Experimental validation of a three-dimensional modulation format for data transmission in RGB visible light communication systems

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Abstract
Transmission of three-dimensional (3D) orthogonal frequency division multiplexing (OFDM) signals over red, green and blue (RGB) visible light communication (VLC) systems is proposed and experimentally validated. The novel 3D modulation format aims to overcome the different luminous response of RGB light-emitting diodes at the same driving current levels, that generates a correlation among the three RGB analog signals instead of considering each channel as independent from each other, as is in classical uniform wavelength division multiplexing transmissions. In the proposed scheme, real and imaginary parts of OFDM signals are sent through the red and blue channels of the VLC transmitter, respectively, while the third dimension of the OFDM symbol is transmitted through the green channel, according to a procedure that allows the maximisation of the Euclidean distance among the 3D constellation symbols. For the OFDM signal reconstruction and decoding at the receiver side, advanced digital signal processing for frame synchronisation and reconstruction of the 3D constellation diagram are implemented. Experimental results are included to validate the transmission of a 27.3 Mbps system through a VLC link of 1.5 m.

1 INTRODUCTION

Limited availability of spectrum, electromagnetic interference from electrical equipment and vulnerability to attacks are notable drawbacks of wireless radio networks that provide insufficient reliability and performance [1]. In this context, optical wireless communication (OWC) becomes a promising solution by using the unlicensed light spectrum, with light sources, to provide enough modulation bandwidth for Internet-of-things (IoT) and Industry 4.0 applications, as well as for the 5G use cases [2]. Visible light communication (VLC) is a kind of OWC system designed for simultaneous illumination and data transmission, using light sources such as light-emitting diodes (LEDs) in the spectrum range around 400−700 nm [3]. Transmission speeds higher than the current WiFi technology, and the possibility of being used in electromagnetic interference places, like airplanes and hospitals, are some of the advantages offered by VLC that has positioned it as a promising technology for the incoming 5G [4, 5].

Both white-LEDs and arrays of red–green–blue (RGB) LEDs have been adopted in VLC implementations [6]. However, for high data transmission rates, RGB LEDs are preferred over white phosphor-based LEDs, because of the larger bandwidth offered for modulation [7], despite the difficulty involved in the generation of white lights from the RGB colours, as reported in [8]. Moreover, RGB LEDs also permit the design of wavelength division multiplexing (WDM) schemes, as well as the fulfillment of multiple-input multiple-output (MIMO) multi-user applications. It is important to mention that, in such scenario, the RGB bands used as dedicated WDM VLC channels may present different transmission performance, because of the different illuminance efficiency afforded by commercially available RGB LEDs. The coding and modulation schemes play important roles in this context.

The Institute of Electrical and Electronics Engineers suggests the adoption of on–off keying (OOK), variable pulse-position modulation (VPPM) and colour-shift keying (CSK) modulation formats in short-range OWC using VLC [9]. Indeed, OOK and classical pulse width modulation (PWM) have been applied for dimming control in VLC systems using white or RGB LEDs [6]. Nevertheless, to provide spectral efficiency (SE) and to combat intersymbol interference (ISI),
orthogonal frequency division multiplexing (OFDM) have been considered in VLC to explore the granularity of its multicarrier nature [10-12]. Undeniable results of OFDM-based VLC systems have been demonstrated aiming, among others, the channel frequency selectivity overcoming [2, 7]. More recently, robust equalisation schemes and the design of robust receivers have been reported to overcome undesired transmission impacts such as inter-channel interference (ICI) [13, 14]. However, the large fluctuation of OFDM signals that introduces non-linearities should be considered in VLC designs. Constant-envelope OFDM schemes can be employed to deal with this inconvenience, despite the inherent decrease of SE provided by those based on phase modulations [15]. The appropriation of the Hermitian symmetry to generate signals with real coefficients is another disadvantage of these multicarrier formats, that also reduces SE.

The benefits of digital signal processing (DSP) schemes can be explored with the general purpose of SE enhancements [14, 16]. Beyond the signal transformation that creates CE-OFDM signals, the generation of asymmetrically clipped OFDM (ACO-OFDM) signals, as well as the employment of the discrete Hartley transform (DHT) in subcarriers multiplexing are some of the DSP benefits that can play important roles in both performance and SE of VLC systems [17, 18]. Therefore, in this paper, we propose a 3D modulation format that creates a correlation among three analog multicarrier signals used to modulate RGB LEDs, instead of considering each one of them as independent signals as is in uniform WDM transmissions, overcoming the challenge of having different channels in an RGB-based WDM VLC.

