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Experimental assessment of the performance of cooperative links in visible light communications☆

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ABSTRACT

Cooperative communication is a technique that is employed in the context of visible light communications (VLC) to improve data rate, reach, coverage area and multi-user capacity of installed systems. In this work, we assess the performance of cooperative links with an experimental setup arranged in three configurations, where the position of source, relay and destination is varied, employing an OFDM modulation scheme. Results show that the cooperation improves the bit error ratio (BER) of VLC links, thus enabling faster data rates and more robust systems. BER analysis of the transmitted OFDM signal shows that an improvement of up to one order of magnitude is achieved when comparing the direct and combined cases.

1. Introduction

Over the last years, visible light communications (VLC) have received growing attention with fast development being observed [1]. The research is motivated by the features and the potential of VLC to innovate and unlock new possibilities within the wireless communication field. VLC refers to wireless data transfer using the visible light spectrum, mainly employing LEDs as the transmission source. By modulating the LED electrical current, information is transmitted over an off-air path and received by photodiodes on the other end [1].

In comparison with radiofrequency (RF) communication, VLC presents advantages such as a 10,000 wider available (and unlicensed) spectrum and security at the physical layer (light is confined within the illuminated environment). An aspect that reduces costs is that part of the infrastructure, the transmitter, is already installed, as LED illumination is a green technology that is becoming widely adopted worldwide [2]. VLC is safe for human health, does not cause interference with RF waves and can provide communication simultaneously with illumination. VLC is capable of communication at high data rates, with recent studies reporting speeds over 10 Gpbs [3,4]. The emerging Light-Fidelity (LiFi) technology aims to standardize a complete wireless networking solution employing VLC [5].

Unlike what happens in RF links, VLC is not susceptible to multipath fading [6], due to the fact that the photodiode area is millions of times large than the visible light wavelengths, resulting in a rich spatial diversity [6–8]. However, the physical characteristics of VLC also imply that it has inherent challenges and limitations that must be overcome before it turns into an adopted and widespread technology. For instance, VLC faces limitations such as intersymbol interference (ISI) and shadowing [7]. As visible light does not travel through opaque structures, establishing a line of sight (LOS) link is almost mandatory for optimal performance, which is not always feasible [1]. Besides that, the high path loss in the optical channel also severely limits the transmission distance. Therefore, low-power situations, such as lights-off and uplink channels, are challenges that concern VLC systems designers [2].

To help overcome such limitations, cooperative communication is a technique that has been receiving attention in the literature. Cooperative communication are firstly applied in RF communication, the technique intends to reach spatial diversity in scenarios where, for practical reasons, it is not feasible to add more elements (antennas) to the system, especially at the receiver side [9,10]. In this technique, besides the source and destination, a third element, called the relay, is included in the system. The role of the relay is to improve the communication performance by retransmitting the source information to the destination, which then combines both source and relay information, respectively, allowing an increase of robustness or even extending the reach of installed systems [10–13]. Besides improving

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signal-to-noise ratio (SNR) and bit error ratio (BER) of VLC systems, cooperative communication can extend communication distance in a hop-on-hop fashion and enable communication when the line-of-sight (LOS) between source and destination is blocked. Therefore, cooperation techniques can work as a support to infrastructure, extending communication reach without additional backbone structure.

Some works have considered the VLC relaying without cooperation, that is, the destination only receives the signal of one light source [1,10,14], while other works consider effectively cooperative communication, where the destination receives the signal of multiple light sources and combines them using some combination technique [11–13]. In cooperative VLC, the relay nodes are placed away from the LOS path so that the relay paths contribute to increasing the system reliability and performance.

In the relay element, a protocol must be adopted for the signal processing before the received signal is retransmitted. There are two main relaying approaches: amplify-and-forward (AF) and decode-and-forward (DF) [9]. In AF, the relay applies a gain to the received signal from the source and then retransmits it; in DF, the relay demodulates and then remodulates the source signal before retransmitting it. In the literature of VLC cooperative systems there are examples of AF [15,16], DF [10] or both [13,17–19].

