25G+ Distance-Adaptive Visible Light Communications Enabled by Entropy Loading

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Abstract: Using probabilistic shaping together with multi-carrier modulation and entropy loading, we experimentally demonstrate a distance-adaptive RGB-VLC system operating with diffuse white light and supporting record-high bit rates of 26–46 Gbit/s over 50-200 cm.

1. Introduction

Visible light communication (VLC) is seen as a promising high-speed indoor wireless communication, providing flexible and secure connections through the visible band of the electromagnetic spectrum (430-790 THz) with hundreds of terahertz of unlicensed bandwidth. In this way, it is possible to complement RF networks that have a highly congested spectrum. Over the past few years, many high-speed VLC systems have been reported, with a progressive increase in data rate. Two main approaches have been considered, using i) light-emitting diode (LED) and ii) laser-diode (LD) based transmitters. With LEDs, the achievable capacity of VLC systems is highly limited by the low bandwidth of the source (typically tens to hundreds of MHz). Nevertheless, some record experiments have been able to demonstrate VLC bit rates up to 20 Gbit/s using red, green and blue (RGB) LEDs [1–4]. With the aim of overcoming this bandwidth limitation imposed by LEDs, the VLC research has been progressively shifting towards the use of LDs, which provide bandwidths in the range of few GHz, thereby enabling recent VLC demonstrations reaching bit-rates in the order of 30 Gbit/s [5, 6]. However, most works tend to consider point-to-point links with collimated light, thus discarding the illumination functionality that is also required for VLC systems. Therefore, some articles recommend the use of a frosted glass to diverge the transmitted light, thereby covering a wide area [7–10]. A summary of the highest reported bit-rates so far using LEDs and LDs with diffuse white light is shown in Fig. 1.

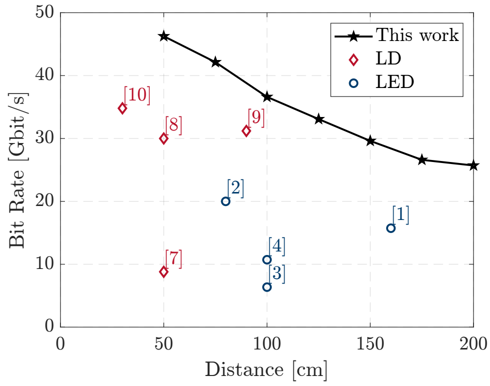

Fig. 1. VLC bit-rates reported so far with diffuse white light.

In a typical indoor downlink application scenario, each user device will have a different distance to the light source transmitter. In order to take full advantage of channel capacity, we propose to use the entropy loading (EL) method to maximize the bit rate. Thus, the system loads continuous entropies to the digital subcarrier multiplexing (SCM) signal, adjusting the probability distribution of the symbols of a quadrature amplitude modulation (QAM) constellation [11]. In this work, we experimentally demonstrate a VLC system capable of changing the bit rate according to the distance between the transmitter and receiver using an EL technique based on probabilistic constellation shaping (PCS), in contrast to our previous work that only considered a fixed distance [9]. After estimating the signal-to-noise ratio (SNR), the system is able to adapt the bit rate between 46 and 26 Gbit/s for distances between 50 cm and 200 cm, respectively. To the best of authors' knowledge, these bit rates correspond to the highest values reported so far for VLC systems with diffused white light, as shown by the black line in Fig. 1.

2. VLC system description

Fig. 2 (a) illustrates the experimental setup of the VLC system. The first step is to generate the SCM signal, performing the QAM symbols mapping after applying EL, pulse shaping, up-sampling and frequency shifting of each subcarrier. Fig. 2 (c) shows an example of 16QAM PCS constellation with an allocated entropy of 3.5 bits/sym. The generated complex signal needs to be converted as real-valued, thus allowing intensity modulation and direct detection (IMDD), as typically used in VLC systems. Therefore, we shifted the baseband signal to an intermediate frequency. Then, the three waveforms are generated using two 2-channel arbitrary waveform generators (AWGs, Keysight M8190A and Tektronix AWG70002A) with an analog bandwidth of 3.5 GHz and 8 GHz and a sample rate of 8 GSa/s and 16 GSa/s. Using linear RF amplifiers, with up to 26 dB variable gain, 6 dB noise figure and 10 GHz bandwidth, the analog signals are amplified to later feed the bias-tee. Laser diode mounts (Thorlabs LDM9T/M, 1 GHz cut-off frequency) with integrated temperature controllers and bias-tee adapters are used for RF modulation of the light. The used laser diodes have a wavelength of 450 nm (blue, OSRAM PLT5450B), 520 nm (green, Thorlabs L520P50) and 650 nm (red, Thorlabs L638P040). After collimating the light with aspheric lenses (Thorlabs C220TMD-A), the three colors are multiplexed with dichroic mirrors (Thorlabs DMSP567T and DMSP490T) and diffused to scatter the white light (Thorlabs ED1-C20-MD).