The proposed 3D modulation format previously groups the data bits in code-words of six bit-length. The code-words are then divided into two main streams, with the first composed of the two most significant bits, used to generate DHT-based signals that modulates the green LED. The second stream is composed of the OFDM symbols generated from the remaining four less significant bits of the code-words. The imaginary part of the OFDM signal obtained with fast Fourier transform (FFT) is used to modulate the blue LED, whereas the real part of this OFDM signal is transmitted through the channel that employs the red LED. An experimental demonstration of the 3D mapper, composed of four levels and 16-QAM subcarrier mapping is described. Experimental results obtained after the transmission of a 27.3 Mbps (in a bandwidth of 5 MHz) OFDM system through a 1.5 m VLC channel, show the feasibility of the proposed system. We believe that the proposed 3D mapping and non-uniform multiplexing paves the way for new modulation format designs for unbalanced WDM transmissions.

1.1 Related works

VLC is being suggested for various use cases, exciting investigations like those outlined in [19, 20] and [21], among others. A soft integration with other technologies like the hybrid solution described in the study presented in [22] is also pursued, in scenarios where a backbone network is demanded. However, the focus of this work is in RGB-based VLC that assist the spectral efficiency requirement.

The experimental realisation described in [7] is one of the first that utilised commercially available RGB LEDs in WDM transmissions. The three LEDs were individually biased and modulated, aligned to the fact that, at the receiver, each colour was tested separately with a selective band-pass optical filter. The authors successfully achieved Gbit/s connectivity without affecting the general illumination of the indoor environments. The same authors increased the length of their VLC links, as can be seen in the demonstrations provided in [23]. Spectral overlaps that can be generated by the wide optical bandwidth of the filters introduce ICI in such WDM optical systems. The authors of [24] joined an RGB transmitter to a complimentary metal oxide semiconductor (CMOS) image sensor as a receiver to address this issue. The implemented MIMO with CMOS sensors mitigates the ICI, demodulating the three independent colours in the rolling shutter pattern. The CMOS image sensing was also explored by Chow et al. in [25] to improve their work using RGB LEDs. Their experimental results demonstrate non-flickering communication in a VLC link of 100 m.

The aforementioned DSP benefits that clearly enhance the SE of the VLC multi-users access scheme proposed in [26] was also exploited in the RGB LED-based optical camera communications (OCC) demonstrated in [27]. The carrierless amplitude, phase modulation and subcarrier multiplexing combination provided in [26], and the undersampled phase-shift OOK, WDM and MIMO aggregation afforded in [27] assure a spectral efficiency and a space efficiency equal to 5.08 b/s/Hz and 3 b/Hz/LED, respectively. The experimental results presented in [27] demonstrate a successful communication in an OCC link of 60 m, using a single commercially available RGB LED and a standard camera.

Spectral efficiency was also experimentally addressed in [28] through a multiplexing of non-orthogonal subcarriers. The authors achievement was counterbalanced by a serious ICI that demanded complex DSP at the receiver. The high bit rate achieved in [28] was tremendously increased by Bian et al. in [29] using off-the-shelf LEDs. The 15.73 Gb/s was achieved in an OFDM-based VLC system with WDM [RGBY (Y: yellow)] and a hard decision forward error correction (FEC) coding. The authors also provides a design of a low cost circuit board that can be adopted in simple VLC receivers.

1.2 Our contributions

In this paper, we consider WDM transmissions in VLC systems with RGB LEDs modulated by three correlated multicarrier signals. The real and imaginary parts of FFT-based OFDM signals are used to modulate the red and the blue LEDs, respectively, whereas the DHT-based OFDM signals modulate the green LED. The feasibility of a 3D mapper, that represents a symbol mapping that results of a 6 bits partition, is experimentally demonstrated in VLC links of at most 1.5 m, employing
commercially off-the-shelf RGB LEDs. Therefore, the contributions of this work include: (I) the transmission over RGB channels of three correlated OFDM signals generated without Hermitian symmetry, thus enhancing the system SE; (II) the proposal of a 3D mapper that exploits euclidean distance enlargement, thus providing performance enhancements and; (III) a suggestion of a simple synchronisation method adapted to the procedure used in offline evaluations, that also avert the need of the redundant cyclic prefix (CP) of conventional OFDM signals.

