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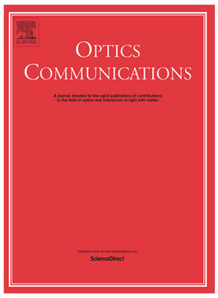

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Experimental Validation of Indoor Relay-assisted Visible Light Communications for a Last-meter Access Network

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ABSTRACT

This paper provides experimental results for a relay assisted visible light communications (VLC) link using a white light-emitting diode (LED) for a last-meter access network. We demonstrate that a relay-based VLC scheme improves the system performance, especially for link spans longer than 5 meters, in the presence of blocking and shadowing by redirecting the transmitted signal. We also demonstrate a multiband carrier-less amplitude and phase modulation (*m*-CAP) VLC link where the decode-and-forward (DF) relay scheme offers improvement in the data rate by 25% and 60% when compared to the amplify-and-forward (AF) relay-based link and single VLC link over a 7 m transmission distance respectively.

1. Introduction

In recent years, end users have increasingly demanded wireless connectivity with improved flexibility, reliability, scalability, data throughput, as well as significantly reduced latency [1]. Although, radio frequency-based wireless technologies (WTs) have addressed these demands, in particular, improved both the spectral and power efficiencies, end users still face spectrum congestion due to the exponential growth in data being used and generated. To address spectral congestion and allow the use of the radio frequency (RF) spectrum in applications where it is most needed, the focus of this research has been on the utilisation of an alternative complementary WT. Within this context, visible light communications (VLC) have been considered as a possible solution for high-speed communications, especially in indoor environments [2, 3].

In VLC systems, white light emitting diode-based lights are used to provide illumination, data communication and indoor localisation within indoor scenarios. VLC links, with a range of data rates R_d over short transmission spans, have been reported in the literature. In [4], a 1 Gb/s real-time line-of-sight (LOS) VLC link based on non-return-to-zero on-off keying (NRZ OOK), with a bit error rate (BER) of 7.36×10^{-4} using a commercial phosphorescent white light emitting diode (LED) over a transmission distance of 1.5 m, was reported. A VLC system employing a micro-LED with R_d of 3.5 Gb/s and [illegible] Gb/s using pulse-amplitude modulation (PAM) and DC-biased optical orthogonal frequency division multiplexing (DCO-OFDM) respectively, over a link span 0.5 m, was demonstrated in [5]. In [6], a combination of a DCO-OFDM and a red-green-blue (RGB) LED-based wavelength division multiplexing (WDM) VLC system was used to demonstrate R_d of 11.28 Gb/s (and 10.4 Gb/s with forward error correction (FEC) overhead reduction) over a link span of 1.5 m.

However, the performance of VLC links depends mostly on the transmission distance between the transmitter (Tx) and the receiver (Rx), and the received optical power via the LOS path (i.e., the dominant path in high-speed VLC links). Thus, higher R_d are associated with the availability of an LOS transmission path, which is not always the case in indoor environments due to mobility, shadowing and blocking effects caused by people and objects within the room.

To address this problem and maintain an uninterrupted data transmission with much reduced interference, even within temporarily shadowed regions in an indoor environment, an angular diversity Rx, together with different combining schemes, was proposed in [7, 8]. An alternative solution to shadowing is to use a hybrid RF/VLC system to ensure link availability at all times. In [9], the authors investigated an indoor data network composed of multiple VLC and RF access points, whereas in [10], the expression for the outage probability of relay-assisted hybrid RF/VLC link for an indoor application was given. In [11], the effect of human induced shadowing on VLC link performance was investigated, but with no effective solutions being proposed to address the problem. To increase VLC link reliability and availability, a full-duplex (FD) relay link using LED-based triangular topology was investigated in [12] and showed improved BER performance compared to LOS VLC. The performance of the cooperative multi-hop relay-based VLC system has been reported in the literature by considering (*i*) the user's mobility and relay probabilities [13]; (*ii*) FD relay compared with a half-duplex (HD) system [14]; (*iii*) OFDM VLC with amplify-and-forward (AF) or decode-and-forward