Theoretical studies have approached different aspects and contexts of cooperative communication. For instance, Na et al. [20] extend the use of the orthogonal frequenf8cy-division multiplexing (OFDM) scheme into a cooperative context, allocating source and relay signals to different subcarriers. Deng et al. [21] investigate a scheduling framework for cooperative VLC to mitigate inter-channel interference. Tiwari et al. [22] analyze the use of cooperation in an uplink context, which is a challenge in VLC systems due to the lower power of the light emitter on the user side. In a previous work, we performed simulations of cooperative VLC [23] in an indoor scenario. The use of a mobile node as a relay is investigated by Pešek et al. [19].

However, experimental results on cooperative VLC schemes have seen limited coverage in the literature, and are concentrated on relay-assisted (multi-hop) configurations, *i.e.*, a relay, or set of relays, that re-transmits the signal to the final destination, with no combination of multiple signals at the receiver. This is the case presented by Sejan et al. [24], which transmits a signal over four relay nodes until the destination. Similarly, Yang et al. [25] developed a system with repeaters to evaluate uplink transmission. Both works present performance improvements by employing relay-assisted VLC in their proposed contexts.

In our study, we use OFDM, which is a multicarrier technique that has been frequently employed in the context of VLC systems [20,26]. It is implemented by applying the inverse fast Fourier transform (IFFT) to a block of digitally modulated symbols, such as M-QAM. The QAM symbols are firstly mapped into different subcarriers in the frequency domain and then converted to the time domain by the IFFT operation, resulting in complex-valued samples. However, as VLC systems are based on intensity modulation and direct detection (IM/DD) optical links, the time domain OFDM signal must be real-valued and positive (unipolar). By imposing Hermitian symmetry on the subcarrier data, the IFFT operation then produces a real signal [27]. A common approach to convert the OFDM signal from bipolar to unipolar is achieved by adding a DC bias to the original signal, which is known as direct current-biased optical OFDM (DCO-OFDM) [26].

In this work, we present experimental results based on the Amplify-and-Forward (AF) scheme employing DCO-OFDM modulation and analyze the performance by means of BER measurements. We arrange the communication elements in three configurations in order to study different indoor scenarios and evaluate the performance of cooperation. From the received waveforms, we measure the BER for the direct and relay links and, by offline processing, we also obtain the performance of the combined link. Results show that cooperation reduces the system BER, enabling improved data rates and robustness.

This work is structured as follows. In Section 2, the employed OFDM technique is detailed. In Section 3, the VLC setup and experimental configurations are described, followed by the discussion of performance results in Section 4. Finally, conclusions are given in Section 5.

2. OFDM signal and amplify-and-forward protocol

To generate real-valued OFDM signals, the input symbols $X(k)$ are constrained to have Hermitian symmetry before being processed by the IFFT block. The real-valued time domain OFDM signal $x(n)$, at the IFFT output at time sample n, for $n = 0, 1, \dots, N-1$, is given by

$$x(n) = \sqrt{\frac{1}{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi kn/N} \tag{1}$$

$$X(0) = X(N) = 0 \quad \text{and} \quad X(N-k) = X^{*}(k) \tag{2}$$

where $k = 0, 1, \dots, N-1$ is the subcarrier index, N is the size of the IFFT, and $*$ denotes complex conjugation.

The block diagram of the DCO-OFDM transceiver used in the demonstration of the cooperative VLC scheme is shown in Fig. 1. The input data bits are encoded into 16-QAM symbols for data transmission. The training signals, used for the OFDM channel estimation, are generated using BPSK modulation. The resulting signal, after Hermitian symmetry, is processed by the IFFT block to create a real signal. The OFDM signal is generated with 88 data subcarriers, and IFFT size of 256. The number of data subcarriers is limited by the available bandwidth of the VLC link, around 2 MHz, which is ultimately set by the low bandwidth of the off-the-shelf LED source employed in the setup. The first subcarrier ($k = 0$) represents the DC term and no data is modulated on it. The subsequent 12 subcarriers are set to zeros to avoid strong signal-to-signal beating interference (SSBI) due to the square-law photodetector characteristic [28].

