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Comparison of Hybrid DCO-OFDM-PWM and DCO-OFDM-PPM Schemes in Cellular Channel

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Abstract— **Optical orthogonal frequency division multiplexing (O-OFDM) based visible light communication (VLC) systems severely suffer from high peak-to-average-power-ratio (PAPR) induced nonlinear distortion due to the non-linearity of the light emitting diode (LED). One possible solution to this problem is to convert OFDM into a digital format prior to intensity modulation of the light source. In this paper, we present the hybrid OFDM-pulse time modulation scheme, and outline the performance of DCO-OFDM-PWM and PPM for cellular and LOS channels. The simulation results show that the cellular configuration offer marginally higher bit error rate (BER) performance compared with the LOS link. Furthermore, we show that the DCO-OFDM-PWM scheme offers an improved BER performance for lower modulation orders compared with the DCO-OFDM-PPM scheme for the cellular channel.**

Keywords: Visible light communications; optical OFDM; DCO-OFDM-PPM; DCO-OFDM-PWM; PAPR; cellular channel

I. INTRODUCTION

To address the radio frequency (RF) spectrum crisis, the visible light communications (VLC) technology has been considered as a complementary alternative [1]. VLC using light emitting diodes (LEDs) have many benefits: the free spectrum licensing, no electromagnetice interference and, reusable visible band because light does not pass through solid objects [2].

There are two popular link configurations for indoor VLC systems: line-of-sight (LOS) and diffuse. The diffuse configuration has a limited channel bandwidth due to multipath effects, thus resulting in lower data rates, higher path losses and multipath induced intersymbol interference (ISI). However, the diffuse links offer higher mobility and a larger coverage area compared with the LOS links. Although the LOS configuration has the best channel impulse response and a high bandwidth, it offers a limited coverage area, thus the need for alignment or tracking. The LOS links also suffer from blocking due to physical objects within a room. Cellular systems have been proposed to address the need for higher data rates and a wider coverage area [3].

In an indoor cellular VLC system, the lighting fixtures are considered as optical access points (APs). An optical cellular layers have been referred as an optical attocell network [4]. In an optical attocell network, optical orthogonal frequency division multiple access (O-OFDMA) could be used, since it provides a flexible allocation of communication resources for all users within a network. The important issue in OFDM based VLC systems is the high PAPR, which can lead to severe non-linear signal distortion and reduced power efficiency due to a very limited dynamic range of LEDs. Several techniques have been proposed to overcome this problem, including the use of pilot symbols, selected mapping, discrete sliding norm transform, and subcarrier grouping [5-10].

Since most indoor environments are relatively static with the optical transmitters being positioned above the users, thus ensuring LOS and non-LOS propagation path, then there are no deep fading being experience by the users compared to the RF wireless channel [11]. Therefore, the optical channel should not be treated as the RF channel and consequently the use of OFDM technique in VLC would be mainly to increase the transmission data rate at the cost of higher PAPR. One possible solution to address the high PAPR would be to convert the OFDM signal into a simple digital format prior to intensity modulation of LEDs. One such an option is the use of pulse time modulation (PTM) schemes including pulse width modulation (PWM), position modulation (PPM), pulse interval modulation, pulse frequency modulation, and etc. The hybrid OFDM-PTM scheme offers significant advantages compared with the traditional ACO-OFDM scheme including lower PAPR, higher luminance, improved bit error rate (BER) performance and enhanced resilience to the source non-linearity [12,13].

In [12], the OFDM-PWM scheme was investigated experimentally, where a linear mapping function was used to convert asymmetrically clipped optical OFDM (ACO-OFDM) into PWM. The results showed that the PAPR is decreased and the BER performance is improved compared with original ACO-OFDM. For example, at a BER of 10^{-4} for OFDM-PWM with 16- and 64-quadrature amplitude modulation (QAM), the signal-to-noise ratio (SNR) gains were ~ 4 dB and ~ 9 dB, respectively, compared with ACO-OFDM. In [13], OFDM-

PWM and OFDM-PPM performance were compared in an ideal channel and it was shown that OFDM-PPM offered improved BER performance compared with OFDM-PWM.

