Relay-Assisted OFDM Transmission for Indoor Visible Light Communication

(Invited Paper)

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***Abstract*—In this study, we investigate a relay-assisted visible light communication (VLC) system where an intermediate light source cooperates with the main light source. Specifically, we consider two light sources in an office space; one is the information source employed on the ceiling and the other one is a task light mounted on a desk. Our system builds upon DC biased optical orthogonal frequency division multiplexing (DCO-OFDM). The task light performs amplify-and-forward relaying to assist the communication and operates in half-duplex mode. We investigate the error rate performance of the proposed OFDM-based relay-assisted VLC system. Furthermore, we present joint AC and DC optimal power allocation in order to improve the performance. The DC power allocation is controlled by sharing the number of LED chips between the terminals and the AC power allocation decides the fraction of the information signal energy to be consumed at the terminals. Simulation results reveal that the VLC system performance can be improved via relay-assisted transmission and the performance gain as much as 6 dB can be achieved.**

***Index Terms*—Visible light communication, DCO-OFDM, amplify-and-forward, half-duplex, power allocation.**

I. INTRODUCTION

Visible light communication (VLC) has emerged as an alternative short range wireless data transmission technique using light emitting diodes (LEDs) [1]. It provides a low-cost and energy-efficient solution since it is able to use the existing illumination infrastructure also for data communication purposes.

VLC is based on intensity modulation direct detection (IM/DD) where an information waveform modulates the LEDs at the transmitter and a photodetector recovers the electrical signal at the receiver. To enable high speeds, recent works have also explored how multicarrier communication, particularly OFDM [2], can be used in conjunction with IM/DD. OFDM has superior features such as its resistivity in frequency selective channels, computational efficiency using FFT/IFFT techniques and robustness to the intersymbol interference and has already been in use of a number of radio frequency technologies including digital broadcasting, cellular and wireless area networks.

The design of optical OFDM (O-OFDM) requires certain modifications to take into account the non-negativity of the optical signal. This can be achieved by different methods including DC biased O-OFDM (DCO-OFDM) [2], asymmetrically clipped O-OFDM (ACO-OFDM) [3] or flip-OFDM [4]. O-OFDM has been extensively investigated in the literature (see [5-7] and the references therein), but the current results are mainly limited to direct (point-to-point) transmission.

In this paper, we consider DC biased O-OFDM and investigate how cooperation between light sources can improve the error rate performance. In our proposed scheme, a task light, such as a desk lamp, acts as an intermediate relaying terminal. Earlier works on relay-assisted (cooperative) VLC systems include [8-11]. In [8], an LED-to-LED multi-hop VLC system for toys is demonstrated. In [9], a multi-user message forwarding protocol for VLC channels is proposed. In the protocol, the message is forwarded through other users to the destination when the destination is shadowed/blocked. In an experimental study [10], an audio signal is successfully delivered to the destination over two intermediate relay terminals. In [11], multi-hop inter-vehicular message forwarding is considered for VLC and the performance is evaluated for the successful package delivery percentage depending on the average inter-vehicle distance. It should be emphasized that none of these works are OFDM-based. Furthermore, they do not take into account the illumination role of VLC systems. In this work, we present an extensive performance evaluation and optimization of relay-assisted O-OFDM VLC systems under lighting constraints.

We consider an office space with two light sources. One of them is placed at the ceiling to provide ambient light to the environment and the other one is used for task lighting. The task lights are commonly used in office spaces and they give each user to control his/her own lighting, reduce the glare, lower the eye strain and increase the overall satisfaction from lighting [12]. They are also preferred for energy consumption reasons. In the considered scenario, the light source at the ceiling is the main information source (source terminal). The task light acts as a relay and performs amplify-and-forward (AF) relaying operation to assist the communication. We present joint AC and DC optimal power allocation in order to improve the BER performance of the half-duplex cooperative transmission. The total consumed DC power in the system depends on the total number of LED chips in the

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environment and allocating the LEDs between the source and relay terminals will give control over the DC power allocation. The total AC power consumed in the system is the electrical OFDM signal power which is to be shared between the source and relay terminals for performance improvement.

