Dimming Consideration for OFDM-Based Visible Light Communications

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Abstract— In the field of indoor wireless networks, visible light communications would be contributing a vital role in the future. This paper investigates the performances of data transmissions using visible light based on unipolar orthogonal frequency division multiplexing (OFDM) and discusses possible approach for light dimming. Asymmetrically clipped optical OFDM (ACO-OFDM) is considered as a unipolar modulation scheme for intensity modulation with direct detection (IM/DD) on which visible light communications is based. This modulation can incorporate light dimming while not corrupting the communication link since, compared to the traditional DC biased optical OFDM (DCO-OFDM), ACO-OFDM noise clipping component does not fall on data carrying subcarrier. To create more dimming levels pulse width modulation (PWM) is proposed to be used in conjunction with ACO-OFDM.

Keywords: Orthogonal frequency division multiplexing (OFDM), light emitting diode (LED), signal clipping, visible light communication.

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1. Introduction

Visible light communications (VLC) uses visible light in the wavelength band of 380-750 nm for establishing wireless communications. The use of light emitting diodes (LEDs) would be the most feasible since LEDs offer long life time, high tolerance to humidity and lower power consumption. VLC transmits data by intensity modulating optical sources, such as LEDs, faster than the persistence of the human eye [1–3].

The brightness of LED light may need to be controlled depending on time and situation as its main function is illumination. A dimmable light offers both energy saving and comfort to the eye. VLC over dimmable light would be suitable at places such as airplanes and hospitals where radio transmission is often limited or forbidden and adjusting the brightness of LED light provides flexibility to the comfort of passengers and patients accordingly.

One VLC standardization is published by the IEEE Standards Association [4]. Generally, VLC uses intensity modulation with a direct detection (IM/DD) scheme, which uses the intensity of light to transmit data. For VLC, a number of modulation methods have been proposed, such as on-off keying (OOK), pulse position modulation (PPM) and pulse width modulation (PWM). Among them OOK and PPM are the modulation schemes considered by the IEEE 802.15 standard group. To support illumination with dimming control and communication simultaneously, VLC can use PPM for communication and PWM for dimming control. However, the main drawback of these modulation schemes is that the data rate is limited by the bandwidth of LEDs and the dispersive nature of VLC channels.

To overcome the limitation of data rates, a modulation scheme called asymmetrically clipped optical OFDM (ACO-OFDM) has been proposed [5] and found to be more power efficient than the traditional DC biased optical OFDM (DCO-OFDM) [6]. For data transmissions with IM/DD, the transmitted signal needs to be unipolar, i.e., real and nonnegative. Hence OFDM with IM/DD is commonly referred to as unipolar OFDM. This unipolar constraint makes optical OFDM systems differ from conventional OFDM using bipolar signals.

Dimming is an essential functionality of modern lighting systems. In the case of LEDs, PWM seems to constitute the most effective means of accurately controlling LED illumination without incurring color rendering of the emitted light [7]. In PWM dimming, the brightness of the LED is controlled by square pulse modulation of the driving current and by adjusting the duty cycle of the pulse train. Dimming in the physical layer is achieved by using PWM so that both brightness control and wireless communications can be achieved at the same time.

2. DCO-OFDM with DC Bias Addition and Signal Clipping

In DCO-OFDM the bipolar OFDM signal is converted to a unipolar signal by adding a DC bias. Since OFDM signal values have a Gaussian distribution, if it is to be unipolar, the negative signal values must first be clipped. This adds a clipping noise component, which increases as the DC bias decrease.

When using large QAM constellations, the receiver requires a high signal-to-noise ratio (SNR). Hence clipping noise must be accordingly low. The DC bias must increase which in turn increases the optical power. This could avert the operation of LEDs under the linear region. Moreover, high peak-to-average power ratios normally observed in OFDM can lead to even higher DC biases to avoid excessive signal clipping.

3. DCO-OFDM with PWM for Dimming Control

The performance of a visible-light communication system combining PWM for dimming was investigated in [7]. If the signal undergoes PWM along with the clipping noise component, there may be significant distortion which affects BER. Hence, dimming control using PWM and DCO-OFDM may suffer from a noise problem.

