Analysis of DCO-OFDM for Indoor Visible Light Communications

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Abstract. A novel orthogonal frequency division multiplexing (OFDM) technique called DC-biased optical OFDM (DCO-OFDM) as-applied to indoor visible light communications (VLC) systems was analysed in this study. Line-of-sight (LOS) and non-LOS (NLOS) models were assumed and the luminance intensity and multipath dispersion of a single reflection were measured for indoor LOS and NLOS models; 1-dB and 3-dB DC biases were applied to DCO-OFDM with 4-, 64-, or 128-QAMs for BER analysis, respectively. The quantity of lighting equipment appropriate for communication based on the model room was determined, as well as the optimal number of sources dependent on illuminance, mean density of pedestrians, room model. The results showed that as M and DC bias values increase, SNR grows excessively (about 2.5 dB) in the LOS model. Reflection, additionally, has a severe impact on BER in NLOS conditions (nearly $10^{-3}$) regardless of M or DC bias value. Compared to the LOS model, the NLOS model requires a loss of about 12 dB of DCO-OFDM SNR.

1. Introduction

The general lack of spectral resources in the radio frequency (RF) region has sparked considerable research interest in the field of visible light communication systems (VLCs) for indoor application, as well as notable advancements in our understanding of visible light spectra [1]. VLCs can be implemented with white light emitting diodes (LEDs) as transmitters and photodiodes (PDs) as detectors [2], however, such systems show limited communication capacity due to the LED bandwidth (about 10 MHz) [3].

The advantages and limitations of different modulation techniques for underwater optical wireless communication were reported in a previous study based on modeling and simulation [4]. In order to meet the intensity modulation and direct detection (IM/DD) requirements of VLCs, the electric OFDM signal must be real-valued and unipolar in the input direction of the LED; this differs from the traditional OFDM in terms of radio frequency [5]. There are a few specialized ODFM methods which account for this, including DC-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), and Flip-OFDM, in which Hermitian symmetry is imposed on the subcarriers in the frequency domain in order to generate real-valued signals after inverse fast Fourier transform (IFFT) [6]. Because the DC-bias in DCO-OFDM is harnessed for illumination purposes, DCO-OFDM can be used to achieve a high spectral efficiency in VLCs [7]. For ACO-OFDM [8], the data is carried
only on the odd frequency OFDM subcarriers while the even subcarriers form a bias signal that ensures that the transmitted OFDM signal meets the non-negativity requirement [9]. In ADO-OFDM, ACO-OFDM is used on the odd subcarriers and DCO-OFDM is used on the even subcarriers. In this paper, we will demonstrate that this setup represents a combination of the advantages of both ACO-OFDM and DCO-OFDM: Because all of the subcarriers are used to carry data, the bandwidth efficiency is better than ACO-OFDM; and because the more power-efficient ACO-OFDM (for all but the largest constellations [10]) is used on half of the subcarriers, the overall optical power efficiency is better than that of DCO-OFDM. The ACO-OFDM component is demodulated as in a conventional ACO-OFDM receiver while the DCO-OFDM component is demodulated using an interference cancellation method. In this study, we analyzed DCO-OFDM in an NLOS model to take advantage of easily configurable DC components and the enhanced spectral efficiency compared to other methods [8].

The remainder of this paper is organized as follows. Section 2 presents an NLOS model of an indoor VLC system. In Section 3, the DCO-OFDM is defined and the simulation results of DCO-OFDM for NLOS are reported. Section 4 provides a brief summary and conclusion.

2. NLOS model of indoor VLC system

2.1. LED model

We set up a 2×2 LED array model consisting of arrays A (5m, 1m, 3m), B (1m, 1m, 3m), C (1m, 5m, 3m), and D (5m, 5m, 3m), in a typical 6×6×3 m³ room. Each LED array contains 8×8 LEDs, as shown in Figure 1(a). A zoomed plot from one of the arrays in this figure clearly shows the uniformly distributed LEDs. Figure 1(b) shows a simulation of the LED model drawn according to the Lambert radiation equation.