The remaining is organised as follows. Section 2 briefly describes a theoretical background about the multicarrier signals and the proposed 3D mapper, as well as the channel model that emulates the VLC channel explored in the experiment. A block diagram of the proposed VLC system is described in Section 3. The experimental setup and the experimental results are described in Sections 4 and 5, respectively. The concluding remarks are made in Section 6.

2 THEORETICAL BACKGROUND

In this section we develop the fundamentals of generation OFDM signals based on FFT and DHT. The proposed 3D mapper is described and a basic theory on the VLC channel model is provided.

2.1 IFFT- and DHT-based OFDM signals

Neglecting the cyclic prefix (CP), a single IFFT-based discrete OFDM signal can be written as

\[
X(n) = \sum_{k=0}^{N-1} X_k \cdot e^{j 2\pi \frac{k}{N} n},
\]

\[
= \sum_{k=0}^{N-1} X_k \cdot \left( \cos(2\pi \frac{k}{N} n) + j \sin(2\pi \frac{k}{N} n) \right),
\]  

(1)

in which \( N \) represents the amount of multiplexed subcarriers and \( X_k \) the constellation points generated by a symbol mappings [30]. Due to the complex-value nature of \( X(n) \), an Hermitian symmetry is required at the input (a set of complex conjugate terms) of the IFFT to ensure real-valued signals, demanded by technologies like VLC [15, 31]. To avert the need of HS, some authors employ the DHT to multiplex real-value constellations such as binary phase-shift keying (BPSK) and pulse amplitude modulation (PAM) [32, 33].

The Hartley transform is closely related to the Fourier transform, with the difference that the Hartley transformation produces a real output for a real input, and is its own inverse. This means that it is not necessary to use HS to obtain real values, which reduces the computational cost because it only requires real arithmetic calculations. A DHT-based OFDM signal can be expressed as

\[
y(n) = \sum_{k=0}^{N-1} Y_k \cdot \cos(2\pi \frac{k}{N} n) + \sin(2\pi \frac{k}{N} n),
\]

\[
= \sum_{k=0}^{N-1} Y_k \cdot \left( \cos(2\pi \frac{k}{N} n) + j \sin(2\pi \frac{k}{N} n) \right),
\]  

(2)

where \( Y_k \) stands for the mapped symbols and \( \text{cas}(\cdot) = \cos(\cdot) + \sin(\cdot) \). Because all subcarriers carry data, the DHT-based OFDM doubles the SE, when compared to the IFFT-based signals with the same modulation level.

2.2 The proposed 3D symbol mapper

The employment of the HS in the OFDM signal generation results in a 50% reduction in the spectral efficiency [34, 35]. It is also aiming the elimination of the HS to enhance SE, that we propose the transmission of three correlated multicarrier signals that results in a 3D constellation. Thus, all \( N \) multiplexed subcarriers carry data, which means that, in our proposal, blocks of \( N \times L \) bits are processed in the generation of the correlated OFDM signals. In other words, a data bitstream of length \( N \times L \) is divided in a sequence \( S = \{s_0, s_1, ..., s_{N-1}\} \) of \( N \) sub-sequences composed of \( L \) bits, before symbol mapping. In its turn, each sub-sequence is divided into sub-blocks of \( M \) bits (the most significant) and \( R \) bits (the remaining), that is, \( L = M + R \). In this work, we used \( L = 6 \) to do the partition shown in Table 1. Then, the bits of \( a_s \) are mapped to QAM symbols denoted as \( x_k + j \cdot y_k \) (for \( j = \sqrt{-1} \)), and the bits of \( b_{a_s} \) mapped to PAM symbols (that designates surfaces) as explained in Algorithm 1.

| TABLE 1  | The bit partitioning             |
|----------|----------------------------------|
| \( M \)  | \( R \)          |                             |
| \( b_5 \) | \( b_4 \) | \( a_3 \) | \( a_2 \) | \( a_1 \) | \( a_0 \) |
| PAM      | QAM                             |