4. ACO-OFDM with Signal Clipping

In ACO-OFDM the bipolar OFDM signal generated by the transmitter is made unipolar by clipping the signal at zero to yield the transmitted signal.

$$x_c(t) = \left\{ \begin{array}{cc} x(t) \ if \ x(t) > 0 \\ 0 \quad ,otherwise \end{array} \right\} \qquad (1)$$

where $x(t)$ is the unclipped OFDM signal.

If only the odd subcarriers are modulated, all of the intermodulation caused by clipping falls on the even subcarriers and does not affect the data-carrying odd subcarriers [5]. The odd subcarrier condition and the Hermitian symmetry together mean that there are only $N/4$ independent complex input values for the N-point IFFT of each OFDM symbol.

In ACO-OFDM only half of the electrical power is used on the odd data-carrying subcarriers. The other half is used on the even subcarriers to make ACO-OFDM signal unipolar [5].
For comparison, in DCO-OFDM, the bipolar OFDM signal is converted to a unipolar signal by adding a DC bias, denoted by B_{DC}. In practice because an OFDM signal has a Gaussian distribution, if B_{DC} is not excessive, the negative signal value must be clipped. This adds a clipping noise component, denoted by Noc, which increases as B_{DC} decreases and affects all subcarriers. Hence the transmitted signal is given by

$$x(t) = x_0(t) + B_{DC} + N\text{oc} \qquad (2)$$

Hence in considering ACO-OFDM, the clipping noise problem can be averted.
It is worth noting that, for DCO-OFDM, the DC bias value depends on the QAM constellation size used for data transmissions. The larger the constellation, the higher the DC bias value. Therefore B_{DC} cannot be fixed for all constellation sizes under DCO-OFDM. In ACO-OFDM the same system configuration is applicable for all constellation sizes, providing yet another benefit over DCO-OFDM.

5. ACO-OFDM with PWM for Dimming Control

In [7], when the OFDM and PWM signals are combined, the current y(t) driving the LED is the product of the OFDM and PWM waveforms, i.e.,

$$y(t) = x(t) \times p_{PWM}(t) \qquad (3)$$

where $p_{PWM}(t)$ is the periodic PWM waveform whose period is the same as the OFDM pulse duration. This combination of PWM and OFDM is referred to as PWM-OFDM modulation [7]. The ratio R of the OFDM pulse duration over the PWM period should not be made smaller than unity.
With various benefits of ACO-OFDM over DCO-OFDM as pointed out in the previous section, it is proposed that a combination of ACO-OFDM with PWM for dimming control be investigated.

6.Transmission System Models DCO-OFDM System Model

Consider a DCO-OFDM transmission system with N subcarriers. In order to obtain a continuous-time analog signal to be transmitted over the physical channel the signal values are passed through a digital-to-analog converter (D/A) using a unit-norm rectangular pulse p(t) given by

$$p(t) = \begin{cases} 1 \ / \ T, t \in [0,T) \\ 0, otherwise \end{cases} \qquad (4)$$

where T is the pulse period. This pulse period is related to the transmission rate R (in bps) for DCO-OFDM by

$$T_{DCO} = \frac{2 \ (N/2-1) \ log_2 M}{R(N + N_{CP})} \qquad (5)$$

where M denotes that M×M QAM is used, and N_{CP} is the length of the cycle prefix of OFDM.

Transmit Optical Power of DCO-OFDM

In [8], it is pointed out that the OFDM signal value s_n can be well approximated as being zero-mean Gaussian. The variance of s_n, denoted by σ_s^2, is computed as

$$\sigma_S{}^2 = \frac{2}{N} \sum_{K=1}^{N/\ 2-1} E_{S,K} \qquad (6)$$

where $E_{s,k}$ is the QAM symbol energy on subcarrier k. With MxM QAM used on all subcarrier, $E_{s,k}$ are equal to a common value denoted by E_s , yielding

$$\sigma_S{}^2 = 2(N/2-1)E_S / N \qquad (7)$$

Using twice the standard deviation of s_n as the DC bias, the signal value are clipped less than approximately 2.3% of the time according to Gaussian distribution. The transmit optical power is

$$P_{opt} = E[\frac{\beta_S}{\sqrt{T}}\left(S_n + B\right)] = 2\beta_S\sqrt{\frac{2(N/2-1)E_S}{NT}} \quad (8)$$