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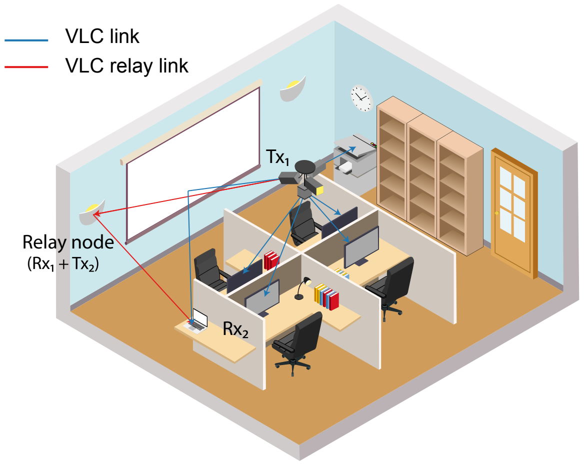

Figure 1: Schematic diagram of a relay-assisted VLC link for an office.

Table 1
VLC system parameters

Parameter	Value
Pseudorandom binary sequence	$2^{15}-1$
LED biased current	480 mA
m-CAP signal bandwidth	5 MHz
Biconvex lenses focal length at Rxs	35 mm
Biconvex lenses focal length at Txs	25 mm
VSG peak-to-peak voltage	300 mV
VSG sample frequency	20 MHz
Oscilloscope sample rate	1 GSa/s
BER limit	3.8×10^{-3}
m-CAP order	10
m-CAP roll-off factor	0.2
m-CAP filter length	10 symbols

(DF) relay schemes over frequency-selective indoor channels while considering different pulse shaping filters [15]; and (*iv*) DCO-OFDM VLC for optimal power allocation and improved BER performance [16]. In most relay-based VLC links, the use of relay nodes has not been fully exploited since they are treated as auxiliary nodes. In [17], an asymmetrically clipped DCO-OFDM (ADO-OFDM) relay-based VLC system with two power allocation factors was investigated and was shown to offer highly stable communications. In [18], an optical bidirectional beacon, composed of RGB LEDs, photodetectors and color filters was proposed as an effective scheme to address the performance degradation in a non-LOS VLC system. In [19], we analytically investigated an OOK HD-based VLC link which used a mobile unit-based relay node to improve link availability and coverage area in a typical office environment. A new analytical description of BER for the AF- and DF-based relay VLC links has been provided.

Nonetheless, none of the existing works have reported an experimental comparison single channel and relay-based VLC link performance. In this paper, we experimentally investigate the performance of multiband carrier-less amplitude and phase (m-CAP) modulation scheme AF relay-assisted systems and DF relay-assisted VLC systems for the last meter access network, as can be seen in a typical scheme illustrated in Fig. 1. In an office environment, the link between the end user (i.e., a laptop (Rx_2)) and the Tx can experience shadowing due to partitioning screens and other objects (fixed or mobile) within a room. In this scenario, the link can be re-established via a relay node (i.e., wall mounted lights) or via non-LOS (i.e., reflections), see Fig. 1. The main contributions of this paper are (*i*) a demonstration of results from an experimental testbed for a relay-based *m*-CAP VLC link, and (*ii*) a performance comparison of LOS, non-LOS and relay-assisted VLC links in terms of R_d.

The rest of the paper is organised as follows: in Section 2, the experimental setup and system parameters are outlined, whereas, in Section 3, the results for the relay-assisted VLC system are presented. Finally, the conclusions are given in Section 4.