As shown in Figure 1, the minimum and maximum values of illumination were 850 lx and 1375 lx, respectively, satisfying ISO requirements (and thus satisfying indoor VLC system requirements.) Figure 1(b) shows the distribution of horizontal illuminance, based on a numerical analysis at the optical receiver on one of the desks. We simulated 10-bounce horizontal illuminance and set the differential area of the reflector surface to 12.5×12.5 cm². Sufficient illuminance, 300 to 1500 lx (according to ISO), was obtained throughout the entire room – so in effect, the manner in which we set the lighting equipment provides acceptable illuminance according to relevant standards and good practices. To alleviate the shadowing problem, we assumed a diverse system that utilizes the multiple lighting sources. Figure 1(b) shows the received optical power at the receiver across the room.
2.2. NLOS model of indoor VLC system

We carefully modeled the VLC channel in order to evaluate the channel characteristic differences of this transmitter simplification. The impulse response is typically used to characterize the VLC channel, and the model contains a direct line-of-sight (LOS) path and reflected paths.

\[ h_E(t, S, R) = \sum_{k=0}^{\infty} h_E^{(k)}(t, S, R) \]

where \( h_E^{(k)}(t, S, R) \) is an impulse response after \( k \) reflections:

\[ h_E^{(k)}(t, S, R) \approx \sum_{i \in \text{wall}} \rho_i \cdot h_E^{(k-1)}(t, S, e'_i) \otimes h_E^{(0)}(t, e'_i, e'_i) \]

where \( \rho_i \) is reflectance (plaster wall: 0.8), \( S \) is the source, \( R \) is the detector, \( E \) is the environment, and \( e'_i \) and \( e'_i \) are the paths from the source to the reflecting surface and from the reflector to the detector, respectively. In the case of a single LED, the impulse response of \( S \) is introduced to the four walls (100×100 units) after one reflection, which is expressed as follows:

\[ h^{(0)}(t, S, R) = \sum_{i \in \text{wall}} \rho_i \cdot h^{(0)}(t, S, e'_i) \otimes h^{(0)}(t, e'_i, e'_i) \]

\[ h^{(1)}(t, S, R) = \sum_{i \in \text{wall}} \rho_i \cdot (h^{(0)}(t, S, e'_i) \otimes h^{(0)}(t, e'_i, e'_i)) \]

\[ h^{(2)}(t, S, R) = \sum_{i \in \text{wall}} \rho_i \cdot (h^{(0)}(t, S, e'_i) \otimes (h^{(0)}(t, e'_i, e'_i) \otimes h^{(0)}(t, e'_i, e'_i))) \]

\[ h^{(3)}(t, S, R) = \sum_{i \in \text{wall}} \rho_i \cdot (h^{(0)}(t, S, e'_i) \otimes (h^{(0)}(t, e'_i, e'_i) \otimes (h^{(0)}(t, e'_i, e'_i) \otimes h^{(0)}(t, e'_i, e'_i)))) \]

where \( d_{SI} \) is the coefficient from \( S \) to the i-th unit on the wall, and \( d_{IR} \) is the coefficient from the i-th unit to the reflector.

The simulation results for received optical power after a single reflection are shown in Figure 2(b). The received power of LOS was 63.6 μW, however, the received power from the reflected paths was smaller than the LOS and dependent on path length. As shown in Figure 2(b), the first peak consists mainly of the direct path from the nearest source while the next peak consists mainly of the direct paths from secondary sources. There were four peaks which passed \( h^{(3)}(t, S, R) \) through Paths 1-4 of the reflected paths, respectively (Figure 2(b)). Because Path 4 was so lengthy, \( h_4 \) was close to zero. Transmission delay for all paths was between 8 ns and 17 ns. Simulation results for the NLOS model are listed in Table 1. We used the data set to obtain the amplitude-frequency response characteristics of the single-reflection situation that we simulated, and observed a deep fade at 0.18 MHz as shown in Figure 3.
Table 1. Simulated NLOS mode.

| Received power [μW] | Delay [ns] | Decay [dB] |
|---------------------|-----------|-----------|
| h1                  | 0.790     | 9.0       | 43.0      |
| h2                  | 0.321     | 11.0      | 8.9       |
| h3                  | 0.170     | 12.5      | 6.3       |

Figure 3. Amplitude-frequency response of NLOS.