**Algorithm 1** 3D mapper

1: Input Bitstream subsequence of size \( L = M + R \)
2: \( b_s \) ← Most significant bits (size \( M \))
3: \( a_s \) ← Remaining bits (size \( R \))
4: QAM symbols ← Mapping of the \( a_s \) bits
5: PAM symbols ← Mapping of the \( b_s \) bits
6: if \( a_s \) is an even integer then
7: QAM(n) symbols ← Phase increment of \( \pi / 4 \)
8: end if
9 return QAM symbols
10 return PAM symbols
If the value obtained from a binary to decimal conversion of the bits $b_n$ is even, the correspondent QAM constellation produced by the $a_n$ bits is rotated according to a phase increment of $\pi/4$ rad, in order to maximise the Euclidean distance between closest symbols of the neighboring QAM constellations. In the rotation process, the used rotation matrix is expressed by

$$
\begin{bmatrix}
x' \k
y' \k
\end{bmatrix} = \begin{bmatrix}
\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta)
\end{bmatrix} \begin{bmatrix}
x \k
y \k
\end{bmatrix}
$$

in which $x'_k$ and $y'_k$ represent the real and imaginary part of the rotated QAM symbols, respectively. After the aforementioned process, two sets of data are obtained, a QAM and a PAM data set. The overall procedure results in a 3D constellation as depicted in Figure 1.

Figure 1 shows different views of an example of the proposed 3D mapper, in which the bitstream is divided in subsequences of $L = 6$ bits. It is possible to observe from Figure 1a unrotated and rotated surfaces. The unrotated surface is represented by the dibit $b_n = 11$ (odd integer) and the rotated by the dibit $b_n = 10$. The two hidden constellations ($b_n = 01$ and $b_n = 00$) appear in the side view depicted in Figure 1b. With each surface addressed by a PAM mapping, it is possible to build the 3D constellation illustrated in Figure 1c.

### 2.3 The VLC channel model

Indoor VLCs can be characterised as LOS and non-LOS links [36]. A non-directed link classification can be defined if a communication between a divergent transmitted beam and a large field-of-view (FOV) receiver is established. Power and data rate, provided by multi-path propagation effects, are limitations of such denominated diffuse links. Nevertheless, the impairments introduced by non-LOS channels is not the focus of this work.

An LOS communication can be conceived with carefully aligned transceivers, in order to overcome the above-mentioned drawbacks. In such scenario, the received power is $P_{LOS} = H_{LOS} \times P_t$, for $P_t$ the average transmitted optical power and $H_{LOS}$ the channel DC gain given by

$$
H_{LOS} = \begin{cases} 
\frac{(m + 1)A_r}{2\pi d^2} \cos^m(\phi)g(\psi)\cos \psi, & 0 \leq \psi \leq \Psi_c, \\
0, & \psi > \Psi_c,
\end{cases}
$$

for $m$ the Lambertian emission order, $A_r$ the photodetection area, $d$ the transmission distance, $\phi$ the irradiance angle, $\psi$ the angle of incidence, $g(\psi)$ the gain of an optical concentrator and $\Psi_c$ is the FOV [37]. The Lambertian order is associated to the LED semi-angle at half-power $\Phi_{1/2}$ and it is obtained as $m = \frac{\ln(2)}{\ln(\cos(\Phi_{1/2}))}$ [37].
3 | SYSTEM MODEL

To transmit the data accommodated in the 3D mapper, we propose the VLC system depicted in Figure 2. The 16-QAM symbols illustrated in Figure 1 are multiplexed via an IFFT, generating a complex-valued OFDM signal. The real ($Re$) and imaginary ($Im$) parts of this signal are managed as two different multicarrier signals. The PAM symbols, that represent the four surfaces illustrated in Figure 1, are multiplexed with the DHT, providing the third multicarrier signal. In order to perform synchronisation and channel estimation at the receiver, we add pilot signals in the beginning of each frame, as shown in Figure 3a. Thus, 10% of the frame duration is composed of five equidistant pieces, three with zeros and two with alternating amplitudes between $-0.25$ and $0.25$, as emphasised in the zoom depicted in Figure 3b. The $Re$ part of the OFDM signals modulates the red LED and the $Im$ the blue one. The real coefficient signals obtained with DHT modulates the green LED. It is important to notice that the analog signals are DC biased before the modulations. Note that no CP is implemented in the proposed system.

After the propagation through a free space LOS channel, that follows the digital-to-analog conversions (D/A), the optical signals are detected with a single photodiode. Optical filters are installed before each receiver to provide wavelength selectivity. Each colour filter only allows the passage of a single colour, which generates individual voltages proportional to the intensity of each colour. This allows a neglect of an ICI that may occur during photodetection [38].