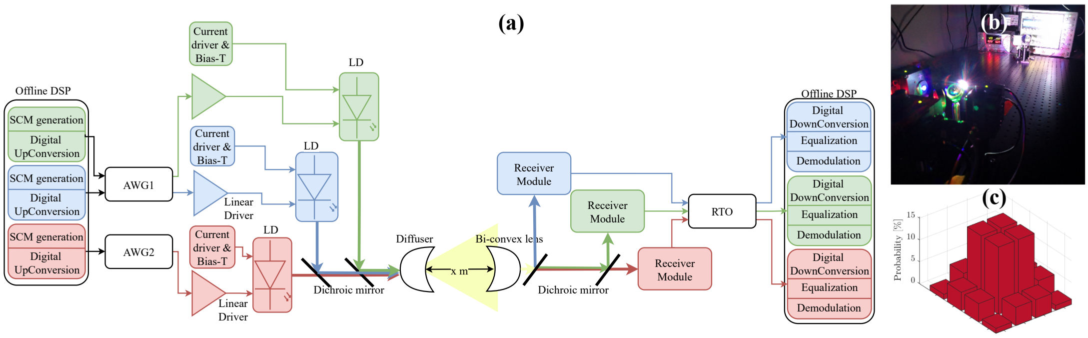

Fig. 2. (a) Architecture of the experimental setup of the VLC system. (b) Photo of the receiver from the transmitter. (c) Example of 16 QAM PCS constellation with an entropy of 3.5 bits/sym.

In Fig. 2 (b) we can see the optical channel, whose distance varies between 50 cm and 200 cm. The demultiplexing of the red, green and blue colors is done with a bi-convex lens (Thorlabs LB1106-A) and two dichroic mirrors. Optical signals are converted to the electrical domain using two types of receiver modules (Hamamatsu c5658 and Eotech ET-2030A). The first has a bandwidth of 1 GHz and includes an integrated avalanche photodiode (APD) and a low-noise amplifier, while the second has a bandwidth of 1.2 GHz and contains a PIN photodiode and a transimpedance amplifier. The received electrical signals at a 4-channel real-time oscilloscope (RTO, Keysight DSO804A), with a bandwidth of 8 GHz and a sample rate of 20 Gsa/s, are digitized to later implement the digital signal processing (DSP) comprising digital downconversion to baseband, adaptive least mean square (LMS) equalization with 101 taps, re-sampling, timing synchronization and de-maping of the received complex symbols to calculate the performance metrics.

3. Experimental Validation

In this section, we present the experimental results of the distance-adaptive bit rate using an EL strategy. The used method was explained in detail in our previous article [9]. This algorithm estimates the maximum entropy supported by the system per subcarrier in the SCM signal, considering a given estimated SNR per subcarrier and normalized generalized mutual information (NGMI) threshold, $\mathrm{NGMI_{th}}$, that guarantees error-free decoding after forward error correction (FEC). In this work, we considered an $\mathrm{NGMI_{th}} = 0.9$, which corresponds to an ideal FEC overhead of 11%. The achievable bit rate of this communication system is calculated as [11], $R_b = R_s \sum_{n=1}^{N_{SC}} \left(H_n - \log_2(M_n)(1 - R_{FEC})\right)$, where R_b is the bit rate, R_s is the symbol rate of the signal, H_n is the entropy of subcarrier n, M_n is the square/cross M-QAM constellation of the n^{th} subcarrier and R_{FEC} is the FEC rate.

The main objective is to maximize the bit rate of the VLC system for a given distance, comparing the performance of the two receiver modules. We considered a 16×100 MHz signal with 0.05 roll-off and a total bandwidth of 1.68 GHz for the receiver module with an APD and a 10×200 MHz signal with 0.05 roll-off and a total bandwidth of 2.10 GHz for the receiver module with a PIN photodiode. Higher bandwidth was used on the second signal due to the greater analog bandwidth of the receiver. In Fig. 3 is shown the entropy allocated in each of the subcarriers, for the three colors using the PIN photodiode and the APD. From Fig. 3 (a), we can see that, for a distance of 100 cm, the entropies are approximately constant up to 1.2 GHz considering a receiver with a PIN photodiode and up to 1 GHz for the APD, corresponding to the bandwidth of the optical receivers. In the remaining subcarriers, the entropy is considerably lower, approaching 2 bits/symbol in the last subcarriers, which