The DC power allocation affects not only communication performance but also illumination performance of the system. For task lighting, Illumination Engineering Society of North America (IES) suggests that the ratio of luminance of the task surface to the remote areas in the room should be less than 10 [13]. Similarly, EN 12464-1 recommends that the luminance ratio of the task surface to the adjacent walls should be less than 5 [14]. These ratios limit the optical power of the relay terminal and put constraint on the DC power allocation. The AC power allocation will affect the received electrical signal level at the destination and accordingly the communication performance.

This paper is organized as follows: Section II briefly reviews the DCO-OFDM scheme which is the basis of relay-assisted VLC system under consideration. Section III introduces a realistic VLC channel model to be used in our simulations. Dual-hop VLC transmission is described in Section IV. In Section V, numerical results for power allocation and simulated error rate performance are presented. Finally, the paper is concluded in Section VI.

II. OPTICAL OFDM

A transmission block diagram for O-OFDM without any intermediate terminal is given in Fig. 1 [2]. The input bit stream is first mapped to the complex symbols according to the chosen modulation scheme. Then, the input vector frame **X** to the N-IFFT block is utilized to form the discrete intensity waveform $x[n]$. One important constraint in optical communication is that the intensity waveform $x[n]$ should be real and non-negative. However, the electrical OFDM signal is usually both complex and bipolar. It is known that when the complex symbol vector **X** satisfies Hermittian symmetry, the IFFT output waveform **x** becomes real. The Hermittian symmetry can be reached by setting the input vector **X** such that $X[k] = X[N-k]^*$ for $0 < k < N/2$ and when $X[0]$ and $X[N/2]$ are set to zero. $*$ denotes complex conjugation.

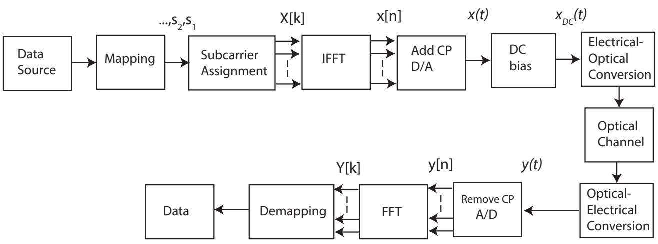

Fig. 1. O-OFDM transmission block diagram.

For DCO-OFDM, N/2-1 symbols are structured in the frame as

$$\mathbf{X} = [0 \ s_1 \ s_2 \dots s_{N/2-1} \ 0 \ s^*_{N/2-1} \cdots s^*_2 \ s^*_1]. \quad (1)$$

The output of the IFFT is the time vector to be emitted by the LEDs and can be obtained as

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j2\pi nk/N}. \quad (2)$$

A cyclic prefix is appended at the beginning of $x[n]$ in order to suppress the intersymbol interference caused by the multipath effects.

In the baseband form, the intensity waveform $x(t)$ becomes

$$x(t) = \sum_{n=0}^{P-1} x[n] p(t - nT_s) \quad (3)$$

where $p(t)$ is the impulse response of the pulse shaping filter, T_s is the sampling interval and P is the total length of the OFDM symbol with appended cyclic prefix where $P = N + N_g$. $x(t)$ is biased with a DC voltage before modulating the LEDs. Due to the limited dynamic range of LEDs, the amplitude levels of $x_{DC}(t)$ exceeding the dynamic range are usually clipped which introduces clipping noise to the transmission.

III. VLC CHANNEL MODEL

A. *Physical Room Model with Task Lighting*

We consider a typical office space with dimensions of 5x5x3 m. As illustrated in Fig. 2, we consider two light sources in the room; the one at the ceiling provides ambient light and the other one is for task lighting. In the considered scenario, both light sources are emitting information in a cooperative manner to deliver information to the destination terminal.

