Comparison of Optical OFDM and M-PAM for LED-Based Communication Systems

Jie Lian†, Mohammad Noshad‡ and Maïté Brandt-Pearce†

***Abstract*—Light-emitting diode (LED)-based communications, such as visible light communications (VLC) and infrared (IR) communications, are candidate techniques to provide short-range and high-speed data transmission. In this paper, M-ary pulse amplitude modulation (M-PAM), used as a high bandwidth efficiency scheme, is compared with three well-known optical orthogonal frequency division multiplexing (OFDM) schemes. Considering the bandwidth limit and constrained peak transmitted power characteristics of LEDs, a bit loading algorithm and single-tap equalizer with an optimized modulation index are used for the optical OFDM schemes tested. To reduce the inter-symbol interference caused by the bandlimited channel, an optimized pulse shape and a minimum mean squared error (MMSE) equalizer are applied to the M-PAM system. From numerical results, M-PAM can provide a substantially higher data rate than OFDM for bandlimited channels. When the channel bandwidth is ample compared with the symbol rate, optical OFDM outperforms M-PAM.**

***Index Terms*—optical wireless communications, visible light communications, infrared communications, pulse shaping, MMSE equalizer, OFDM, bit loading, M-PAM**

I. Introduction

LIGHT-emitting diode (LED)-based communications, typically used for short-range optical wireless systems, has attracted much attention in recent research due to its many advantages over radio-frequency (RF) communications. By using LEDs as transmitters, visible light communications (VLC) and infrared (IR) communications are immune to RF interference, have low power consumption, have low impact on human health, can offer higher security, and can provide potentially high-data-rate transmission. In this paper, we compare two modulation schemes often used with LED-based systems: M-ary pulse amplitude modulation (M-PAM) and orthogonal frequency division multiplexing (OFDM).

Recently, OFDM has been proposed for optical wireless communication (OWC) systems due to its resistance to inter-symbol interference (ISI) and high spectral efficiency [1]. Since intensity modulation and direct detection (IM/DD) are used in OWC systems, the transmitted signal cannot be negative, and, therefore, conventional OFDM cannot be applied directly in OWC. DC-biased optical OFDM (DCO-OFDM) is commonly used in OWC due to its simplicity [2]. However, because of the nonlinear response of LEDs, the DCO-OFDM signal must be clipped at zero and peak LED power, distorting the signal. Unipolar OFDM (U-OFDM), also know as Flip-OFDM, successively transmits the positive and negative parts of the signal, using two frames to represent one OFDM symbol, which doubles the bandwidth requirement compared to DCO-OFDM for the same data rate [3], [4]. Asymmetrically clipped optical OFDM (ACO-OFDM) is a peak to average power ratio (PAPR) reduction method where only the odd subcarriers are modulated, which results in a low bandwidth utilization efficiency [5]. These last two techniques are still susceptible to peak-power clipping. For all of these optical OFDM techniques, M-ary quadrature amplitude modulation (M-QAM) is used for a high spectral efficiency. The IM transmitted baseband signals are real-valued.

Alternatively, pulse-based M-PAM has been explored to yield a $(\log_2 M)$-fold increase in the data rate compared with on-off keying (OOK). However, the transmitted data rate is still limited by the slow-rise time of LEDs. When the transmitted symbol rate is high, ISI can affect the system performance. Equalization is an effective way to reduce the ISI caused by the narrow LED bandwidth. Some researchers have discussed pre/post-equalization, software equalization and hardware equalization methods for VLC [6]–[8].

In this paper, we compare the performance of DCO-, ACO- and U-OFDM with M-PAM for LED-based communication systems. For the optical OFDM techniques, we model the clipping noise caused by the LEDs' nonlinearity (clipping at both zero and peak power) [9], [10]. The symbol rate, modulation index, and the bits loaded on each subcarrier are jointly optimized to maximize the transmitted bit rate despite the limited LED bandwidth. For the optical OFDM systems tested, a single-tap equalizer is applied to compensate the channel phase distortion at each subcarrier. For M-PAM, although there is no clipping, the ISI limits the data rate severely. Recently, some researchers proposed a joint waveform design and minimum mean squared error (MMSE) equalization algorithm to combat ISI and multiple access interference in [11]. In this work, we employ the method in [11] to find the optimal pulse-shape (PS) and receiver filter to reduce ISI, assuming a single user.

