50 MHz bandwidth, a rate of 96.09 Mbps

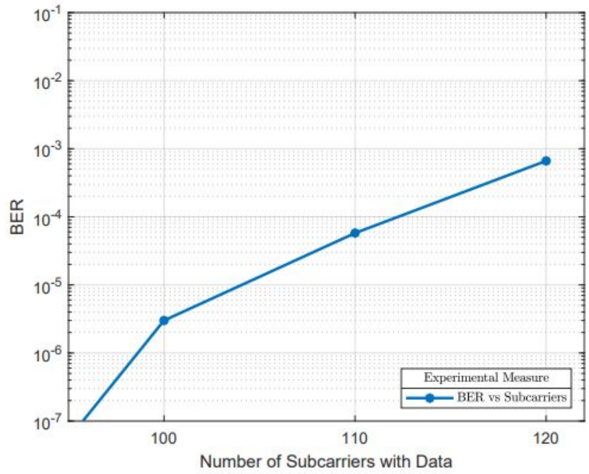

Fig. 7. BER versus the number of OFDM subcarriers

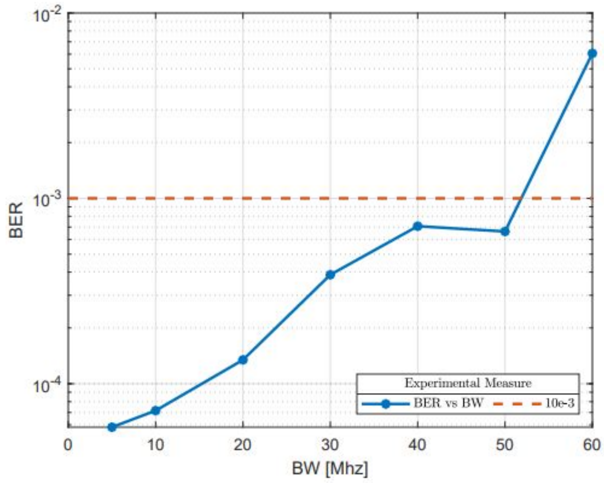

Fig. 8. BER versus the bandwidth of the OFDM signal.

is obtained. This is the maximum rate that can be obtained with the configured parameters. In the same figure it can be seen that for a bandwidth greater than 50 MHz, the data rate begins to decrease, which is in accordance with Figure 8, where for a bandwidth greater than 50 MHz, the BER has a value greater than 10^{-3}

Figure 10 shows the 4, 16 and 64 QAM constellations obtained for the case with the highest data rate seen in the previous Figure .

VI. CONCLUSION

In this work, the optimization of a VLC link with a LW W5SM LED using OFDM modulation for indoor applications was performed. The dual functionality of lighting and communication was achieved by maintaining the illumination at 300 lux while providing communication. By configuring different signal parameters, an approximate bandwidth of 50 MHz was determined to maximize the performance. The optimized parameters allowed a transmission rate of 96 Mbps to be obtained for a 16-QAM mapping at a BER $\leq 10^{-3}$. In order to increase the distance between the transmitter

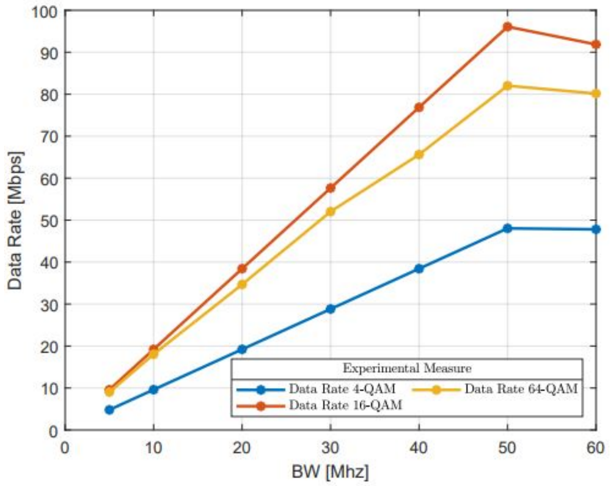

Fig. 9. Data Rate versus the OFDM signal bandwidth for 4, 16 and 64 QAM constellations.

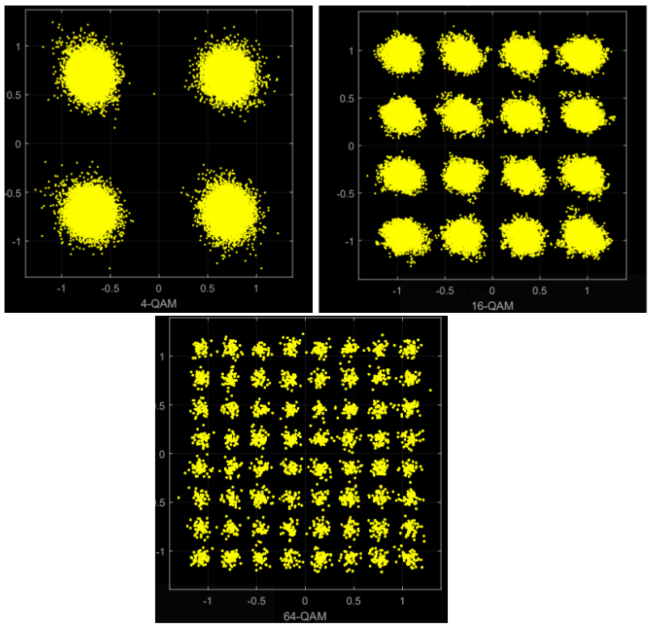

Fig. 10. QAM constellations with maximum data rate: 4-QAM ≈ 48.04 Mbps, 16-QAM ≈ 96.09 Mbps, 64-QAM ≈ 82.03 Mbps.

and receiver, optical lenses were used which allowed the illumination to be maintained at 300 lux at a distance of 2 meters between the transmitter and receiver. Although the illumination at that distance was only concentrated on the receiver, it can be deduced that by increasing the number of LEDs using luminaries, the coverage area can be improved while maintaining the transmission rate.

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