Since the PTM signal can be bipolar, the DC biased optical OFDM (DCO-OFDM) samples with no DC-biasing or zero clipping are mapped into a PTM signal. Also in ACO-OFDM, because of its anti-symmetry property, only the first half of bipolar samples are mapped into a PTM signal with no zero clipping. In this paper, we convert the DCO-OFDM samples into PWM and PPM formats and investigate the BER performance in a cellular channel. We show that at a BER of 10^{-3} for DCO-OFDM-PWM, the SNR gains are ~ 0.9 dB and ~ 0.1 dB compared with DCO-OFDM-PPM for 8- and 16-QAM, respectively. Also we show that DCO-OFDM-PPM offers improved BER performance for 64-QAM compared with DCO-OFDM-PWM. The rest of the paper is organized as follows. The hybrid DCO-OFDM-PWM/PPM scheme and a cellular channel is studied in Section II. In Section III, we present the simulation of both schemes for cellular configuration. Finally, Section IV concludes the paper.

II.   SYSTEM DESCRIPTION

A. Hybrid DCO-OFDM-PWM/PPM

There are a number of PTM schemes that can be adopted in hybrid schemes. PPM and PWM are two important and most widely used members of the series, in which the sample determines pulse position and pulse width respectively. PPM is more power efficient and is suitable for LOS links than on and off keying (OOK) and PWM, but at the cost of reduced bandwidth efficiency and increased system complexity due to clock synchronization [14]. The PWM and PPM pulse shapes are given by [16]:

$$s_{pwm}(t) = \begin{cases} A, & 0 \le t \le \alpha T_s \\ 0, & \alpha T_s \le t \le LT_s \end{cases} \quad \alpha = 1,2,3 \dots L \quad (1)$$

$$s_{ppm}(t) = \begin{cases} 0, & t \le nT_s \\ A, & nT_s \le t \le (n+1)T_s \end{cases} \quad (2)$$

where $n \in \{1, 2, 3 \dots L\}$, L = 2^M, and M is the bit resolution. T_s is the slot duration, and A is the pulse peak amplitude.

The block diagram of the proposed DCO-OFDM-PPM/PWM scheme is illustrated in Figure 1. Input data are modulated with QAM modulation. Standard OFDM building blocks are used to generate the DCO-OFDM signal. Applying Hermitian symmetry constraint into the OFDM symbol results real-valued signal samples. In DCO-OFDM, to ensure non-negative signal, a DC bias is added to the signal and the remaining negative signal is clipped [15]. However, because of the PWM/PPM signal can be bipolar, DCO-OFDM samples with no DC-biasing or zero clipping are mapped into the PWM/PPM format. To simplify the conversion of DCO-OFDM samples into PWM/PPM symbols, the symbol (frame) period is divided into L number of slots. DCO-OFDM-PWM and DCO-OFDM-PPM signals are given by [16]:

$$s_{PWM}(n) = \begin{cases} C & 0 \le N_{s(n)} \le N_\tau \\ 0 & N_\tau < N_{s(n)} \le L \end{cases} \quad (3)$$

$$s_{PPM}(n) = \begin{cases} 0 & 0 \le N_{s(n)} \le N_\tau \\ C & N_\tau < N_{s(n)} \le N_\tau + 1 \\ 0 & N_\tau + 1 < N_{s(n)} \le L \end{cases} \quad (4)$$

where $N_{S(n)}$ is the number of time slots in PWM and PPM symbols, and C represents the peak power. N_τ which determines the pulse width in PWM or pulse position in PPM is given by:

$$N_\tau = \frac{x(n) - x_{max}}{x_{max} - x_{min}} \times L \quad (5)$$

where x_{min} and x_{max} are the maximum and minimum amplitudes of the DCO-OFDM symbol, respectively.
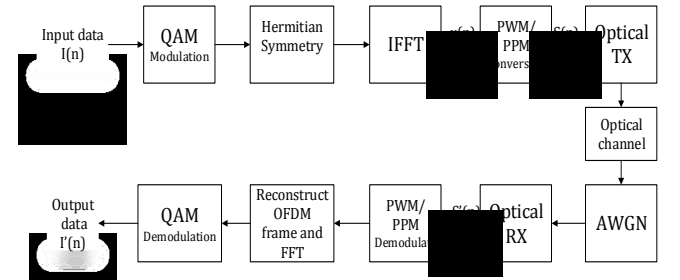

Figure 1: Block diagram of hybrid DCO-OFDM-PTM scheme.

