# Performance Evaluation of ASCO-OFDM Based LiFi

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Abstract-Light fidelity (LiFi) is a means of high speed wireless data transmission along with room illumination. As a data encoder for LiFi, different variants of orthogonal multiplexing division (OFDM) frequency such as asymmetrically clipped optical OFDM (ACO-OFDM), asymmetrically clipped DC biased optical OFDM (ADO-OFDM) and asymmetrically and symmetrically clipped optical OFDM (ASCO-OFDM) have been considered. This paper provides a framework using pulse-width modulation (PWM) for dimming control of ASCO-OFDM based LiFi. In this framework, the generated ASCO-OFDM signal in the electrical domain is multiplied with the PWM signal, and the resultant signal is converted to the optical signal by optical modulators. The pulse width of the PWM based ASCO-OFDM signal is varied accordance with the dimming or brightness level. Next, the bit error rate (BER) performance is evaluated for PWM based ASCO-OFDM. Finally, results show that with PWM dimming, ASCO-OFDM is more electrical power efficient than others for a given data rate. Results indicate that for low data rates, both ASCO-OFDM and ACO-OFDM, and for higher data rates, ASCO-OFDM and ADO-OFDM are good choices in terms of optical power efficiency. Moreover, 4-QAM ASCO-OFDM system ensures low BER even for large dimming or lower signal power level.

*Index Terms*—Bandwidth, bit error rate, LiFi, PWM, ASCO-'OFDM, data encoder, dimming.

## I. INTRODUCTION

The demand for high speed wireless data is increasing rapidly. To fulfill this enormous demand, optical wireless communication (OWC) is being considered as a supplementary to radio frequency (RF) communication [1]-[9]. One major advantage of OWC is that theoretically optical spectrum has thousand times greater bandwidth than radio signals. OWC is also free from electromagnetic interference. There are multiple forms of OWC including free space optics, pixelated optical communication [5]-[8] and light fidelity (LiFi) [2]. LiFi is the conversion of the light bulb into a wireless communication path that can complement wireless fidelity (WiFi). LiFi is a bidirectional subset of OWC. LiFi uses visible light spectrum to transmit data, as its spectral width is much larger than the conventional radio frequencies, so it has the potential to transmit higher bandwidth. LiFi uses common everyday LED (light emitting diode) light bulbs to transmit data. Data transmission speeds through LED light bulbs of up to 224 gigabits per second. As long as a light bulb is available this technology can offer a wireless internet connection. The number of the world's light bulbs is still growing predictable at about 14 billion. For this fact every street light can become an internet access point. LiFi and WiFi are quite same as both of them transmit data electromagnetically, but WiFi uses radio waves while LiFi runs on visible light.

To transmit high data rates in LiFi, orthogonal frequency division multiplexing (OFDM) is the preferred choice of encoder as reported in the literature [10]-[26]. OFDM is a multicarrier modulation scheme, where a large frequency bandwidth is divided into smaller frequency bands, and data is transmitted in parallel on each of the separate bands. The transmitted subcarriers are orthogonal to each other; therefore each subcarrier can be demodulated without any interference from other subcarriers. OFDM is used widely in wired and radio frequency (RF) communication systems; due to its robustness against inter symbol interference (ISI) and the requirement for only simple equalization at the receiver. It is also used in some vehicular communication systems and has begun to gain attention as a possible modulation scheme in optical wireless systems. In conventional OFDM system the signal transmission is bipolar in nature but light transmission is unipolar in nature, so the signal has to be converted to unipolar for LiFi transmission.

Different variants of orthogonal frequency division multiplexing (OFDM) [23] are used in LiFi. These are direct current biased optical orthogonal frequency division multiplexing (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM) and asymmetrically clipped DCbiased optical OFDM (ADO-OFDM) [24]. Recently another form of OFDM termed as asymmetrically and symmetrically clipping optical (ASCO-OFDM) has been developed [4]. Basically. ASCO-OFDM is a combination of asymmetrically clipped optical OFDM (ACO-OFDM) and symmetrically clipping optical OFDM (SCO-OFDM). In an ACO-OFDM scheme, only the odd subcarriers can be modulated to transmit optical signal. For the case of ASCO-OFDM, the ACO-OFDM part is used to modulate the odd subcarriers, while SCO-OFDM component is used to transmit the even subcarriers. In an ASCO-OFDM scheme, no DC bias is added and thus it achieves better performance than other modulation schemes in terms of both power efficiency and bit error rate (BER). Since ASCO-OFDM has been evaluated in terms of only communication performance, research is required to find the effectiveness of ASCO-OFDM for LiFi while considering both illumination and communication performances.