In this work, an OFDM frame starts with 8 training symbols (as a training sequence) and is followed by 200 data symbols. After the IFFT block, a cyclic prefix (CP) with a length of 32 is added and the OFDM signal is parallel-to-serial (P/S) converted and uploaded into the arbitrary waveform generator (AWG), which is configured with a DAC sample rate of 5 MS/s. The total OFDM bandwidth is 1.96 MHz and the total bit rate (excluding CP) is $4 \times 5\text{M} \times 88/256 = 6.87$ Mbit/s. Thus, the spectral efficiency is around 3.5 bit/s/Hz.

After the AWG, the signal is properly amplified and biased and then transmitted over the VLC link. At the receiver end, after photodetection, the electrical signal is ADC converted by the digital storage oscilloscope (DSO), with a sample rate of 50 MS/s, and offline processed using Matlab.

The DSP flow at the receiver (see Fig. 1) is described as follows. Firstly, the received signal is downsampled at a ratio of 10:1 and a symbol synchronization algorithm is employed to identify the start of each OFDM symbol. Our time alignment algorithm is based on cross-correlation and known training sequences. Then, after removing the CP, the signal is fed into the FFT block for OFDM demodulation. This is followed by channel estimation and equalization. Finally, the resulting signal is parallel-to-serial converted and QAM decoded for BER analysis.

To obtain the BER of the cooperative link, we combine the waveforms of the received direct and relay OFDM signals by means of software post-processing employing the maximum ratio combining (MRC) technique, in which the amplitudes of both received signals are weighted summed according to each component's signal quality, considering a higher weight to the signal with a better SNR [29]. The MRC technique presents the best performance for the combination of received signals when compared to other combination techniques such as equal gain combining (EGC) or select best combining (SBC) [29,30]. Our DSP-based signal combination approach can be applied, for example, to the case of spatial diversity with simultaneous measurement. For instance, two photodetectors could be used in the receiver side, each

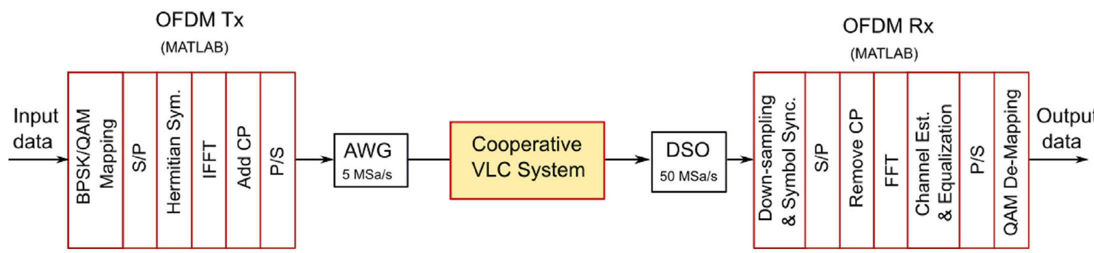


Fig. 1. Block diagram of the DCO-OFDM transceiver.

one aligned to either the direct or the relay LED, and a time alignment algorithm would be used to remove the time delay difference between the direct and the relay paths.

The time delay in relay-assisted (cooperative) VLC systems is created by the length difference between the direct and relay links and the processing time of the relay node. Considering the distances from the source to the relay node as d_{sr} and from the relay node to the destination as d_{rd} (see Fig. 5), the delay of the relay path is given by

$$\tau_r = \tau_p + \frac{d_{sr} + d_{rd}}{c}, \tag{3}$$

where τ_p is the processing delay caused by the relay node and c is the light speed in free space. The delay of the direct path with length d_{sd} (wireless part only) is given by

$$\tau_d = \frac{d_{sd}}{c}. \tag{4}$$

Thus, the delay spread in the received signal due to the difference between the time delays of the two paths is $\tau_d = \tau_r - \tau_d$.