At the receiver, the $Re$ and $Im$ signals are combined after photodetection, analog-to-digital conversions (A/D) and pilot removal. The joined complex-valued signal is then demultiplexed via the FFT processing, before conventional equalisation through one-tap equaliser [39]. A similar process is used in the signal obtained from green channel, excepting the demultiplexing provided by the DHT and the demapping by a common PAM decision.
3.1 Computational complexity analysis

A computational complexity analysis, based on the formulas specified in [40] and on the contributions of [32], is provided in this section. It is made in terms of the minimum number of real multiplications and additions that are necessary in the transmission of a single sequence $s = \{s_0, s_1, ..., s_{N-1}\}$, as well as in the symbols demodulation and recovery. Therefore, knowing that in the proposed modulation format all $N$ multiplexed subcarriers carry data, and considering that the number of real multiplications and additions required in the multiplexing process are $N\log_2(N) - 3 + 4$ and $3N\log_2(N) - 1 + 4$, respectively [40], the total number of real operations required in the multiplexing of the complex-valued symbols generated by the remaining bits $R$ is given by

$$C_R^{\text{DFT}} = 2[N\log_2(N) - 3] + 4N,$$  \hspace{1cm} (5)

$$A_R^{\text{DFT}} = 2[3N\log_2(N) - 1] + 4 + 2N,$$  \hspace{1cm} (6)

for $C_R^{\text{DFT}}$ the number of multiplications and $A_R^{\text{DFT}}$ the number of additions. It is important to notice that these numbers consider that a one-tap equaliser is employed in the channel equalisation process.

The total number of operations required in the DHT multiplexing of the symbols generated by the bits $M$ is given by [32]

$$C_M^{\text{DHT}} = N\log_2(N) - 3N + 4 + 4N,$$  \hspace{1cm} (7)

$$A_M^{\text{DHT}} = 3N\log_2(N) - 5N + 6 + 2N,$$  \hspace{1cm} (8)

for $C_M^{\text{DHT}}$ the number of multiplications and $A_M^{\text{DHT}}$ the number of additions. In this case, it is considered that the same multiplexing process is used in the demultiplexing, and the one-tap equaliser is also used in the channel equalisation.

Thus, in case of 64 data subcarriers, the minimum total number of operations required in the proposed modulation format is obtained considering $C_R^{\text{DFT}} = 648$, $A_R^{\text{DFT}} = 2056$, $C_M^{\text{DHT}} = 452$ and $A_M^{\text{DHT}} = 966$.

3.2 Model validation through numerical simulations

In order to validate the proposed model, we conduct numerical simulations of the above-described system in additive white Gaussian noise (AWGN) channels. We consider that one data frame is composed of 93 OFDM signals, each one comprised of 64 data subcarriers, in both IFFT and DHT multiplexing. This size of the frame was chosen due to the limitation introduced by a mixed domain oscilloscope (MDO) used in the experiments as A/D. It limits the capture window to a maximum of 10,000 points for offline signal processing. Therefore, it should be stressed that, to obtain each value of BER, each data frame (composed of 93 pseudo-random binary sequence $\text{PRBS} = \log_2(L) \times 2^6$) was transmitted 20 times in both numerical and experimental evaluations. Figure 4 shows performance evaluations in terms of bit error rate (BER) at several values of energy per bit to noise power spectral density ($E_b/N_0$), considering different modulation levels in the 3D mapping.

The approximation between the numerical and the theoretical curves (expression in [41]) shown in Figure 4 validate the implemented numerical model. For the experimental demonstration, we choose the 4-PAM and 16-QAM configuration, illustrated in Figure 4b, for the bit partitioning described in Table 1, due to the trade-off between complexity and bit rate imposed by the proposed scheme. This configuration provides bit rates higher that the 4-PAM and 8-QAM with the performance provided in Figure 4a, and it is less complex that the one with the performance provided in Figure 4c.
4 | EXPERIMENTAL SETUP

A block diagram of the setup used to validate the proposed VLC system is illustrated in Figure 5. The 5 MHz digital signals were generated offline using Matlab and loaded into a 250 Msample/s arbitrary function generator (AFG) used as D/A. The analog signals were amplified and superimposed onto bias currents of ≈300 mA (for a bias voltages between 7 and 11 V), to increase of the modulation depth of the LEDs. The output of the Picosecond Pulse Labs Bias-Tee (I_{DC} ≤ 500 mA) was directly supplied to the off-the-shelf RGB LEDs, centered in the wavelengths shown in Figure 6. The transmitter lens (Model 41734.2E) has a focal length of +100 mm.