Light dimming means to lower the brightness of a light. Dimming is an important feature of light applications in order to be able to adjust illumination conditions in a room based on personal preferences and in order to save energy. Dimming control reduces the output and energy consumption of light sources. The main goal of introducing dimming control to VLC is to lessen the power consumption of the LEDs and for user suitability. The LED is used as the

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source of light and as a medium for wireless communication. Hence, it is not desirable to switch the LED on with a full brightness at all the time. For a typical office environment the required illumination ranges between 200-1000 lux [1]. Hence, the illumination should be preserved between these ranges. Dimming control has also an opposing effect in VLC systems. Forming a communication medium after dimming the LED light decreases the average signal strength. It also increases the BER. In order to control the brightness of the light without troubling the communication medium, a reliable and efficient dimming control technique needs to be developed.

The main contributions of this paper can be summarized as follows:

- A framework is developed to incorporate the PWM scheme for ASCO-OFDM transmitters and receivers. For this, the generated ASCO-OFDM signal in the electrical domain is multiplied with the PWM signal and the resultant signal is converted to the optical signal by optical modulators.
- Simulations using MATLAB tool are performed to evaluate the BER performances of PWM based ASCO-OFDM, ADO-OFDM, DCO-OFDM and ACO-OFDM for both electrical and optical power limited channels. The performance evaluation is done for a number of OFDM subcarriers and for different constellation sizes.

The rest of the paper is organized as follows. Section II presents a comprehensive literature review on the development of LiFi. This review includes the different modulation formats particularly different forms of OFDM usable for LiFi. The dimming aspect of LiFi is also described in Section II. The transmission and reception techniques of ASCO-OFDM based LiFi are presented in Section III. An overview of different dimming schemes and the PWM based dimming for ASCO-OFDM is described in Section IV. The comparative performance results of ASCO-OFDM with other OFDM forms are shown in Section V. Finally, Section VI provides the concluding remarks.

# II. LITERATURE REVIEW ON LIFI SYSTEMS

LiFi utilises light spectrum for high speed, stable and secure data connectivity. The speciality of LiFi lies in the fact that it can provide data communications through ubiquitous light bulbs surrounding us. To this date LiFi is the only form of optical wireless system that incorporates bidirectional transmission of light waves. LiFi system employs both infrared and visible light spectra to support multiuser access and user mobility. The radio frequency spectrum crunch paves the path for the development of LiFi technology. Speech transmission through light beam was invented by Alexandar Graham Bell in 1880 using photo phone [2]. Over the years, with the advancement of high speed off-the-shelf LED lights, Japanese researchers started working on the concept of transmitting data wirelessly through LED lights in 2000. In the subsequent years, many projects such as the OMEGA research project by European Union, Smart Lighting Communications project by US National Science Foundation were conducted to enhance the one way LED based visible light communications. Finally, in 2011 on TED Talk Dr. Herald Hass demonstrated LiFi that is LED based two way communications [2]. This overhead LED light based bidirectional communications works like a VLC system yet considered as optical wireless communications. In a typical LiFi system, the transmitter is consisting of LED light that transmit high speed data and an infrared photo detector to receive signal from user equipment. The light fixture is driven by a LiFi chip which gets data and power through power over Ethernet (PoE) or power line communication technology from high speed core network. Each light bulb in an indoor environment can act as a small cell, having radii less than 5m, is called LiFi autocell [2]. The LiFi autocell network in indoor environment can spread optical wireless communications beyond WiFi and cellular technology by providing ultrahigh speed securely and thus can meet user experience challenges [2]. As a LED based technology only intensity modulation and direct detection (IM/DD) method is applied between LiFi transmitter and receiver. Multicarrier OFDM modulation technique can offer viable solution for LiFi in terms of power, spectral efficiency and computational complexity. At present, different types of multicarrier OFDM schemes are proposed for LiFi system. However, when every light bulb surrounding us will be integrated in a LiFi system, dimming of light illumination will become a vital necessity to be achieved. The simplest type of dimming control is analog dimming that is the amplitude modulation of the input signal or continuous current reduction to LED. Analog modulation lowers the input current amplitude to LEDs in a linear way to control and adjust the optical flux to be radiated. However, one demerits of this technique is that amplitude modulation suffers from color shift [10]. The asymmetrical hybrid optical orthogonal frequency division multiplexing (AHO-OFDM) has been proposed in [11] uses analog dimming principle to utilise full dynamic range to transmitter LEDs. The AHO-OFDM consists of asymmetrically clipped optical OFDM (ACO-OFDM) or pulse-amplitude modulated discrete multitone (PAM-DMT) signal in such a way that one of them is inverted. The resultant AHO-OFDM signal become asymmetrical to the DC bias applied. The experimental results proposed in [12] shows that the hybrid AHO-OFDM system has wide dimming capability but suffers from data rate fluctuation. Also a very recent study in [13] reveals that AHO-OFDM signal is strong in dimming of LEDs luminaires but poor in terms of power efficiency and bit error rate performance.