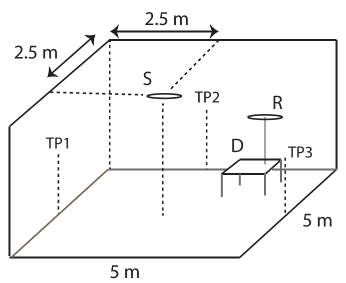

Fig. 2. Physical room model.

We assume that the task light is mounted on a desk of height 0.7m and the detector of the task light is directed towards the source. Reflection coefficients of the walls, ceiling, floor and desk surface are 0.8, 0.8, 0.3 and 0.8, respectvily [12][15]. The locations of the source, relay and destination terminals are chosen as (0,0,3), (2.0,1.8,2.0) and (1.7,1.9,0.7), respectively.

The emitted optical powers from the source and relay terminals will affect both communication and lighting performance of the cooperative system. The task light should provide comfortable lighting to the user; it should not shine strongly and also they are not recommended in darkened rooms. In an office space, it is recommended that the luminance ratio of the task surface to the adjacent walls within the field of vision should be less than 5 [14].

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Controlling the brightness of the source and relay terminals would require adjusting the DC biasing level at each terminal which affects the OFDM performance [16]. Instead, we define the parameter K_L to control the fraction of LED chips to be employed at the terminals. Assuming the total number of LED chips is L_T, the source terminal employs $L_T K_L$ chips and the relay terminal employs $L_T(1-K_L)$ chips.

The luminance L (cd/m^2) is related to the illuminance as L = $E_l \rho / \pi$, where ρ is the reflectivity index (%) and E_l is the illuminance (lux) on the surface. Illuminance defines the light falling on a surface and it is defined as luminous flux per unit area. The horizontal and vertical illuminance are given as

$$E_h = I(0)cos^m(\theta)cos(\psi)/d^2, \tag{4}$$

$$E_v = I(0)cos^m(\theta)sin(\psi)/d^2 \tag{5}$$

where $I(0)$ is the center luminous intensity (cd), θ is the angle of irradiance, ψ is the angle of incidence, d is the distance between the light source and the surface and m is the Lambertian index.

We have considered three test points on the surrounding walls and obtained the luminance ratios between the task and the test points. The location of the test points are given in Fig. 2. The reflection index of the task surface is set to 0.80. Lambertian index is taken as 1.56. Fig. 3 gives the luminance ratios between the task and the test points for different K_L. It is seen that when K_L is 0.77, the luminance ratio of 5 is achieved.

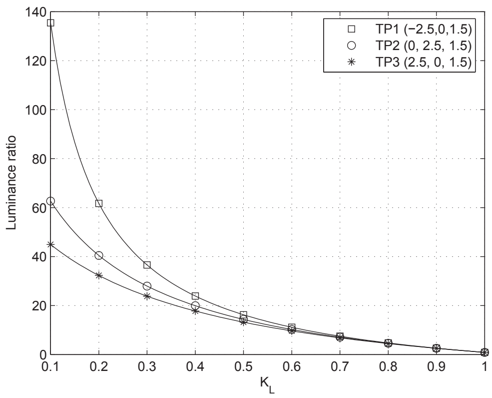

Fig. 3. Luminance ratio between the task and the test points versus K_L.

B. Channel Model based on Ray Tracing

Channel impulse responses are obtained through ray tracing simulations with Zemax® software [17]. The areas of detectors at the both relay and destination terminals are taken as 1 cm^2 and the field-of-view (FOV)'s are set to 85^o. In the simulations, 10^6 number of rays have been traced per light source with Lambertian emission pattern.

Figures 4(a), (b) and (c) illustrate the channel impulse responses $c_{sr}(t)$, $c_{sd}(t)$ and $c_{rd}(t)$ obtained from the simulations for the source-to-relay (S→R), source-to-destination (S→D) and relay-to-destination (R→D) links, respectively. The channel impulse responses are given with respect to 1W transmitted optical power.