3. Experimental setup

As VLC presents the potential of being used in illumination and communication, the LED, or set of LEDs, must be driven by a signal that combines both these features. Illumination, *i.e.*, lighting up the LEDs, requires an adequate DC power. The communication aspect is an AC signal that contains the modulated information. These signals are combined in a bias-T, whose output is the sum of the DC and AC signals and drives the LED.

Fig. 3 shows the block diagram of the experimental setup, which is composed of four elements: the LED, the relay receiver, the relay transmitter and the photodetector. To enable the modulation of the LED with an appropriate signal amplitude, an amplifier (Mini-Circuits ZHL-6A+) is employed, and then the signal is sent to the bias-T that drives the LED and amplified by another ZHL-6A+ amplifier, which provides a linear gain of approximately 25 dB. The signal is then summed with the DC signal at the relay bias-T to drive the LED of the relay transmitter.

The transmitters are the SP-02-T9 SinkPAD II LED modules from Luxeon Star LEDs, that holds seven white LEDs, model LX18-P150-3. For the sum of the AC and DC signals, we employed the ZFBT-4R2GW+ bias-T from Mini-Circuits at the source and at the relay module. At the receivers we employ Hamamatsu C12702 series photodetector modules, using the C12702-11 and C12702-12 models. These modules employ APDs (avalanche photodiodes) and present high gain (> 30 dB). The main difference between these two APD modules concerns the photodetection area, which is 7.1 mm^2 (⌀ 3 mm) for the C12702-12 and 0.78 mm^2 (⌀ 1 mm) for the C12702-11, respectively. Its output provides solely the modulated part of the transmitted signal (*i.e.*, there is no DC level).

The measured electrical powers at the output of both APD modules versus frequency are shown in Fig. 2. These measurements were obtained when a sine wave is applied to the LED with a frequency varying from 0.2 to 3 MHz. From the figure it is possible to observe the frequency response of the VLC link composed of LED + APD modules. For reference, the grayed area represents the frequency range of the employed OFDM signal used for the BER results, which is from 0.24 to 1.96 MHz. From Fig. 2, it can be seen that the VLC link shows a power decrease of 2.86 dB between the lower and higher OFDM subcarriers. According to the APD datasheets, the frequency responses of the two APDs are flat within the OFDM bandwidth. Thus, the measured power decrease is due to the uneven frequency response of the LED. It is important to note that, as the bandwidth of one OFDM subcarrier is around 19.5 kHz in the present system, the power fading within each subcarrier is much smaller than 2.86 dB, which facilitates the equalization process.

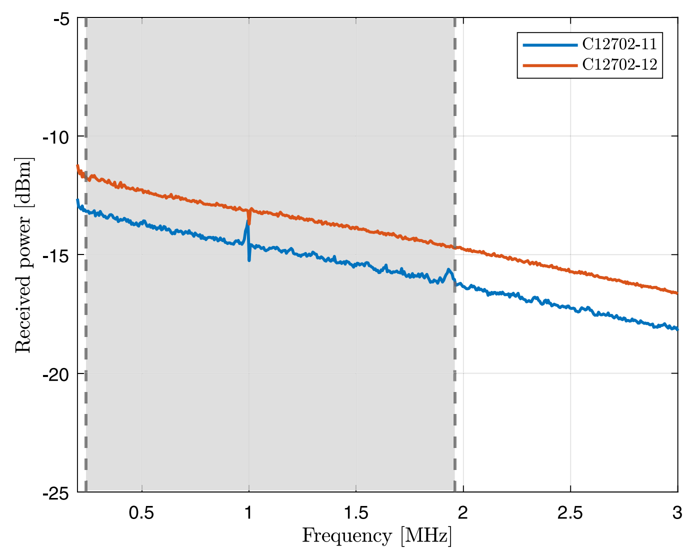


Fig. 2. The measured electrical power at the output of APD modules (C12702-11 and C12702-12) versus frequency. Grayed area represents the frequency range of employed OFDM signal.