After propagation over a LOS channel supported by bi-convex optical lenses, the VLC signals were detected by a HAMAMATSU S10784 photodiode, before A/D conversion by a 2.5 Gsample/s MDO and offline processing of the IFFT-based and the DHT-based OFDM demodulations. Due to the restrictions of the experimental setup, the reception was made independently (one channel at a time) using the same receiver, but changing the colour filter. Therefore, the synchronisation issue related to latency, provided by the transmission of different wavelengths combined to multi-path effects, is not the focus of this work [38].

4.1 | The RGB LEDs characterisation

The optical modulation bandwidth and the driving current of each LED are crucial parameters of the experiment. The drive current determines the available signal amplitude limits above which clipping distortions are introduced due to the LED non-linearity. Hence, to quickly forecast the performance of our proposal, we first measure the frequency response and output linearity of the employed LEDs in terms of illuminance. Figure 7a shows that −3 dB bandwidths around 10 MHz are evident in all RGB LEDs.

It can be seen from Figure 7b that the output illuminance of the LEDs are significantly different. At the same driving current of 300 mA, the green shows the highest output illuminance. The blue achieves an output power almost 39% of the green, whereas the value measured for the red is almost 30%. For these reasons, we choose to modulate the green LED with the signal obtained with the mapped bits that represent the surfaces, that is, the PAM axis of the 3D mapper used to separate the QAM plans.

5 | EXPERIMENTAL RESULTS

Figure 8 shows a received constellation after propagation through a VLC channel, in which the distance between the transmitter and the receiver is 1 m. The diagram of Figure 8a illustrates the rotation described in Section 2.2, and the surfaces depicted in Figure 8b demonstrates the feasibility of the proposed VLC system at the mentioned distance, highlighted by the 3D plot depicted in Figure 8c.

In order to reveal potential penalties provided by signal saturation at short reach and by signal attenuation at longer distances (> 1 m), we evaluate performance analysis of the proposed system in terms of error vector magnitude (EVM)
FIGURE 7  (a) Measured electrical frequency response of the LEDs. (b) Measured illuminance versus drive current of the three LEDs.

FIGURE 8  Received constellation (16-QAM in four surfaces obtained by 4-PAM mapping) after propagation through 1 m of VLC channel. (a) The top view, (b) the side view and (c) the overall 3D constellation.
FIGURE 9  EVM versus distance between the LEDs and the PD. The inset constellation were measured at the PAM surface $-1 (b_n = 01)$ at different distances. Figure 9 shows the EVM in terms of distance, measured at all 16-QAM signals in all PAM surfaces.

As expected, Figure 9 shows that the performance deteriorates with the link length, especially for distances greater than 1 m. With the PAM surface $-1 (b_n = 01)$ at 1 m, the measured EVM is around $-20$ dB, contrasting with an EVM $\approx -10$ dB measured at a distance of 2 m, as illustrated by the constellations shown in the inset of Figure 9. The performance of all surfaces are almost the same, with a slight difference for the PAM surface $-1$ at 0.5 m. Although the fact that this can be explained by signal saturation, we can assert that, at the implemented conditions, this non-linear effect does not affect the overall system performance.

6 | CONCLUSION

A VLC system with RGB LEDs for transmission of multicarrier OFDM signals that uses all available spectrum, was proposed and experimentally demonstrated. The system employs a FFT to multiplex QAM symbols organised in a 3D signal mapper, designed with the support of PAM symbols multiplexed by a DHT. To avert the need of Hermitian symmetry, the real coefficient signals of the FFT-based OFDM signals were transmitted in the red LED and their imaginary coefficient through the blue LED. The real signals provided by the DHT were transmitted via the green LED.

Experimental results obtained after the transmission of a 27.3 Mbps OFDM system through a 1.5 m VLC channel show the feasibility of the proposed system in indoor environments. A simultaneous RGB transmission is part of our future works, to address the impact of propagation delays among others non-linear effects, and therefore, encompass applications like visible light positioning, as well as massive multi-user schemes.

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