The spatial optical OFDM (SO-OFDM) has been proposed in [14]. In SO-OFDM, the output signal is formed by summing spatial signals in optical domain. The SD-OFDM is based on the idea that is the level of dimming is represented by the number of flashed light emitting diodes (LEDs) in a typical LED lamp fixture. Here, in SD-OFDM each subcarrier is transmitted by different LED in an array of LEDs. The SO-OFDM has better BER performance than DCO-OFDM as shown in[14].

The digital dimming scheme deals with the controlling of illumination levels by setting various duty cycles of pulse width modulation. The reverse polarity optical OFDM (RPO-OFDM) has been proposed in [15] shows integration with pulse width modulation to provide higher degree of control on dimming of light. RPO-OFDM being unipolar has lower spectral efficiency than DCO-OFDM but can

utilize full dynamic range of LEDs to achieve dimming without any effect on data rate. Although RPO-OFDM can fulfil the requirements of LiFi system, complexity has aroused as proper synchronization of PWM signal is required between transmitter and receiver. However, it is reported that SE of RPO-OFDM is half of that of DCO-OFDM. As a result, the power efficiency advantage over DCO-OFDM starts to diminish as the SE increases. Recently, enhanced ACO-OFDM (eACO-OFDM) has been introduced in [16]. In eACO-OFDM transmitter, subcarriers are divided in a harmonic sequence and each sequence is clipped and combined together in frequency domain for transmission. The eACO-OFDM can provide two times better SE than conventional ACO-OFDM which is almost identical to DCO-OFDM and also possess considerable signal to noise ratio gains over ACO-OFDM as shown in [16]. It has been also reported that eACO-OFDM with 1024 QAM size can provide 7dB better optical power efficiency than DCO-OFDM. Higher optical energy dissipation is a desirable property for illumination based LiFi applications, but it is considered as a disadvantage for dimmable based LiFi applications. However, eACO-OFDM is suitable candidate for dimmable based LiFi applications due to their optical SNR performance.

Similar to the dimming mechanism of AHO-OFDM, by controlling the average amplitude of feeding signal of LED, hybrid layered asymmetrically clipped OFDM (HLACO-OFDM) is proposed in [17]. The simulation results have been shown that HLACO-OFDM provides 1~99% wide dimming facility with stable spectral output than DCO-OFDM. In [18] fractional reversed polarity OFDM (FRPO-OFDM) is studied. The FRPO-OFDM uses ACO-OFDM signal sequence with information carrying brightness control sequence to provide as wide as 10~90% measured brightness level in room environment. Another optical OFDM method which is presented in [19] has showed that, multiple pulse position modulation aided reverse polarity optical OFDM (MPPM RPO-OFDM) can be able to provide better effective spectral efficiency than AHO-OFDM and RPO-OFDM.

Despite all the above mentioned studies, the most appropriate OFDM format for LiFi is still not clear. This work investigates the performance of ASCO-OFDM based LiFi in terms of power efficiency and dimming capacity. The next section describes an ASCO-OFDM system.