A time delay occurs at the destination due to the processing electronics between the received signal at the relay and its re-transmission, when compared with the signal, which comes directly from the source. Thus, each received signal is measured one at a time. For the purpose of BER measurements, the signal combining is accomplished offline, by correcting the phase between the two signals through signal processing.

We measured the time delays of around 30 ns and 63 ns for the direct and relay paths, respectively, in response to a step signal and with the setup of Fig. 3 set at the following distances: d_{sd} = 1 m, d_{sr} = 0.4 m and d_{rd} = 0.2 m. Thus, the delay spread due to the addition of the relay path and for the specific distances used is 33 ns. The time delay of each link will change for different distances, but the reported result gives a reference for future investigations. Fig. 4 presents the oscilloscope's screen capture of the delay analysis for both links. For better visualization, additional annotations of the time delays are included in Fig. 4.

For BER measurements, three configurations of the cooperative communication setup were employed concerning the distance between source, relay and destination, by changing their positions, which are

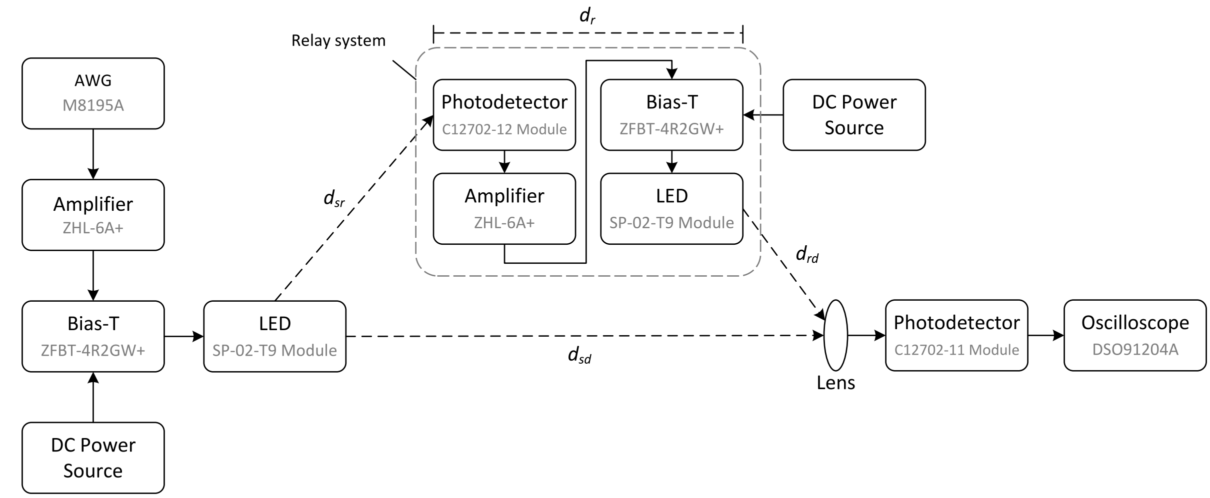
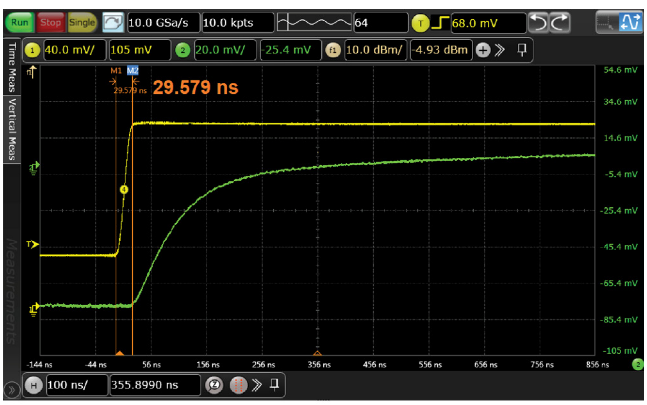
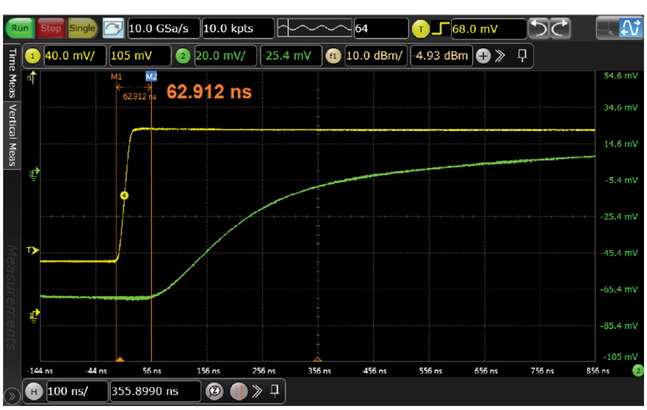