The QAM symbol energy in relation to the QAM symbol distance d by

$$E_S = \frac{d^2(M-1)}{6}$$

Hence, the QAM symbol distance is

$$d = \frac{P_{opt}}{\beta_S}\sqrt{\frac{3NT}{4(N/2-1)(M-1)}} \quad (9)$$

Dynamic Range of DCO-OFDM

The dynamic range of DCO-OFDM is denoted by

$$DR_{DCO} = \left[-2K\frac{\sigma_S}{\sqrt{T_{DCO}}}, 2K\frac{\sigma_S}{\sqrt{T_{DCO}}}\right]$$

where K is the DR factor, which should be set sufficiently high so that signal clipping does not significantly degrade the BER

ACO-OFDM System Model

In ACO-OFDM, QAM symbols are transmitted on odd-number subcarriers only. Together with the Hermitian symmetry condition, the QAM symbols on the N subcarrier are of the form

$$[0,\ X_1, 0, X_3, \ldots\ldots, X_{N/2-1}, 0, X^*_{N/2-1},\ 0\ ,\ \ldots\ldots X^*{}_3, 0\ , X^*{}_1]$$

As in DCO-OFDM, the rectangular pulse shape is used, but with the pulse period T given by

$$T_{ACO} = \frac{2\ \left(N/4\right)log_2 M}{R\left(N + N_{CP}\right)} \quad (10)$$

Transmit Optical Power of ACO-OFDM

In [8], the mean of the OFDM signal value s_n^+ is computed as

$$E\left[S_n^+\right] = \sqrt{\frac{1}{\pi N}\sum_{k=1,3,\ldots}^{N/2-1} E_{S,K}} \quad (11)$$

With MxM QAM constellation used on all subcarriers,

$$E\left[S_n^+\right] = \sqrt{\frac{E_S}{4\pi}} \quad (12)$$

Accordingly, the transmitted optical power is

$$P_{opt} = \beta_s\sqrt{\frac{E_S}{4\pi T}} \quad (13)$$

In addition,QAM symbol distance is

$$d = \frac{\sqrt{24\pi T}\,P_{opt}}{\beta_s\sqrt{M-1}} \quad (14)$$

Dynamic Range of ACO-OFDM

The dynamic range of ACO-OFDM is denoted by:

$$DR_{ACO} = \left[0, K\frac{\sigma_S}{\sqrt{T_{ACO}}}\right] \quad (15)$$

Note that the dynamic range of ACO-OFDM starts from 0 since ACO-OFDM signal value are clipped without DC bias addition.

7. Simulation Results

Computer simulation is performed using the MATLAB software to investigate the BER performance of ACO-OFDM in comparison to DCO-OFDM. The relevant system parameter is shown in Table 1

I. **Table 1:** System parameters for DCO OFDM and ACO-OFDM transmissions

Parameter	*Value*
Bit rate	10 Mbps
No. of OFDM subcarriers	16
Length of CP	4
QAM constellation size	4,16
DC channel gain	10^{-6}
DR factor	2(ACO) , 2.28(DCO)
No. of transmitted OFDM symbols	10^4
PSD of AWGN	$3.05\text{x}10^{-23}$ A^2/Hz

Figure 1 plot the BER versus the transmit optical power for DCO-OFDM and ACO-OFDM without the consideration of a limited dynamic range, i.e., no signal clipping. It can be observed that, for both DCO-OFDM and ACO-OFDM, there is a decrease in the BER with an increase in the transmit optical power. In addition, ACO-OFDM is more power efficient than DCO-OFDM since it requires less transmit power for the same BER. Thus, DCO-OFDM and ACO-OFDM can be used to provide two dimming levels for a fixed transmission performance.