IV. RELAY-ASSISTED VLC TRANSMISSION

In this section, we first provide the non-cooperative system model which will be used as a benchmark. Then, we introduce details on the proposed relay-assisted system.

A. Non-Cooperative (Direct) Transmission

In direct transmission, we assume only the S→D link with no intermediate relay terminal. Assume that an OFDM waveform $x_S(t)$ is emitted with unit energy from the source. When the total amount of available energy is E, the received electrical signal at the receiver is given by

$$y(t) = rg\sqrt{E}x_S(t) \otimes h_{sd}(t) + v(t) \tag{6}$$

where $\otimes$ is the convolution operation, r is the responsivity (W/A) of the photo-detector, g is the gain of an LED (W/A) and $h_{sd}(t)$ is the composite channel response for S→D with unit energy $\int h_{sd}(t)^2 dt$ = 1. Here, $v(t)$ is the white Gaussian noise term with zero mean and variance of σ_n^2 which includes the thermal noise and the shot noise due to the ambient light. In this work, we assume rg = 1 for brevity of presentation.

The multipath channel $h_{sd}(t)$ in electrical baseband form can be written as $h_{sd}(t)$ = $p(t) \otimes c_{sd}(t) \otimes p(-t)$. The channel gain per subcarrier $H_{sd}[k]$ can be written as

$$H_{sd}[k] = \sum_{n=0}^{P-1} h_{sd}[n] e^{-j2\pi nk/N}. \tag{7}$$

where $h_{sd}[n]$ = $h_{sd}(nT_s)$. After performing FFT at the receiver, the received symbols can be obtained as

$$Y[k] = \sqrt{E}X[k]H_{sd}[k] + W[k]. \tag{8}$$

The transmitted data symbols $X[k]$ can be recovered using single tap equalizer, $\hat{X}[k]$ = $Y[k]/H[k]$. Assuming the amplitude of the intensity waveform is in the dynamic range of the LEDs, the average electrical SNR per subcarrier for the direct transmission becomes γ = E/σ_n^2.

B. Relay-assisted Transmission

Consider a three-node dual-hop communication scenario where the source terminal communicates with the destination though a relay terminal. In the considered scenario, the cooperation is performed in half-duplex mode with two phases. In the broadcasting phase, the source terminal transmits the information to both the relay and destination terminals. In the relaying phase, the source terminal remains silent and the relay terminal forwards the broadcasted message to the destination terminal.

The available average energy to be used in two cooperation phases is set to $2E$. We define an optimization parameter K_E which controls the fraction of the electrical energy to be shared between the terminals. In the set up, all the LED chips at the source and relay terminals are biased with the

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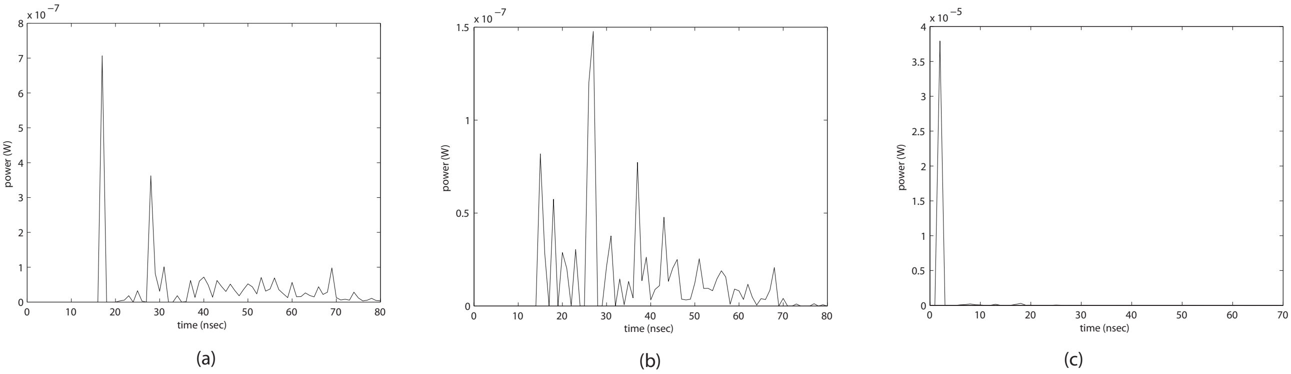