Fig. 3. Block diagram of the cooperative communication VLC experimental setup.



(a) Direct transmission.



(b) Relay transmission.

Fig. 4. Delay analysis for (a) direct and (b) relay links. The yellow curve refers to the reference back-to-back signal and the green line refers to the VLC link.

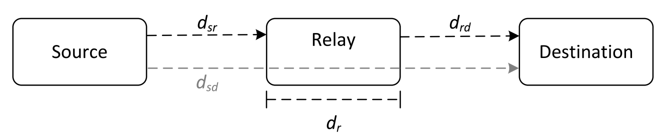


Fig. 5. Reference block diagram of the experimental configurations.

Table 1
Distance between elements for the BER measurements. Values in centimeters.

Exp.	d_{sd}	d_{sr}	d_r	d_{rd}
1	$80 + d_{rd}$	40	40	20 to 100
2	120	10 to 50	$(50 - d_{sr}) + 30$	40
3	120	10 to 50	30	$90 - d_{sr}$

moved or remain fixed according to the arrangement. Fig. 5 serves as a reference to describe these configurations.

We refer to these configurations in the text as 1, 2 and 3 for the ease of description. d_{sr} is the distance from the source to the relay's photodetector; d_{rd} is the distance from the relay's LED module to the destination; d_{sd} is the distance of the direct transmission, *i.e.*, from source to destination; d_r is the distance from the relay's receiver to its transmitter. A lens is employed at the receiver in order to improve performance. Table 1 summarizes the varied or fixed distances, as described in Fig. 5. In all configurations, the source, relay and destination elements are positioned in a straight line.

In configuration 1, the distance from source to relay is fixed, while increasing the distance between source and destination. In configuration 2, the distance between the source and the destination is fixed, while the distance between the source and the relay is varied. This means that the received power at the relay decreases as its distance from the source increases. Configuration 3 is similar, but in this case, the relay elements (receiver and transmitter) are moved together, hence d_r is fixed.

4. Results and discussion

With configuration 1, we evaluate the scheme where both source and relay remain fixed and the user moves away from both, considering that the relay is closer to the user than the source itself. Fig. 6(a) shows the measured BER (see data points in the plots) for this case. The combined curve, which represents the performance of the cooperative VLC link, follows a similar pattern as the direct link curve, but achieving a lower BER. In practice, this improved BER can provide higher data rates, large maximum link distances or a more robust system overall. For configuration 1, the BER varies from 7.0×10^{-5} to 2.2×10^{-4} and from 6.5×10^{-6} to around 5.3×10^{-5} for the direct and the combined transmissions, respectively, when the distance between source and destination increases from 1 to 1.8 m. This indicates that a BER improvement of at least a half order of magnitude is observed when employing cooperation, in contrast with the direct link.

In configuration 2, we analyze the effect of the relay receiving different optical powers to drive the LED transmitter at the relay (by varying d_{sr}), while its distance towards the destination is fixed (d_{rd}). Results are presented in Fig. 6(b). In this case, for distances between source and relay up to 0.4 m, the measured BER of the relay link is better than that of the direct link. This indicates a case in which the relay may solely act as the VLC access point for a given area, under the condition that the receiver of the relay is close to the source. As with configuration 1, for most of the measured results, BER improvements of up to one order of magnitude are achieved with the proposed cooperative approach in comparison with the direct link case. The BER for the direct path is constant at 1.7×10^{-4}, while the combined BER values were in the range of the 10^{-5} mark.