In both PWM and PPM schemes, the minimum pulse duration is $1/L$ times smaller than O-OFDM. Therefore, the required bandwidth of OFDM-PWM/PPM is L times larger than that of O-OFDM. In order to reduce the required bandwidth, the duty cycle is extended by a factor of N_C, in which $0 \le N_c \le L$. In this case, OFDM-PWM and PPM signals are given by [20]:

$$s_{PWM}(n) = \begin{cases} c & 0 \le N_{s(n)} \le N_\tau + N_c \\ 0 & N_\tau + N_c < N_{s(n)} \le L + N_c \end{cases} \quad (6)$$

$$s_{PPM}(n) = \begin{cases} 0 & 0 \le N_{s(n)} \le N_\tau \\ c & N_\tau < N_{s(n)} \le N_\tau + N_c + 1 \\ 0 & N_\tau + N_c + 1 < N_{s(n)} \le L + N_c \end{cases} \quad (7)$$

For $N_C = L$, the required bandwidth of OFDM-PWM/PPM is the same as that of O-OFDM. Following optical detection, the received OFDM-PWM/PPM signal is given by:

$$s'(n) = s(n) \otimes h(n) + z(n) \quad (8)$$

where $s(n)$ is the transmitted signal. Also, $h(n)$ is the channel impulse response, $z(n)$ is the additive white Gaussian noise (AWGN) with zero mean, and $\otimes$ denotes the convolution operation. At the receiver, after determining a pulse width or

position, standard OFDM demodulation building blocks are used to extract the data information.

B. Channel model

We considered a single wavelength to cover the entire area (i.e., no wavelength reuse). In cellular systems, overlapping between coverage areas should be kept to a minimum level to achieve the optimum power efficiency. There are a number of cell shapes that could be adopted such as circular, square, equilateral triangle and hexagon. Each cell has an optical base station (LED) located at the center of it [17]. The indoor optical wireless cellular scenario considered in this paper is shown in Figure 2, where four LEDs are installed on the ceiling that transmit data. The dimensions of the room are $(5 \times 5 \times 3)$ m. The four LEDs have identical semi-angles of 70. We also assumed that the receiver is located at the center of the room. Using narrow FOV light sources provide higher data rates (i.e., LOS) but reduced transmit power due to the eye safety, ambient noise and a coverage area [18]. The channel simulation parameters are presented in Table 1.
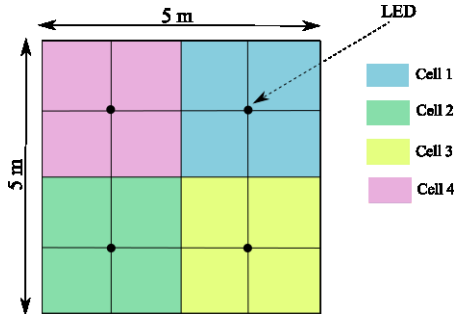

Figure 2: The top-view of the room, LED luminaire location and the cells' geometry structure.

In general, the received signal is made up of two components: LOS and the diffuse, which are considered in this work. In this case, the received power from a single transmitter is given by [19]:

$$P_{r-nlos} = \left(H_{los}(0) + H_{nlos}(0)\right)P_t \qquad (9)$$
$$= \left(H_{los}(0) + \sum_{refl} H_{refl}(0)\right)P_t$$

where P_t is transmitted power of signal. Also, H_{los} and H_{nlos} are the DC gains of LOS and non-LOS component.

Table 1: Cellular channel simulation parameters.

	Parameter	Value
	Room size	$5 \times 5 \times 3$ m³
	Reflection coefficient of walls	0.8
Source	Location	(1.25,1.25,2.15)
		(-1.25,1.25,2.15)
		(-1.25,-1.25,2.15)
		(1.25,-1.25,2.15)
Receiver	Semi-angle at half power	30º
	power	1 W
	Location	(0,0,0)
	Active area	1 cm²
	Half angle FOV	60º

III. RESULTS AND DISCUSSION

We used Matlab to simulate and evaluate the performance of the proposed schemes. The number of IFFT points and slots per PTM symbol are set to 256 and 100, respectively. All the key simulation parameters are presented in Table 2.