We compare optical OFDM and M-PAM techniques assuming a bandlimited LED with a fixed peak power. We assume that the channel response is dominated by the response of the LED, which is modeled as a first-order lowpass filter. From the numerical results, the pulse-shaped M-PAM scheme can support a higher data rate than the optical OFDM with the same bit error rate (BER) performance when the bandwidth is severely limited. For an LED with a broad bandwidth, the

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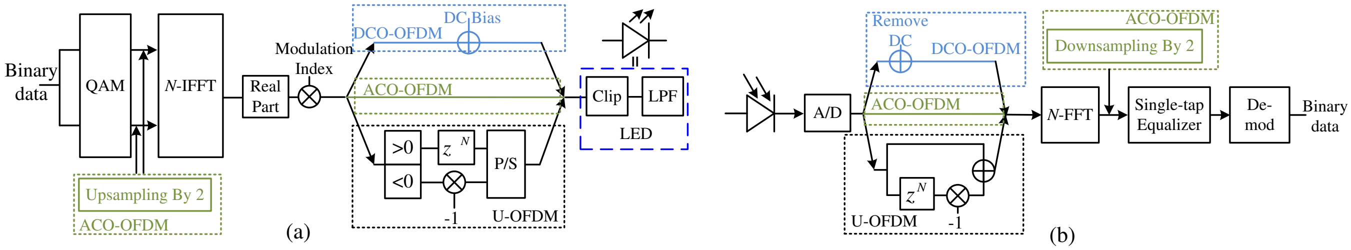

Fig. 1. Block Diagram of optical OFDM. (a) Structure of the transmitter for DCO-, ACO- and U-OFDM. (b) DCO-, ACO- and U-OFDM receivers with a single-tap equalizer.

optical OFDM techniques tested outperform M-PAM.

This paper presents a more realistic comparison between M-PAM and optical OFDM for LED-based communications than was given in [12], where M-PAM with a minimum mean squared error (MMSE) decision feedback equalizer was shown to have a better performance than optical OFDM. In [12], only zero-clipping of the optical OFDM is modeled and the average power is considered (unlike the peak-power constraint presented here), which is important for eye-safety in laser-based systems and to control the average illumination in VLC systems. For many LED-based OWC systems, such as VLC and IR communications, the transmitters are nonlinear devices with a peak radiation power limit that distorts the transmitted signal for optical OFDM systems due to their high PAPR. The average optical power is considered as a constraint in [12], but no signal distortion caused by the peak power limit is taken into account, unlike here.

The remainder of the paper is organized as follows. The optimized optical OFDM technique is described in Section II. In Section III, we describe the M-PAM system with the pulse-shaping algorithm. The optical OFDM and M-PAM are compared in Section IV. The paper is concluded in Section V.

II. Optimized Optical OFDM Techniques

In this section, we briefly introduce DCO-, ACO- and U-OFDM, and describe how we optimize these optical OFDM systems. We ignore the requisite cyclic prefix by modeling a single OFDM symbol transmitted. The modulation index used in generating the OFDM signal, which controls the scale of the OFDM signal magnitude, is optimized to trade off the signal power and the clipping noise due to the LED nonlinearity [9], [10]. For a given required bit error rate (BER), the order of the QAM modulation on each subcarrier is chosen to maximize the transmitted bit rate (standard bit-loading). In addition, the optimal symbol rate can be selected by using a brute-force search.