## III. ASCO-OFDM SYSTEM

In this section ASCO-OFDM modulation scheme is described briefly. ASCO-OFDM is a mixture of ACO-OFDM and SCO-OFDM. For the case of ASCO-OFDM, the ACO-OFDM part is used to modulate the odd subcarriers, and SCO-OFDM component is used to transmit the even subcarriers. No DC bias is added in an ASCO-OFDM scheme; thus it achieves better performance than other modulation schemes in terms of both power efficiency and BER. The block diagram of an ASCO-OFDM system is shown in Fig. 1 [4].

In ASCO-OFDM transmitter, the input block of complex symbols is first divided into three parts, two  $(N/2) \times 1$ 

signal vectors  $X_{odd}^i$  and  $X_{odd}^j$ , one  $(N/2 - 1) \times 1$  signal vector  $X_{even}$ . In order to ensure the output signal from IFFT block is real, Hermitian symmetry is maintained for the signals. Then 2N-point IFFT is applied on  $X_{odd}^{i}$ ,  $X_{odd}^{j}$ , and  $X_{even}$  to generate real bipolar signal vectors  $x_{odd}^i$ ,  $x_{odd}^j$  and  $x_{even}$  respectively. To guarantee the non-negative prerequisite of the transmitted signals, all negative values in  $x_{odd}^{i}$  and  $x_{odd}^{j}$  are clipped to zero to make  $x_{odd}^{i,c}$  and  $x_{odd}^{j,c}$ , respectively. Since each sample in  $x_{even}$  is converted from even subcarriers, it has the relationship of  $x_{even}(n) =$  $x_{even}(n+N)$ . Since the negative values are clipped, half of the information carried in  $x_{even}$  is lost. Thus, two signal vectors,  $x_{even}^{cn}$  and  $x_{even}^{cp}$ , are produced for transmitting the information in  $x_{even}$  where  $x_{even}^{cn}$  has only the positive values of  $x_{even}$ , and  $x_{even}^{cp}$  has only the negative values of  $x_{even}$  which are inverted to positive magnitude. The transmitted signal contains two successive sub-blocks,  $x_{ASCO}^{i}$  and  $x_{ASCO}^{j}$  where  $x_{ASCO}^{i} = x_{odd}^{i,c} + x_{even}^{cn}$  and  $x_{ASCO}^{j} =$  $x_{odd}^{j,c} + x_{even}^{cp}$ . When added with the cyclic prefix, the signals,  $x_{ASCO}^{i}$  and  $x_{ASCO}^{j}$  are denoted by  $\tilde{x}_{ASCO}^{i}$  and  $\tilde{x}_{ASCO}^{j}$ . respectively. These signals are transmitted through an optical channel by an LED.

In the ASCO-OFDM receiver, After removing the cyclic prefix, the arrival signals,  $y_{ASCO}^i$  and  $y_{ASCO}^j$ , are, respectively, transformed by a 2N-point FFT into the frequency domain to yield  $Y_{ASCO}^{i}$  and  $Y_{ASCO}^{j}$ . Then, a frequency domain equalizer with the knowledge of channel state information is applied to  $Y_{ASCO}^{i}$  and  $Y_{ASCO}^{j}$  to yield  $Y^{i}$  and  $Y^{j}$ , respectively. The time domain equivalence of the odd components of  $Y^i$  and  $Y^j$  are represented as  $y^i_{odd}$  and  $y^j_{odd}$ . These signals are clipped and the clipped versions of  $y_{odd}^i$  and  $y_{odd}^j$  are denoted as  $y_{odd}^{i,c}$  and  $y_{odd}^{j,c}$ , respectively. These signals are then transformed into the frequency domain by using FFT to form  $Y_{odd}^{i,c}$  and  $Y_{odd}^{j,c}$ , respectively. Compared to  $y_{odd}^i$  and  $y_{odd}^{j}$ ,  $y_{odd}^{i,c}$  and  $y_{odd}^{j,c}$  have the same symbol on the odd subcarriers, but the clipping noise appears on the even subcarriers. Therefore,  $Y_{even}^{cn}$  and  $Y_{even}^{cp}$  even are obtained by subtracting  $Y_{odd}^{i,c}$  and  $Y_{odd}^{j,c}$  from  $Y^i$  and  $Y^j$ , respectively. By subtracting  $Y_{even}^{cp}$  from  $Y_{even}^{cn}$ ,  $Y_{even}$  can be obtained as  $Y_{even} = Y_{even}^{cn} - Y_{even}^{cp}.$ 

## IV. DIMMING CONTROL OF ASCO-OFDM SYSTEM

This section discusses about two dimming control methods and describes an ASCO-OFDM system having dimming control. Firstly, dimming control is discussed.