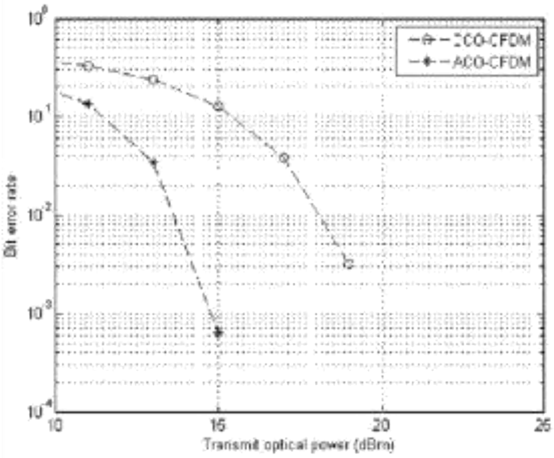

Figure 1: *BER versus transmit optical power for 4-QAM OFDM without considering a limited dynamic range: BER value below* 10^{-4} *are not shown*

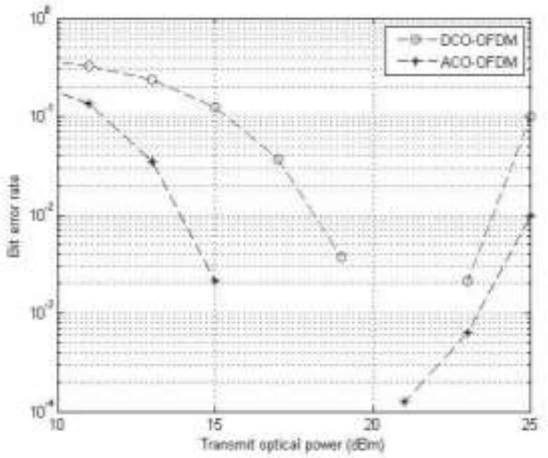

***Figure 2**: BER versus transmit optical power for 4-QAM OFDM considering a limited dynamic range.*

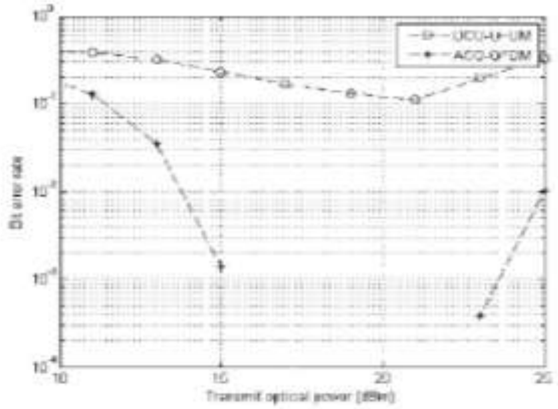

***Figure 3**: BER versus transmit optical power for 16-QAM OFDM considering a limited dynamic range.*

Figure 2 shows the same information as Figure 1, but with a limited signal dynamic range beyond which signal values are clipped at both ends of the dynamic range. It can be seen that the limited dynamic range can degrade the BER significantly. However ACO-OFDM still outperforms DCO-OFDM at all power levels

Figure 3 shows the same information as Figure 2, but with 16-QAM instead of 4-QAM. Roughly speaking, the larger constellation size tends to degrade the BER performance. As before, ACO-OFDM still outperforms DCO-OFDM at all power level

8. Conclusion

This paper considers light dimming under unipolar OFDM transmissions for VLC system. Two unipolar OFDM schemes, namely DCO-OFDM and ACO-OFDM, are discussed and compared. Simulation programs were developed to analyze the BER performance of DCO-OFDM and ACO-OFDM as the transmit optical power varies. Simulation results confirm that ACO-OFDM is more power efficient than DCO-OFDM. Accordingly, for a fixed transmission performance, DCO-OFDM and ACO-OFDM can be used to provide two different dimming levels.

It is argued that DCO-OFDM can suffer from the clipping noise while ACO-OFDM does not. Since DCO-OFDM has been used in conjunction with PWM for dimming control, it is proposed that the combination of ACO-OFDM and PWM for dimming control be used as a power efficient alternative to provide dimming control.

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