A block diagram modeling the optical OFDM transmitter for each scheme is shown in Fig. 1 (a). For DCO-OFDM, a DC bias is added to generate the non-negative signal. Due to the peak transmitted power constraint, the optimal bias value is set to be the half of the peak power. U-OFDM does not require a DC bias to create non-negative signals. Instead, two frames with the same duration are used to generate the unipolar signal by successively transmitting the positive and negative parts of the bipolar signal. ACO-OFDM can avoid the zero clipping distortion without adding a DC bias by only

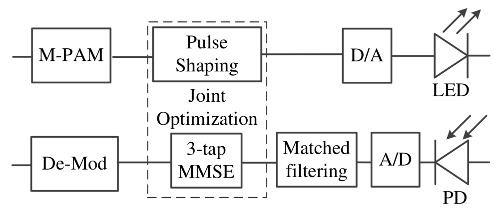

Fig. 2. A block diagram of the design of the optimal pulse-shape and MMSE filter for M-PAM.

using the odd numbered frequency subcarriers for modulation, sacrificing half of the bandwidth. For each OFDM technique, we optimize the modulation index, which, considering the nonlinear distortion caused by the peak power constraint, determines the signal to noise and interference ratio (SINR).

We assume the number of subcarriers is N; thus, an N-point IFFT and FFT are used at the transmitter and at the receiver, shown in Fig. 1 (a) and (b), respectively. Therefore, the computational complexity of the algorithm is on the order of $\log_2 N$ (usually a small integer) per QAM data symbol. The real part of the OFDM signal is then transmitted due to the baseband nature of IM/DD systems.

III. M-PAM using Optimized Pulse-Shape

In this section, an optimally shaped pulse supporting M-PAM data, proposed in [11], is transmitted through the bandlimited channel. This optimized pulse is designed jointly with the MMSE filter at the receiver, as shown in Fig. 2, to reduce ISI by maximizing the SINR. For a given bandlimited channel, the pulse needs to be optimized for the specific transmission symbol rate. An example of two optimized pulse-shapes (after the bandlimiting filter) for different symbol rates is shown in Fig. 3, where the lower symbol rate is better able to suppress the interference at the symbol sample points. The pulse-shape is non-negative yet similar to a Nyquist waveform, which is well-known to eliminate ISI. Details of the pulse shaping optimization process can be found in [11].

In optical systems, the overall channel response can be accurately estimated since there is no fading and the channel varies slowly (indoor communications with pedestrian motion). Thus, a pulse shape look-up table for different symbol rates can be pre-established for a given bandlimited LED and various symbol rates. The proper pulse-shape can be selected from this look-up table. This approach requires little real-time computational and memory resources.

At the receiver, the signal is sampled at twice the Nyquist rate (2-3 samples per symbol), digitally matched filtered, and

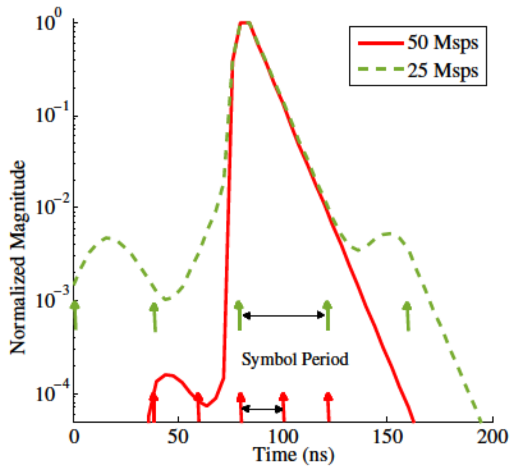

Fig. 3. Optimal pulse-shapes, after the bandlimiting filter, for two M-PAM symbol rates. The 3 dB bandwidth of the channel is 10 MHz.

TABLE I
PARAMETERS USED FOR NUMERICAL RESULTS

3 dB bandwidth of LEDs, f_{3dB}	10 MHz
Noise spectral density, N_0	3×10^{-9} mW/Hz
Required BER for bit loading,	10^{-3}
Peak received power, $P_{\max}$	15 mW
Channel loss	1
Number of subcarriers for OFDM, N	32
Number of taps for MMSE filter	3

down-sampled to the symbol rate. Then, an MMSE filter with a few taps (3 taps in this paper) is applied to further reduce the ISI and noise. Compared with the single-tap equalizer in optical OFDM, the MMSE filter in M-PAM has the same order of complexity.

