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Performance analysis and optimization of unipolar OFDM based relay-assisted visible light communications☆

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ABSTRACT

In this paper, we consider a relay-assisted visible light communication (VLC) system where an intermediate light source cooperates with the main light source. Following the IEEE 802.15.7r1 VLC reference channel model, we assume the presence of two different light sources in an office space. The first one is the ceiling light that serves as the source terminal while the second one is the desk lamp that serves as the relay terminal. Our system builds upon unipolar optical orthogonal frequency division multiplexing (U-OFDM) where the desk light performs amplify-and-forward relaying to assist the ceiling light and operates in a half-duplex mode. In addition, we consider the use of enhanced U-OFDM (eU-OFDM) which doubles the spectral efficiency of U-OFDM at the expense of additional computational complexity. We analyze the bit error rate performance of the relay-assisted VLC system building on these two OFDM types and quantify performance improvements over point-to-point (i.e., no relaying) VLC systems. In an effort to further improve system performance, we investigate optimal power allocation between source and relay terminals.

1. Introduction

Visible light communication (VLC) is an emerging technology that provides low-cost, energy efficient and high speed wireless access solutions in order to satisfy the increasing user demands. Since the range of visible light spectrum is 400–790 terahertz (THz), VLC does not interfere with radio frequency (RF) techniques and is considered as a promising complementary technique to RF-based wireless access [1]. VLC uses light emitting diodes (LEDs) [2] as data transmitters and photodetectors (PDs) as receivers. Due to the non-coherent characteristics of LEDs, complex or bipolar signals cannot be transmitted through LEDs. Therefore, intensity modulation and direct detection (IM/DD) is used in VLC to deal with these constraints. In respect to this, initial works on the field of VLC are based on simple modulation techniques such as on–off keying (OOK) and pulse position modulation (PPM) [3]. However, VLC channel is of multipath nature and targeting data rates on the order of multiple Gbits/s over a multipath VLC channel with typical delay spreads of nanoseconds requires to deal with severe intersymbol interference (ISI). This can be mitigated either via the use of time-domain equalization in single-carrier systems or multi-carrier communication techniques, particularly in the form of orthogonal frequency-division multiplexing (OFDM).

In order to satisfy the VLC constraints, several modified OFDM-based solutions have been proposed in the literature [4–8]. These include asymmetrically-clipped optical OFDM (ACO-OFDM) [4], direct current biased optical orthogonal frequency-

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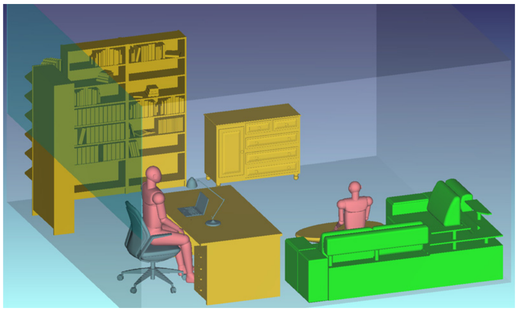

Fig. 1. Indoor room environment [11].

division multiplexing (DCO-OFDM) [5], unipolar OFDM (U-OFDM) [6], flip OFDM [7] and enhanced U-OFDM (eU-OFDM) [8]. The main objective of all these different solutions is essentially the same. They aim to generate a real and unipolar signal that drives the LED. To obtain a real-valued signal at the output of inverse discrete Fourier transform (IDFT) block, the frame structures in these solutions are rearranged with respect to Hermitian symmetry. Among these modified OFDM schemes, ACO-OFDM [4] loses 3/4 of spectral efficiency with respect to conventional OFDM transmission. Similarly, U-OFDM [6], also known as flip OFDM [7], loses more than 3/4 of spectral efficiency and, in addition, some noise enhancement occurs. On the other hand, DCO-OFDM [5] uses less than 1/2 subcarriers for data transmission. Even though DCO-OFDM technique has the maximum achievable spectral efficiency among the proposed solutions, it suffers from additional electrical DC power consumption. Alternatively, eU-OFDM [8] which doubles the spectral efficiency of U-OFDM has been recently proposed and its spectral efficiency approaches to DCO-OFDM without any DC power penalty.

The powerful combination of OFDM and relay-assisted transmission was proposed in our previous works [9,10]. Those works were built upon DCO-OFDM. In this paper, we investigate the performance of relay-assisted VLC systems building upon U-OFDM and eU-OFDM. Our contributions in this paper can be summarized as three-fold: (i) We analyse the bit-error-rate (BER) performance of relay-assisted VLC system using IEEE 802.15.7r1 reference channel model [11] and further taking into account the low pass filter characteristic of LEDs. (ii) We perform optimum power allocation (OPA) between source and relay terminals to improve the BER performance. Our results reveal that U-OFDM transmission outperforms eU-OFDM at lower modulation orders, however, the advantages of enhanced version ensues for larger constellation sizes. OPA is also shown to bring additional performance gains. (iii) We further discuss illumination aspects and related constraints for indoor room environment including relay terminal.

The rest of the paper is organized as follows. In Section 2, we briefly summarize the IEEE 802.15.7r1 channel model including non-ideal characteristics of LEDs. In Section 3, we first present the point-to-point VLC system model as a benchmark, then provide the description of the proposed relay-assisted VLC system. In Section 4, we discuss illumination aspects and related constraints. In Section 5, we provide the BER performance analysis and optimization through OPA. In Section 6, we present the numerical results and demonstrate the superiority of the proposed system. Finally, we conclude in Section 7.

Notations: $(.)^*$, $(.)^T$ and $E[.]$ denote complex conjugate, transpose and statistical averaging, respectively. $\otimes$ is convolution operator and $\delta(t)$ is the dirac impulse. $\Theta(.)$ is the probability density function of standard normal distribution. $Q(.)$ is the tail probability of standard normal distribution. $x[n] \overset{DFT}{\leftrightarrow} X[k] = \sum_{n=0}^{N-1} x[n] e^{-j2\pi nk/N}$ for $n, k \in \{0, 1, \ldots N-1\}$ denotes N-point discrete Fourier transform (DFT) pair.

2. Channel model

We use the reference channel model (see Fig. 1) adopted by IEEE 802.15.7r1 Task Group "Short Range Optical Wireless Communication" [11,12]. An office environment with the dimensions of 5 m × 5 m × 3 m is considered. The ceiling light is connected to the backbone network and the desk light which does not have any access to the backbone network acts as a relay terminal. The coordinates of the source LED, relay PD, relay LED and destination PD are respectively set to (0,0,3), (−1.26,1.28,1.5), (−1.19,1.35,1.33) and (−1.19,1.35,0.88), while the center of the ground is set to (0,0,0).

A detailed illustration of the desk light (i.e., relay terminal) is provided in Fig. 2. The relay receiver (PD) is located on the top of desk light with 45° rotation towards the source on the ceiling. The relay transmitter (LED luminary) is facing towards destination. The half viewing angle of LED is 40°. The field of view and the area of PD are respectively 85° and 1 cm^2.

The optical channel impulse response (CIR) CIR from terminal A to terminal B and corresponding channel frequency response (CFR) are respectively denoted as $c_{AB}(t)$ and $C_{AB}(f)$. CIRs for source-to-destination (S → D), source-to-relay (S → R) and relay-to-destination (R → D) are provided in [10]. In addition to the multipath propagation characteristics, the effects of LED sources should be further taken into account in the channel modelling. The frequency response of LED is assumed to be [13]

$$H_{\text{LED}}(f) = \frac{1}{1 + j(f/f_{\text{cut-off}})}, \tag{1}$$

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