# A. Dimming Control

Dimming control is better than on-off control in terms of energy savings. It has better align lighting facility with human needs and lengthen lamp life. Unluckily, they also increase complexity and expense and may shorten lamp life under some conditions. The intensity or brightness of an LED can be adjusted by controlling the forward current through the LED. There are generally two possible methods by which LEDs dimming can be possible; they are: (1) analog dimming and (2) digital dimming. Analog dimming is also recognized as amplitude modulation (AM) or continuous current reduction (CCR), and the simplest

example of digital dimming modulation techniques is pulse width modulation (PWM) [22], [26].



Fig. 1. ASCO-OFDM transmitter and receiver configuration with PWM dimming system.





In CCR, brightness control is accomplished by decreasing the forward current and in the PWM scheme; the duty cycle of the forward current is changed. Dimming can be achieved by reducing the forward current and it is a cost effective way for dimming LEDs. The luminous intensity is reduced proportionally to the current and a brightness level of 10% of maximum is reachable. PWM is the preferred solution in industry for dimming LEDs because it has a wide dimming range capacity and a linear relationship between the light output and the duty cycle [1]. The LED manufacturers also recommend PWM for dimming LEDs as many of them belief that LEDs exhibit low chromaticity shift under this dimming technique. In contrast, the experiments performed in [20], [21] show that the chromaticity shift is small under both dimming schemes (CCR and PWM) for phosphorconverted (PC) white LEDs. But the CCR dimming scheme results higher luminous efficiency, irrespective of the LED type.

#### B. Dimming Control for ASCO-OFDM

PWM is an efficient means of perfectly controlling LED illumination without suffering color rendering of the emitted light. PWM is a very well organized means for changing the average optical power emitted by an LED over a wide dimming range [22]. The PWM signal uses a train of pulses, whose widths are adjustable, thus resulting in the variation of the DC level of the waveform. PWM pulses are flat-topped and have the same amplitude. The pulse recurrence rate (the number of pulses per second) is constant. Data are transferred by the width of the pulses. Assuming the period of the PWM signal as  $T_{PWM}$ , the PWM signal p(t) is given by

$$p(t) = \begin{cases} 1, \ 0 \le t \le T_1 \\ 0, \ T_1 < t \le T_{PWM} \end{cases}$$
(1)

where  $0 \le t \le T_{PWM}$ . In this case, p(t) has a duty cycle of  $d = T_1/T_{PWM}$  where  $T_1$  is the duration of the PWM pulse and  $T_{PWM}$  is the period of the PWM signal. Since PWM signal is periodic so it can also be expressed in terms of a Fourier series as follows.

$$p(t) = \sum_{n=-\infty}^{\infty} C_n e^{j2\pi nt/T_{PWM}}$$
(2)

where  $C_n$  represents the Fourier coefficients of p(t). In the following, a PWM dimming based ASCO-OFDM system is discussed. The block diagram of the overall system is shown in Fig. 1. As shown in the transmission part of Fig. 1, the

output of the cyclic prefix (CP) block,  $x_{ASCO}^{ij}(n)$  is multiplied with the p(t). The PWM based ASCO-OFDM signal is shown in Fig. 2. The term  $x_{ASCO}^{ij}(n)$  can be expressed as follows.

$$x_{APWM}^{ij}(n) = p(t) \times x_{ASCO}^{ij}(n)$$
(3)

When we add cyclic prefix then the transmitted signals,  $x_{ASCO}^i$  and  $x_{ASCO}^j$ , are respectively denoted by  $\tilde{x}_{ASCO}^i$  and  $\tilde{x}_{ASCO}^j$ .

$$x_{APWM}^{ij}(n) = \tilde{x}_{ASCO}^{i}(n) + \tilde{x}_{ASCO}^{j}(n)$$
(4)