IV. SIMULATION RESULTS AND COMPARISON

In this section, numerical results of the comparison between optical OFDM and M-PAM are shown. To obtain a fair comparison, the same parameters are used for the optical OFDM techniques tested and M-PAM. Unless otherwise noted, the parameters used to obtain the numerical results are shown in Table I. In this paper, we model the channel as a first-order lowpass filter, and the channel loss is not taken into account, with a unit electrical-optical-electrical conversion assumed. Note that IM systems typically use baseband signals, and care must be taken to model the OFDM transmitted signal as real-valued, unlike the complex envelope often used in modeling RF bandpass systems.

All results are computed using analytical expressions, except for M-PAM with no equalization, which is found through Monte Carlo simulation. The relevant equations for DCO-OFDM U-OFDM, and ACO-OFDM can be found in [3], [9], [13], respectively. For M-PAM, the analysis is given in [11].

A BER comparison of M-PAM and optical OFDM techniques for different effective modulated symbol rates is shown in Fig. 4. In this figure, the modulation constellation size is fixed for both OFDM and M-PAM. With the help of pulse-shaping and MMSE equalization, M-PAM can achieve a lower average BER than the optical OFDM techniques

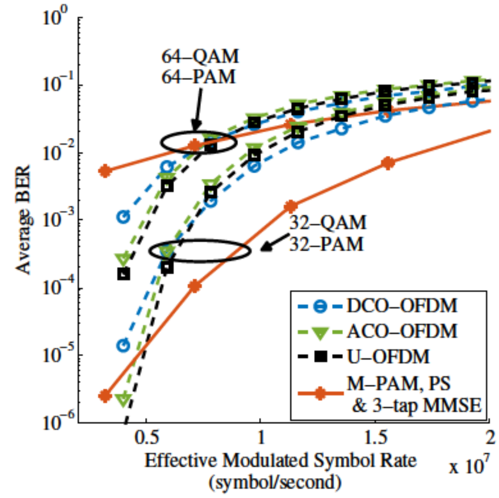

Fig. 4. BER comparison of DCO-, ACO-, U-OFDM and M-PAM. Single-tap equalizer and 3-tap MMSE filter are applied to the optical OFDM and M-PAM, respectively.

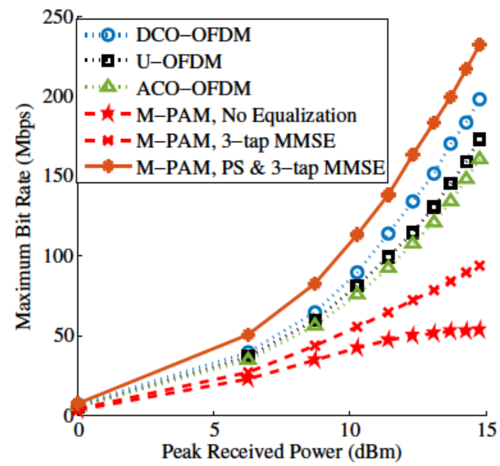

Fig. 5. Throughput comparison of DCO-, ACO-, U-OFDM and M-PAM. A bit loading and single-tap equalizer are used for optical OFDM. M-PAM with different equalization techniques are compared.

with the same modulation constellation size at high symbol rates compared with the channel bandwidth. For a required BER = 10^{-3}, 32-PAM can support a 5 Msps higher symbol rate than ACO-, DCO- and U-OFDM using 32-QAM. For low symbol rate cases, pulse-shaping is no longer useful, and optical OFDM outperforms M-PAM due to the larger minimum distance of M-QAM compared with M-PAM.

Among the optical OFDM techniques tested, DCO-OFDM performs better than the others when the symbol rate is high, since ACO- and U-OFDM have lower bandwidth efficiency. When the symbol rate is low, U-OFDM can provide a better BER performance due to its higher resistance to nonlinear distortion and higher power efficiency than DCO- and ACO-OFDM.

For a given bandlimited channel and required BER performance, the maximum achievable bit rates of DCO-, ACO-, U-OFDM and M-PAM are compared in Fig. 5. A bit loading algorithm is used in the optical OFDM systems to increase the throughput. In general, as the peak received power increases, the bit rate gradually improves. For the optical OFDM techniques tested, DCO-OFDM can provide a higher bit rate than the others for the given bandlimited channel since ACO- and U-OFDM are less bandwidth efficient. M-PAM using PS and a 3-tap MMSE filter can provide about a 15% higher bit rate than DCO-OFDM. If the M-PAM technique uses the 3-tap MMSE filter but no PS, it performs worse than OFDM, but better than M-PAM with no equalization at all.