Fig. 4. The channel impulse responses for the (a) S→R link $c_{sr}(t)$ (b) S→D link $c_{sd}(t)$ (c) R→D link $c_{rd}(t)$.

same DC value. The optimization parameter K_L controls the fraction of the total number of LED chips which is to be shared between the source and relay terminals. This will make the total consumed AC and DC powers the same as in non-cooperative transmission. Furthermore, in order to incorporate the effects of room geometry, assuming the channel gain for the S→D link is unity, we consider relative gains G_{rd} and G_{sr} for the R→D and S→R links, respectively.

Let $x_S(t)$ denote the transmitted OFDM signal (before the addition of DC term) from the source with unit energy. The electrical signal received by the destination and relay terminals in the first phase can be written as,

$$y_{D1}(t) = K_L\sqrt{2EK_E}x_S(t) \otimes h_{sd}(t) + v_{D1}(t) \qquad (9)$$

$$y_R(t) = K_L\sqrt{2EK_E G_{sr}}x_S(t) \otimes h_{sr}(t) + v_R(t) \qquad (10)$$

where $v_{D1}(t)$ and $v_R(t)$ are the additive white Gaussian noise terms with zero mean and variance of σ_n^2.

In the AF mode, the relay terminal simply performs a scaling operation on the received signal. We assume the amplification is performed in electrical domain where the relay node first removes the DC component in the received signal and then scales the energy of the intensity waveform to $2E(1-K_E)$. Finally, the relay node adds a DC term to the information signal and modulates its LEDs. The amplification gain at the relay terminal in electrical domain is

$$G_A = \sqrt{\frac{2E(1-K_E)}{2EK_E K_L^2 G_{sr} + \sigma_n^2}}. \qquad (11)$$

The signal received by the destination terminal in the second phase is given by

$$y_{D2}(t) = (1-K_L)G_A\sqrt{G_{rd}}y_R(t) \otimes h_{rd}(t) + v_{D2}(t). \quad (12)$$

Then, the destination performs maximal-ratio-combining (MRC) to combine (9) and (12). The SNR at the output of MRC is obtained as

$$\mathrm{SNR} = 2K_E K_L^2\gamma + \frac{K_L^2 2\gamma K_E G_{sr}}{\frac{2\gamma K_E K_L^2 G_{sr}+1}{(1-K_L)^2 G_{rd} 2\gamma(1-K_E)} + 1} \qquad (13)$$

where γ is E/σ_n^2.

V. SIMULATION RESULTS

In this section, we present Monte Carlo simulation results to evaluate the performance of relay-assisted VLC system under consideration. We also present our results on optimized power allocation for performance improvements. In the simulations, the number of subcarriers N is 64, the number of guard band subcarriers N_g is 2 and the transmission bandwidth is 20 MHz. The pulse shaping filter is taken as a truncated sinc pulse of $2T_s$ support where T_s is 50 nsec. Considering BPSK for the direct transmission and 4-PSK for the relay-assisted transmission, the data rate becomes 9.68 Mbps for DCO-OFDM. With the considered OFDM parameters and the channel impulse responses given in Fig. 4, the normalized geometric channel gains are obtained as G_{sr} = 8.5 dB and G_{rd} = 36.7 dB.

A. Optimized AC/DC Power Allocation

The BER for 4-PSK over AWGN channels is Q($\sqrt{\mathrm{SNR}}$). Using (13), the optimum K_L and K_E values which minimize the BER are obtained numerically. Table I lists the optimum K_L and K_E values for different SNRs in the direct transmission. If we do not put any constraint in task lighting in terms of luminance ratio, the optimum K_E and K_L values are both around 0.84. This value of K_L corresponds to luminance ratio of around 4 which is in the recommended range. When the luminance ratio is increased to 5 (K_L is 0.77), the optimum K_E value suggests using 92% of the total AC power at the source and the remaining power at the relay terminal.