2. System setup

The system setup for AF and DF relay-assisted VLC systems is depicted in Fig. 2. A ($2^{15}-1$) long pseudorandom binary sequence (PRBS) $x_b(t)$ is generated for each *m*-CAP subcarrier (SC) and mapped into *M*-ary quadrature amplitude modulation (*M*-QAM) symbols, where *M* is the order of modulation. The mapped data is up-sampled and split into its real and imaginary parts prior to being applied to the square root raised cosine pulse shaping (SRRC) filters. Note, the impulse responses form a Hilbert pair, i.e., being orthogonal in the time domain and shifted by 90° in phase; more details of *m*-CAP modulation scheme can be found, e.g., in [20]. The generated signals are loaded to a vector signal generator (VSG) (Rohde & Schwarz SMW200A) the output of which is DC-biased prior to the intensity modulation of two commercially available LEDs (OSRAM Golden Dragon) used for Tx_1 and Tx_2. The white LED 3 dB modulation bandwidth, with no pre-equalization, is limited to 1.5 MHz. For the measurement, we set the transmitted signal bandwidth to 5 MHz. Biconvex lenses, with focal lengths f_1 and f_2 of 25 mm and 35 mm respectively, are used at the Txs and the Rxs to increase the received optical power level.

The complexity of *m*-CAP depends mainly on (*i*) filter length L_s; (*ii*) roll-off factor β; and (*iii*) the number of SCs (i.e., *m*). Following our previous works [21, 22], we have set L_s to 10 symbols (since for $L_s > 10$ there is marginal performance improvement), β to 0.2 and *m* to 10, which offers the best trade-off between complexity and R_d.

Following a transmission over the first channel, the relaying schemes are applied. The relay node is composed of an optical Rx_1 (an adjustable gain Si avalanche photodetector with a low noise transimpedance amplifier (Thorlabs APD430A)), an LED driver and the Tx_2. For the AF-scheme, the received signal is amplified to its initial power level and

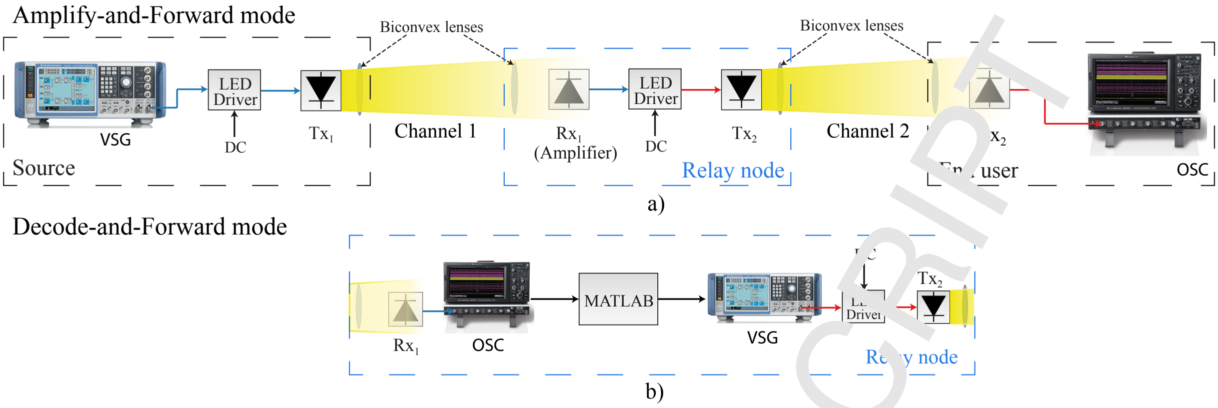

Figure 2: Experimental setup for the relay-assisted VLC link with: (a) AF, and (b) DF relay nodes.

retransmitted over the second channel. Whereas for the DF-scheme, the received signal is captured using a real-time digital oscilloscope (OSC, LeCroy WaveRunner Z640i) and processed (i.e., demodulated) off-line in Matlab. The processed and regenerated signal is loaded to VSG and retransmitted via the Tx_2 over channel 2. At the Rx_2 (Thorlabs PDA10A2), following optical detection, the signal is resampled to the sampling frequency of the transmitted signal, then demodulated to recover the estimated version of $x_i(t)$. All the key parameters adopted in the proposed system are shown in Table 1. An application improvement could be done using biconvex lenses with shorter focal lengths or by lenses integration on a chip.