The PAPR factor is defined as the ratio of the maximum instantaneous power to average power, characterized by the complementary cumulative distribution function (CCDF) as given by [20]:

$$CCDF = P(PAPR > PAPR_0)$$
$$= 1 - P(PAPR \leq PAPR_0) = 1 - CDF \qquad (10)$$

where $PAPR_0$ is the reference of PAPR. Figure 3 shows CCDF against PAPR for 64-QAM DCO-OFDM-PWM, DCO-OFDM-PPM, and original ACO-OFDM schemes. The PAPR values for PWM and PPM are ~3 dB and ~10 dB, respectively. As is seen, the PAPR value is reduced significantly.

Table 2: Simulation parameters.

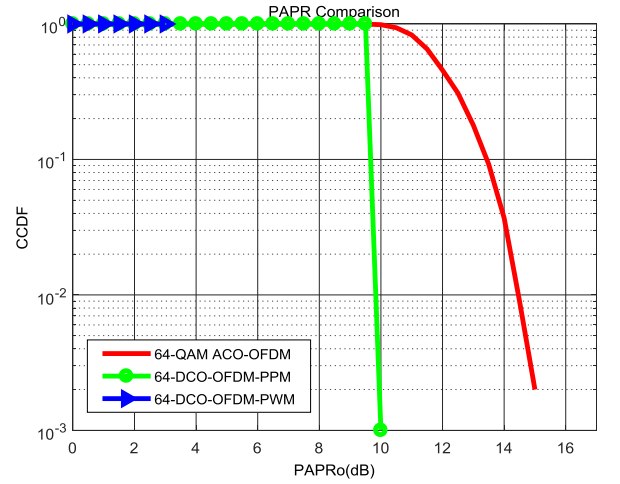| Parameter	Value
Modulation	8, 16, 64 QAM
FFT/IFFT size	256
Number of subcarrier (N_{SC})	256
Number of slots per PTM symbols (L)	100
Extended factor	10
Symbol rate	36×10^6 symbol/second
Iteration	1000

Figure 3: PAPR analysis for original ACO-OFDM, DCO-OFDM-PWM and DCO-OFDM-PPM (N_{SC}=256, L=100).

The severity of interference induced by a multipath propagation is quantified using the root mean square (RMS) delay spread D_{rms} as given by [19]:

$$D_{rms} = \left[\frac{\int (t-\mu)^2 h^2(t)dt}{\int h^2(t)dt}\right]^{1/2} \qquad (10)$$

where the mean delay μ is given by:

$$\mu = \frac{\int t h^2(t) dt}{\int h^2(t) dt} \tag{11}$$

The RMS delay spread of cellular and LOS channels determined using Eq. (10) is illustrated in Figures 4(a) and 4(b), respectively. In LOS link, the locations of the transmitter and the receiver are (0,0,2.15) and (0,0,0), respectively. The maximum values for the mean RMS are ~ 1.26 ns and ~ 0.29 ns for the cellular and LOS links, respectively. Although the cellular configuration provides lower transmission capacity it offers an increased uniform coverage area.
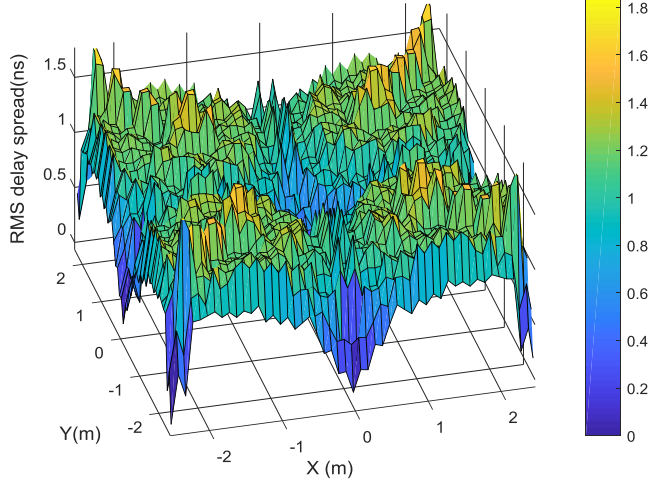
(a)
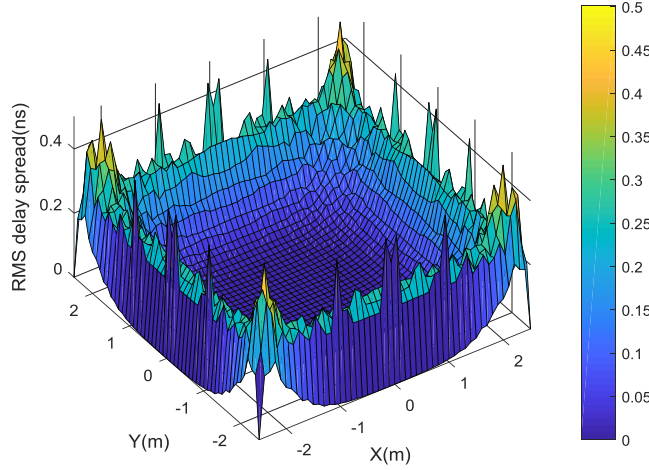
(b)

Figure 4: The RMS delay spread for: (a) cellular, and (b) LOS channels.

The BER performance against the signal to noise ratio (SNR) for DCO-OFDM-PWM and DCO-OFDM-PPM for 8-, 16- and 64-QAM for the cellular (see Figure 2) and LOS channels are illustrated in Figure 5. The channels are considered non-ideal and only the single reflections from walls are taken into account. As can be seen, the DCO-OFDM-PWM/PPM schemes have lower SNRs for the LOS link, this is because the LOS path offers lower multipath induced ISI than cellular configuration. Furthermore, DCO-OFDM-PWM display improved BER performance for the lower order modulations. For example, for the cellular channel at a BER of 10^{-3} for DCO-OFDM-PWM the SNR gains are ~ 0.9 dB, ~ 0.1 dB and ~ -1.1 dB for 8-, 16- and 64-QAM, respectively compared with DCO-OFDM-PPM.
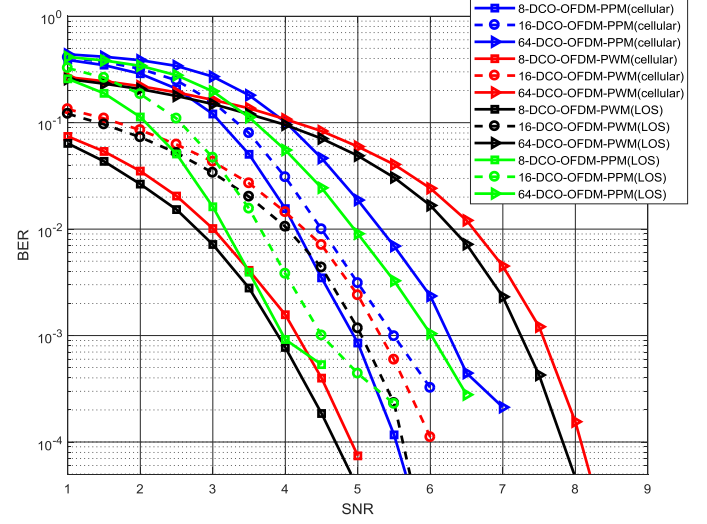
Figure 5: BER against the SNR for DCO-OFDM-PWM and DCO-OFDM-PPM with N_{SC}=256, and L=100.

IV. CONCLUSION

In this paper, the hybrid DCO-OFDM-PTM scheme based on the conversion of a DCO-OFDM sample into a PTM format for the cellular and LOS channels was studied. The cellular channel decraded the BER performace, but offered an increased uniform coverage area. For the cellular channel,,simulation results showed that at a BER of 10^{-3} for DCO-OFDM-PWM the SNR gains are ~ 0.9 dB, ~ 0.1 dB and ~ -1.1 dB for 8-, 16- and 64-QAM, respectively compared with DCO-OFDM-PPM.

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