TABLE II
AVERAGE OPTICAL POWER FOR DCO-, ACO-, U-OFDM AND M-PAM FOR THE RESULTS IN FIG. 5, IN dBM

$P_{\max}$	DCO-	ACO-	U-	M-PAM
10	6.9	3.6	2.1	4.1
15	11.9	8.6	7.1	9.2

In this paper, optimizing the average optical power is not the objective, as we consider a peak power limit and maximum data rate instead. However, in Table II we compare the average optical power transmitted using the optimized parameters for the maximum bit rate shown in Fig. 5. For VLC systems, this average power represents the achieved illumination level when the highest throughput is achieved. From the results, ACO- and M-PAM have a similar average optical power, with U-OFDM slightly lower. Due to the DC offset, DCO-OFDM can provide a higher average optical power than the others.

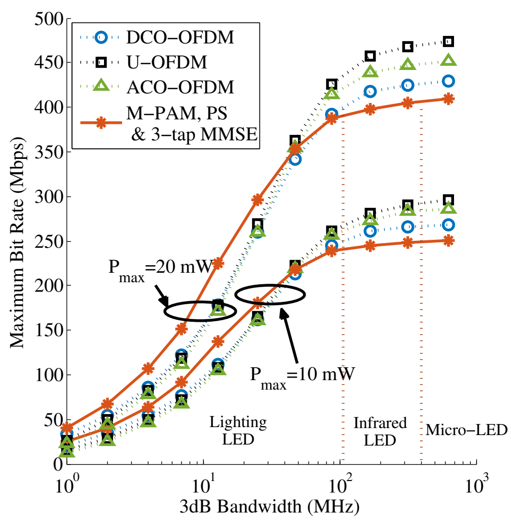

Fig. 6. Throughput comparison of DCO-, ACO-, U-OFDM and M-PAM under different channel bandwidths. A bit loading and single-tap equalizer are used in the optical OFDM systems. PS and a 3-tap MMSE are used for M-PAM. The peak received power is 10 mW.

Fig. 6 shows a maximum throughput comparison of M-PAM and optical OFDM techniques as the 3 dB bandwidth of the channel increases. The achievable bit rate for all the tested techniques first improves dramatically, then flattens due to the transmitted power limitation. From the optical OFDM techniques tested, DCO-OFDM supports a higher bit rate when the channel bandwidth is severely limited. For a channel with a broad bandwidth, ACO- and U-OFDM perform better than DCO-OFDM due to a lower nonlinear distortion. In Fig. 6, M-PAM using PS and a 3-tap MMSE filter outperforms the optical OFDM techniques tested when the 3 dB bandwidth of the channel is less than about 80 MHz (considered as a severely bandlimited case). When the bandwidth of the channel is broader, optical OFDM can provide a higher bit rate than M-PAM, which is consistent with the results in Fig. 4.

Since the 3 dB bandwidth of current commercial lighting LEDs is just a few tens of MHz, M-PAM using PS with a MMSE filter should be selected as the modulation scheme rather than optical OFDM, due to its higher throughput. For systems using micro-LEDs or infrared LEDs that typically have a larger bandwidth, optical OFDM techniques should be selected to achieve a higher data rate.

V. CONCLUSION

In this paper, we compare the performance of DCO-, ACO-, U-OFDM and M-PAM for LED-based communication systems. The bandlimited characteristic and constrained transmitted power of LEDs are taken into account. For the optical OFDM techniques tested, the modulation index is optimized to reduce the clipping distortion caused by the power constraint and maximize the SINR. A bit loading and single-tap equalizer are applied to the optical OFDM systems to improve the throughput. M-PAM using an optimal pulse-shape and a 3-tap MMSE equalizer is compared with the OFDM systems. From the numerical results we see that when the channel is bandlimited compared with the symbol rate and the transmitter is power limited, M-PAM can provide about a 15% higher bit rate than the optimized optical OFDM systems. For a broader bandwidth channel, optical OFDM schemes outperform M-PAM by about 12% of the bit rate.

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