Configuration 3 shows the system performance while changing the whole relay position (keeping d_r fixed while d_{sr} and d_{rd} changes as the relay is displaced), that is, it is intended to evaluate the case, in which the relay may be better positioned closer to the source, to the destination or if there is a better intermediary position. Results are presented in Fig. 6(c). In this scenario, the relay always presents a worse performance than the case for the direct link. As for the relay position, there is a trade-off between received power (better closer to the source) and path loss (better closer to the destination) that must be considered. In any case, however, when combining both received source and relay OFDM signals, the system performance improves. While the BER for the direct link is constant at 1.7×10^{-4} as in the previous scenario, the combined BER result ranges between 1.4×10^{-5} and 6.7×10^{-5}.

In order to visualize the behavior of the received signals, constellation diagrams for the direct, relay and combined signals are shown in Fig. 7. The presented constellations refer to the worst case of configuration 1, *e.g.*, taken at the maximum measured distance of $d_{sd} = 1.8$ m.

In these plots, we can observe the difference that the BER results have on the quality of the constellations. For instance, as presented in Fig. 6(a), the relay transmission has the poorest BER of the three links, which corresponds to its constellation, where symbols are spread over a larger area and closer to its neighbors. In the same sense, Fig. 7(c) shows the combined transmission, which has the clearest constellation of the three, with the direct transmission showing a performance between these cases, but closer to the combined link than to the relay, as we expect from the analysis of the BER measurements.