B. BER Results

In Fig. 5, the BER curves are demonstrated for the direct and relay-assisted transmission with equal and optimum power allocations. In the equal power allocation (EPA), both the AC and DC powers are equally shared between the source and relay terminals, (K_L = 0.5, K_E = 0.5). Whereas, in the optimum power allocation (OPA), the AC and DC powers are shared according to the Table I. No lighting constraints are considered in this figure. While no performance improvement is observed

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TABLE I
OPTIMUM K_L AND K_E FOR RELAY ASSISTED DCO-OFDM

SNR (dB)	w/o Lighting Constraint		with Lighting Constraint	
	K_L	K_E	K_L	K_E
0	0.8389	0.8388	0.7700	0.9231
2	0.8399	0.8400	0.7700	0.9272
4	0.8406	0.8407	0.7700	0.9301
6	0.8411	0.8410	0.7700	0.9320
8	0.8414	0.8413	0.7700	0.9332
10	0.8415	0.8416	0.7700	0.9340

with EPA, OPA provides performance improvement of 6 dB for targeted BER of 10^{-5}. It should be also emphasized that EPA suggests to set K_L equal to 0.5 indicating that the task surface is around 15 times more brighter than the surroundings which is not recommended for comfortable lighting.

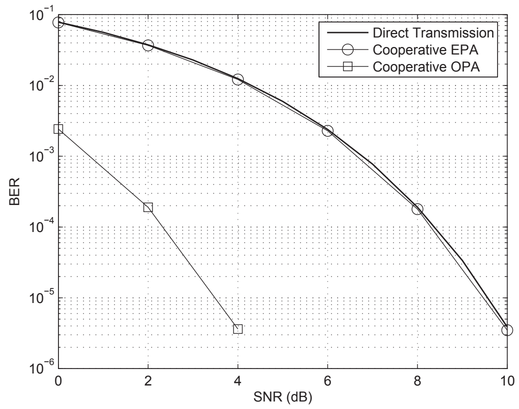

Fig. 5. BER for relay-assisted VLC schemes with EPA and OPA. No lighting constraint is considered.

In Fig. 6, we further take into account lighting constraints and set the luminance ratio to 5 and present BER curves for the direct and relay-assisted transmissions with equal and optimum power allocations. In this case, OPA (K_L = 0.77, K_E = 0.92) outperforms EPA (K_L = 0.77, K_E = 0.5) with 1.9 dB gain. Performance gain of 5.7 dB at a targeted BER = 10^{-5} is observed with OPA with respect to the direct transmission.

VI. CONCLUSION

In this work, we have investigated relay-assisted transmission in the context of indoor VLC systems. Particularly, we have considered an OFDM-based VLC system where a task light acts as a relay to the main ceiling light source. We have investigated joint AC and DC optimal power allocation in order to improve the BER performance of the half-duplex cooperative transmission. Our results have shown that up to 6 dB performance improvements can be obtained through optimal power allocation.

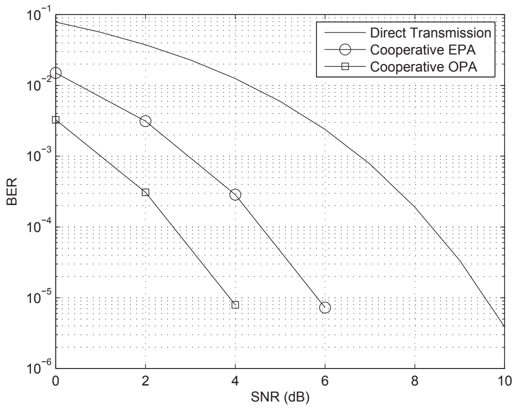

Fig. 6. BER for relay-assisted VLC schemes with EPA and OPA with lighting constraints.

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