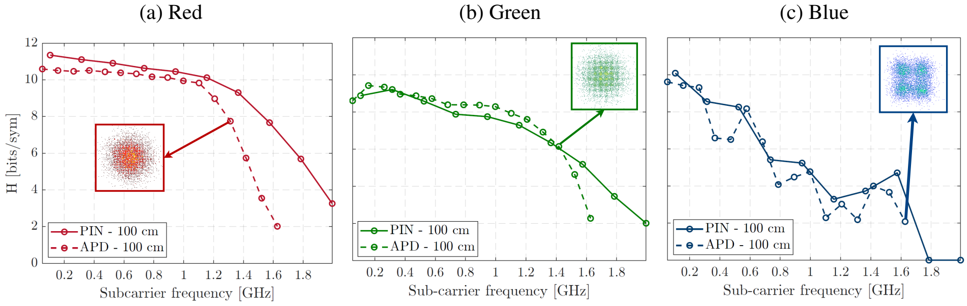

Fig. 3. Allocated entropy per subcarrier for the (a) red, (b) green and (c) blue LDs at 100 cm distance.

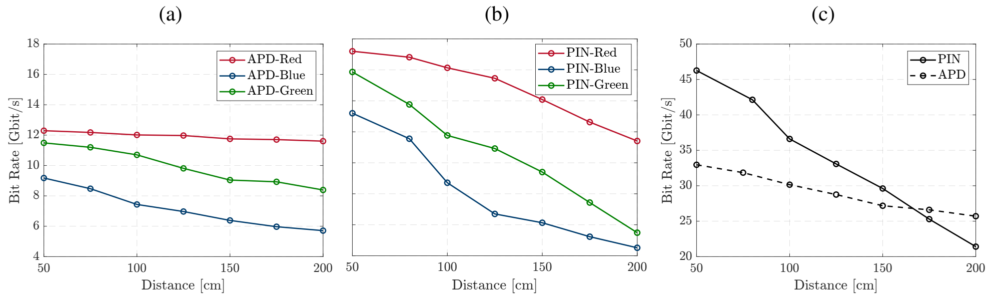

Fig. 4. Calculated bit rate as a function of the distance per color for (a) APD and (b) PIN. (c) Aggregated bit rate as a function of the distance for APD and PIN.

corresponds to the minimum value allowed by PCS. This is the main advantage of the EL method: it self-adapts to the available analog bandwidth, by simply reducing the entropy on the high frequency subcarriers down to the limit of discarding them, while allocating high entropies on the subcarriers with higher SNR. Regarding the green and blue colors, a more significant decrease is already noticed in Fig. 3 (b) and (c), which is due to the receivers being designed for wavelengths close to the red color, with blue having a more chaotic entropy assignment due to its non-flat frequency response. In Figs. 3 (a), (b) and (c), we also present some received constellations for three different entropies and it is possible to verify that for high entropy values the constellation follows a quasi-Gaussian shape, while at smaller entropies it starts to converge towards a QPSK constellation. Figs. 4 (a) and (b) show the measured bit rate as a function of the distance, which varies between 50 cm and 200 cm in 25 cm steps, for the APD and PIN, respectively. With the APD receivers, small variations are verified over distance, with bit-rate reductions of about 0.7 Gbit/s, 3 Gbit/s and 3.5 Gbit/s for the red, green and blue colors, respectively. In contrast, the PIN receivers present a more significant degradation for longer distances (5.8 Gbit/s, 10.4 Gbit/s and 8.7 Gbit/s for the red, green and blue colors, respectively). This behavior can be justified by the higher sensitivity of the APD receivers, together with the embedded automatic gain control, which allows a more constant performance over the distance. On the other hand, owing to its higher bandwidth, the PIN receivers enable to achieve significantly higher bit rates at short distances, where the sensitivity requirements are not so critical. The aggregated achievable bit rate for both receivers is depicted in Fig. 4 (c). At shorter distances, it is clear that the PIN photodiode allows to reach considerably higher bit rates (roughly 40% higher bit-rate at 50 cm). However, with increasing distance, its performance drops, making the APD a better option after 175 cm, with more than 4 Gbit/s advantage at 200 cm.

4. Conclusions

We have experimentally demonstrated a VLC system with the ability of adapting the bit rate for a wide range of communication distances. The proposed strategy is practically supported by probabilistic constellation shaping modulation and entropy loading over subcarrier multiplexing signals. A maximum bit rate of 46 Gbit/s at 50 cm is reported, which linearly decreases over the distance, down to 26 Gbit/s after 200 cm. To the best knowledge of the authors, these results correspond to the highest RGB-VLC capacity demonstrated so far resorting for a non-collimated (diffused) light source.

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