3. DCO-OFDM of NLOS model

3.1. DCO-OFDM Scheme

A block diagram of the DCO-OFDM scheme is shown in Figure 4, where the electrical and optical links are marked with different arrows. The input data was divided into a number of parallel data streams denoted by X_i=[X_0,X_1,X_2,...,X_i] and mapped by M-QAM constellation X_i^*=Ae^{jθ}. After employing IFFT, plus cyclic prefix (CP) and string conversion, X_i^* becomes S(k). Signal S(k) then changes to S(t) after D/A conversion. The bipolar time signal S(t) must be converted to unipolarity in order to match the LED modulation, so in the DCO-OFDM scheme, S(t) was converted to the unipolar time signal S'(t) by adding a DC bias and clipping the remaining negative domain. Finally, the time domain signal x(t) is given by:

\[
x(t) = x_i(t) + d_0 = \text{Re}\left\{\sum_{k=0}^{N-1} X_k e^{-ij2\pi k T} \right\} + d_0, \quad 0 \leq t < T
\]

where N is the number of points on the IFFT and X_n is the component of signal X. The d_0 variable is related to the DC bias, denoted by DC_{dB}, and is expressed as DC_{dB}=20\times\log_{10}(E(x)+d_0)/E(x)]).

The BER calculation results of OFDM in the AWGN channel and the multipath fading Rayleigh channel can be obtained through equation (5) and (6), respectively:

\[
P_e = \frac{2(M-1)}{M \log_2 M} \left( 1 - \frac{\log_2 M}{M^2 - 1} \right) \text{ AWGN}
\]
\[ P_e = M^{-1} M \log_{10} M - Q(1 - \frac{3\gamma \log_{10} M / (M^2 - 1)}{3\gamma \log_{10} M / (M^2 - 1) + 1}) \text{ Rayleigh} \]

where \( \gamma = \frac{E_b}{N_0} \) and \( Q = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{\infty} e^{-t^2/2} dt \).

In the same manner, the BER of the DCO-OFDM for a LOS VLC system can be simulated (and the AWGN channel taken into account) based on the parameters listed in Table 1I. Figure 5 shows where as DC\(_{\text{dB}} \) and M of the M-QAM increased, BER performance gradually declined.

| Subcarrier modulation method | 4, 64, 128-QAM |
|-----------------------------|----------------|
| Number of IFFT points N     | 64             |
| Number of CP points         | 16             |
| Number of virtual carriers  | 16             |
| Number of OFDM symbols      | 3              |
| (one frame)                 |                |
| Number of training symbols  | 2              |
| (one frame)                 |                |
| Eb/N0                       | [0:2:20]       |
| DC\(_{\text{dB}}\)          | 0, 1, 3 dB     |

3.2. Simulation Results of DCO-OFDM for NLOS

Figure 6 shows the FFT signal waveform the DCO-OFDM signal received by the NLOS model after one reflection. To determine the BER performance of DCO-OFDM in the LOS VLC system, we set parameters 4-QAM and DC\(_{\text{dB}}\)=3 dB to create balance between communication capacity and BER, then analyzed the amplitude-frequency response while the system received a waveform with a distortion at 0.18 MHz. For a more detailed BER analysis of DCO-OFDM for the NLOS VLC system, we evaluated all parameters in Table 1I as shown in Figure 7. The NLOS channel weakened the DCO-OFDM signal severely – BER was almost \( 10^{-3} \) regardless of the M or DC\(_{\text{dB}}\) values. Compared to the LOS model, the NLOS model requires a loss of about 12 dB of SNR of DCO-OFDM.
4. Conclusion

DCO-OFDM performed well in the LOS VLC system, effectively inhibiting ISI and improving SNR gain 6 dB over the Rayleigh conditions, however, as M and DC dB values increased, the BER became increasingly problematic. Simulation results of the 4-QAM-DCO-OFDM were optimal compared to other parameters. When DC dB=0dB, BER was reduced to $10^{-4}$ when SNR>8 dB, but in order to obtain a positive signal, the system needed an additional DC bias. Thus, when DC dB=1 dB, BER dropped to $10^{-4}$, requiring considerable power gain and pushing SNR beyond 12 dB. Basically, large M and bias appeared to benefit communication capacity though they greatly reduced the reliability of the system or came at the expense of a substantial need for additional transmission power. This was more obvious in the NLOS VLC system, where reflection had a severe impact on BER (BER>$10^{-3}$, regardless of SNR).

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