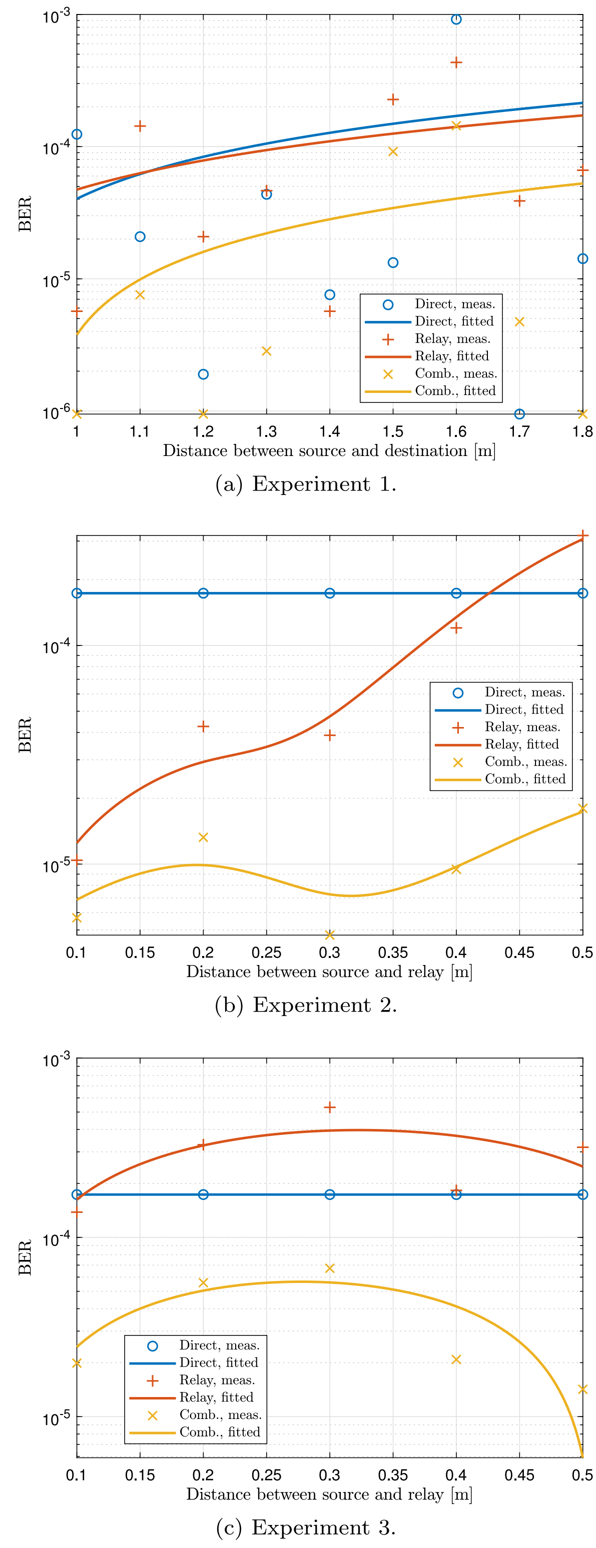


Fig. 6. BER versus distance for experimental schemes (a) 1, (b) 2 and (c) 3.

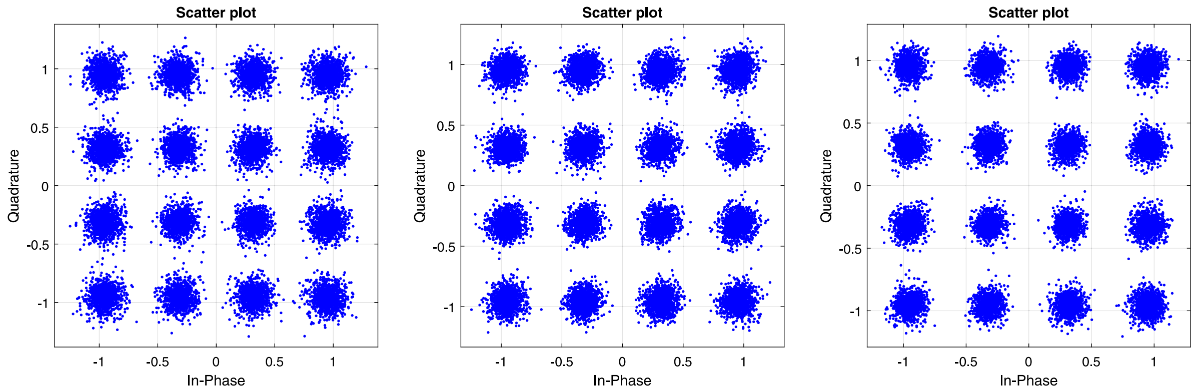
5. Conclusions

An experimental VLC cooperative communication setup was assembled and performance results were obtained considering three configurations for the position of the source, relay and the receiver at destination. Results of the three tested schemes demonstrate that the combination of the relay and source signals with the help of maximum ratio combining improves the bit error rate in all scenarios.

Results also demonstrate that, at least at closer distances, the relay acting alone is capable of providing the communication. This is relevant because it can act as the VLC access point in the infrastructure of a room or part of a room. So, it is important for the deployment of VLC systems as it allows the signal coverage to be expanded without additional backbone infrastructure, *i.e.*, extending cabling through the roof, inner or outer walls to connect all luminaires to the backbone. Configuration 3 indicates that, when installing a relay-assisted or cooperative VLC setup in a given environment, the relay must be positioned in a way that it presents an optimal performance, considering the source and destination positions.

In future work the trade-offs between the signal parameters and the performance of cooperative OFDM-VLC systems can be addressed in order to optimize the OFDM parameters. We have not considered the lighting performance of the LED sources, as this work focused on the communication aspects and the link performance. We believe that with well positioned and small size relay nodes the indoor illuminance generated by the arrangement can be made to comply with recommended light levels.

In conclusion, VLC links are benefited from the use of cooperative communication, increasing the performance or enabling the communication where the source to destination link has a poor BER/SNR or there is no line of sight. In this work, we demonstrate that choosing the correct position of the relay is an important factor to be considered in order to obtain optimal performance.



(a) Direct transmission. (b) Relay transmission. (c) Combined transmission, relay + direct.

Fig. 7. Constellations for received OFDM 16-QAM signals for configuration 1, for (a) direct, (b) relay and (c) combined links.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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