After that they are transmitted by an LED through an optical channel. The received signals are given by:

$$\tilde{y}^{i}_{APWM}(n) = \tilde{x}^{i}_{APWM}(n) \otimes h(n) + w^{i}(n)$$
(5)

$$\tilde{\mathbf{y}}_{APWM}^{j}(n) = \tilde{\mathbf{x}}_{APWM}^{j}(n) \otimes h(n) + w^{j}(n)$$
(6)

where h(n) is the impulse response of optical channel which is designed as  $h(n) = [h(0), h(1), \dots, h(l)]$ , and the sum of all noise,  $w^i(n)$  or  $w^j(n)$ , is approximately designed as additive white Gaussian noise. The term  $x_{APWM}^{ij}(n)$  is fed to the digital to analog and electrical to optical block and we got the  $x_{APWM}^{ij}(t)$  which is analog and then by optical channel we got the output  $y_{APWM}^{ij}(t)$ . Next it is fed to the analog to digital and optical to electrical PD block which made the output  $y_{APWM}^{ij}(n)$ . After removing the cyclic prefix, the arrival signals,  $y_{ASCO}^i$  and  $y_{ASCO}^j$ , are, respectively, altered by a 2N-point FFT into the frequency domain to yield  $Y_{ASCO}^i$  and  $Y_{ASCO}^j$ .  $Y^i$  and  $Y^j$  can be shown in the frequency domain.

## V. SIMULATION RESULTS

In this section, the performance of four modulation schemes ACO-OFDM, DCO-OFDM, ADO-OFDM and ASCO-OFDM are compared using simulations with MATLAB tool. The metrics used to evaluate the performance of these modulation scheme is the electrical energy per bit to noise power spectral density,  $E_{b(Elec)}/N_o$ , and optical energy per bit to noise power spectral density,  $E_{b(Opt)}/N_o$ . Furthermore, AWGN channels are taken into consideration. The results are shown for ideal illumination level that is 50% dimming level. For fair comparison of power efficiency, the data rate per unit normalized bandwidth, R/B, has to be the same for different modulation schemes. For example, a R/B value of 2 can be achieved by 16-OAM ACO-OFDM or by 4-OAM DCO-OFDM. This is because DCO-OFDM uses all the subcarriers whereas ACO-OFDM uses only the odd subcarriers to carry the data. For the case of ADO-OFDM, the use of 4-QAM by odd and even subcarriers ensures a R/B value of 2. On the other hand, ASCO-OFDM using 4-QAM, 8-QAM, 16-QAM and 64-QAM provide R/B values of 1.5, 2.25, 3 and 4.5, respectively. This is because the ACO (odd) subcarriers in ASCO-OFDM carry half independent data and SCO (even) elements carry full independent data. The performance of DCO-OFDM and ADO-OFDM depend on the amount of DC bias applied. It is shown in [27] that for 4-QAM DCO-OFDM and for 4-QAM ADO-OFDM, the level of optimum DC bias is 1.5 and 1.25, respectively times the standard deviation of the unclipped bipolar OFDM signal. These bias values are considered in the simulations of this work. Moreover, similar to the work in [27], the ACO element in 4-QAM ADO-OFDM and 16-QAM ADO-OFDM are assumed to be 0.2 (20%) and 0.6 (60%), respectively, of the total signal power.

Fig. 3 shows the plots of  $E_{b(Elec)}/N_o$  versus BER for the OFDM modulation schemes at a R/B value in between 1.5 to 2.25. In this case, 4-QAM DCO-OFDM, 4-QAM ADO-OFDM and 16-OAM ACO-OFDM have R/B values of 2, while 4-QAM ASCO-OFDM has a R/B value of 1.5 and 8-OAM ASCO-OFDM has a R/B value of 2.25. It is observed that ASCO-OFDM has the best, while ADO-OFDM has the worst electrical power efficiency compared to others. 4-QAM ASCO-OFDM has 4.5 dB better electrical power efficiency than 16-QAM ACO-OFDM and 4-QAM DCO-OFDM at a BER of 10<sup>-4</sup>. However, 4-QAM ASCO-OFDM has a R/B value of 1.5 which is only 75% of R/B value of 2 in 16-OAM ACO or 4-OAM DCO-OFDM. However, 8-QAM ASCO-OFDM with a R/B value of 2.25, is 2 dB more electrically power efficient than ACO-OFDM and DCO-OFDM with R/B value of 2. Hence, 8-QAM ASCO-OFDM can provide more  $E_{b(Elec)}/N_o$  efficiency even at providing a 12.5% greater data rate than ACO-OFDM or DCO-OFDM.