3. Experimental results

The primary objective is to analyse the performance of relay-assisted *m*-CAP VLC systems for a range of link spans in terms of R_d. Note, the same conditions were adopted during the experimental measurements to compare both AF and DF schemes (i.e., keeping the same transmit power level and a BER threshold level of 3.8×10^{-3} (corresponding to the 7% FEC limit)).

3.1. Reflected link performance

As illustrated in Fig. 1, the signal can reach end users via non-LOS paths by means of reflections from walls or any other surfaces within the room. To this end, an experimental measurement for R_d with reflections from whiteboard for a range of L_1 and L_2 was conducted. Note that both the end user's Rxs and the ceiling-based LEDs (Txs) were pointing to a whiteboard at an angle of 45° as shown in the inset of Fig. 3. For the sake of simplification, the Rx and the Tx were positioned at the same height. The distortion and absorption of the light signal by the whiteboard results in a significant reduction in R_d with respect to L_2. To achieve a maximum R_d, we used a pilot binary phase-shift keying (BPSK) signal to load the appropriate number of bits/symbol to each individual SC based on the measured signal-to-noise ratio (SNR) level. For a 2 m long L_1, increasing L_2 by about 2 m

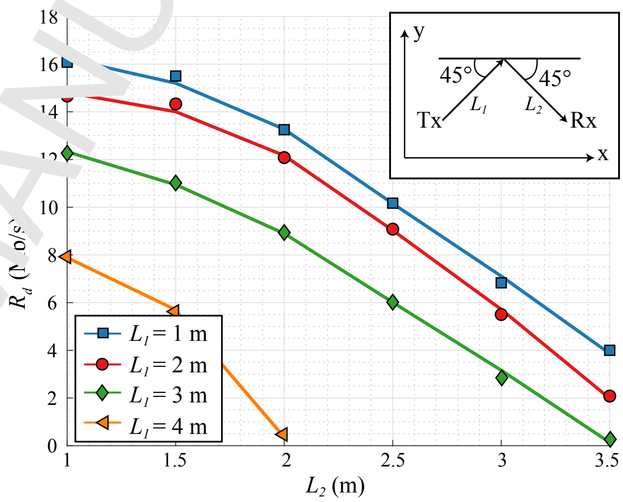

Figure 3: Measured *m*-CAP VLC link performance with reflections from a whiteboard for a range of L_1 and L_2.

results in R_d being reduced by ~9.5 Mb/s. Nonetheless, in the worst-case scenario, only a 2 m transmission extension can lead to reduced R_d 0.5 Mb/s due to the reflected beam distortion.

3.2. Dependences of relay links spans

Thus, in the next part, R_d was measured as a function of the first channel length L_1 and a range of second channel spans L_2 for both AF and DF relay-based *m*-CAP VLC links.

As shown in Fig. 4, the maximum R_d of 31 Mb/s is achieved for the shortest link with DF and a BER below the 7% FEC threshold level of 3.8×10^{-3}. The extension of the transmission link span (either in channel 1 or channel 2) has resulted in a reduced received optical power level, thus leading to the deterioration of the link's SNR performance. The difference in R_d between the two schemes is from 4 to 6 Mb/s depending on the link span. The performance difference is caused by noise accumulation and amplification at the relay node in AF protocol, while noise is eliminated during processing in the DF scheme. By extending the channels and

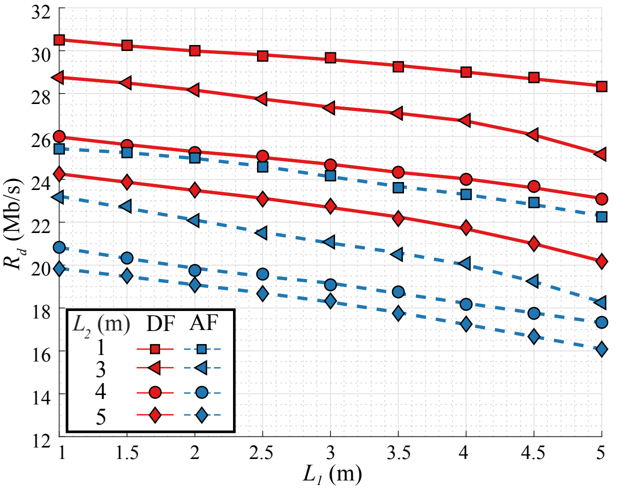

Figure 4: Measured data rates against L_1 for AF and DF based m-CAP VLC for a range of L_2 link spans.

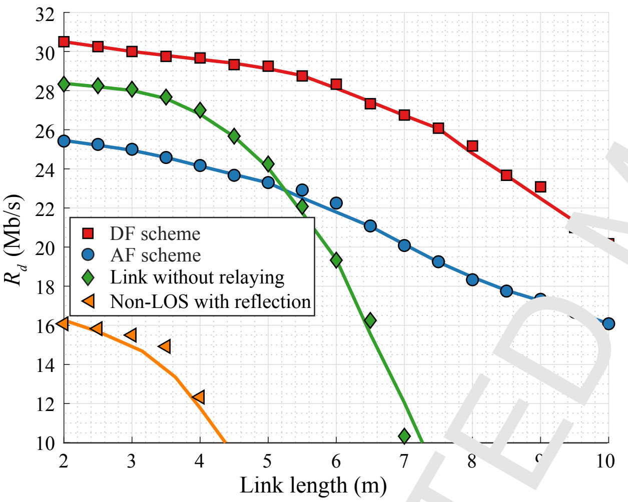

Figure 5: Experimentally measured data rates of the VLC systems: DF (red), AF (blue), link without relaying (green) and non-LOS with reflection (orange).

keeping the same BER value around the FEC limit, the AF scheme is influenced more by the limited received optical power level, i.e., a decrease in the data rates of 3.5 Mb/s and 4.92 Mb/s for DF and AF, respectively for $L_2 = 3$ m and L_1 increased by 4 m (i.e., from 1 m to 5 m).

3.3. Performance of the entire relay-assisted link

Figure 5 illustrates the comparison of aggregated m-CAP R_d (i.e., maximum achieved performance) of the entire VLC link over link distance for the following scenarios (*i*) with the relay scheme (i.e., AF and DF); note in this case, we plot the best achieved R_d from all combinations of L_1 and L_2; (*ii*) LOS without relay, i.e., a direct link - maximally measured either within channel 1 or channel 2; and (*iii*) NLOS VLC with a reflection. The maximum R_d is reached in the case of the DF-relay VLC link. An LOS link without the relaying scheme can offer improved performance for up to a 5 m link compared to the AF scheme. This is due to the limited 3 dB modulation bandwidth of the OSRAM Golden Dragon LED. Note that with no regeneration as in the case in AF, the received signal with low SNR is again degenerated by an LED. However, for a transmission range of beyond 5 m, link performance without relaying is marginally decreased due to lower SNR. The measured data rates for the non-LOS link (i.e., reflected) are approximately half that of the DF system for a link span of up to 3.5 m and decreases to less than 10 Mb/s for link spans longer than 4.5 m. For a data rate of 16 Mb/s, the AF scheme offers five times greater transmission length compared to non-LOS VLC link.

4. Conclusion

In this paper, an m-CAP-based relay-assisted VLC system was experimentally investigated. It was demonstrated that relay VLC links can provide higher data rates compared to a direct VLC link. This is particularly important for link distances longer than 5 m. For relay VLC systems, it was shown that m-CAP-based DF VLC offered higher data rates of ∼25% over a link span of 10 m when compared to AF VLC.

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