Fig. 4 shows the plots of  $E_{b(Opt)}/N_o$  versus BER results for the OFDM formats. It can be seen that at a BER of  $10^{-4}$ , 4-QAM ASCO-OFDM has 25% less data rate, but 2 dB, 6 dB and 8 dB better optical power efficiency than 16-QAM ACO-OFDM, 4-QAM DCO-OFDM, and 4-QAM ADO-OFDM, respectively. On the other hand, 8-OAM ASCO-OFDM has 12.5% more data rate, but 3 dB and 4 dB better optical power efficiency than 4-QAM DCO-OFDM and 4-QAM ADO-OFDM, respectively. 8-QAM ASCO-OFDM has 12.5% more data rate but 1 dB less optical power efficiency than 16-QAM ACO-OFDM. Hence, both 16-QAM ACO-OFDM and 8-QAM ASCO-OFDM have excellent optical power efficiency when operating near R/Bvalue of 2. From Fig. 4 it can also be seen that for greater dimming (lower illumination), 4-QAM ASCO-OFDM provides good BER performance. For example, at  $E_{h(Ont)}/$  $N_o$  of 5 dB, it has a low BER of 10<sup>-3</sup>, for  $E_{b(Opt)}/N_o$ ranging from 5 dB to 8 dB, the BER is between 10<sup>-3</sup> to 10<sup>-4</sup>. This values of BER can be reduced to 10<sup>-9</sup> by the use of convolutional or turbo channel encoders.

Next, the optical power efficiency of ASCO-OFDM is compared with other OFDM formats for the case of higher order modulations at a R/B value in between 4 to 4.5. Fig. 5 shows the plots of  $E_{b(Opt)}/N_o$  versus BER results for 256-QAM ACO-OFDM, 16-QAM DCO-OFDM, 64/4 QAM ADO-OFDM (64 QAM ACO and 4 QAM DCO), 16-QAM ASCO-OFDM and 64-QAM ASCO-OFDM. It can be seen that at a BER of 10<sup>-4</sup>, 16-QAM ASCO-OFDM has 25% less data rate, but 5 dB, 7 dB and 9 dB better optical power efficiency than 64/4-QAM ADO-OFDM, 256-QAM ACO- OFDM, 16-QAM DCO-OFDM, and respectively. On the other hand, 64-QAM ASCO-OFDM has 12.5% more data rate, as well as 0.5 dB, 2.5 dB and 5 dB more optical power efficiency than 64/4-QAM ADO-OFDM, 256-QAM ACO-OFDM and 16-QAM DCO-OFDM, respectively. Hence, at a R/B value around 4, 64/4-QAM ADO-OFDM and 64-QAM ASCO-OFDM have excellent optical power efficiency, where 64-QAM ASCO-OFDM is slightly superior to ADO-OFDM when data rate and optical power efficiency are taken into consideration.



Fig. 3. Plots of  $E_{b(Elec)}/N_o$  versus BER to compare electrical power efficiency of optical OFDM.



Fig. 4. Plots of  $E_{b(Opt)}/N_o$  versus BER at lower constellations.



Fig. 5. Plots of  $E_{b(Opt)}/N_o$  versus BER at higher constellations.

# VI. CONCLUSION

This paper describes a framework to incorporate the PWM scheme for ASCO-OFDM transmitters and receivers.

For this, the generated ASCO-OFDM signal in the electrical domain is multiplied with the PWM signal and the resultant signal is converted to the optical signal by optical modulators. Next, the BER performance results are presented for PWM based ASCO-OFDM and other optical OFDM formats. When the signal illumination is ideal, the ASCO-OFDM exhibits better electrical power efficiency compared to ACO-OFDM, DCO-OFDM and ADO-OFDM. It is shown that at a R/B value around 2, 8-QAM ASCO-OFDM has 12.5% more data rate and better optical power efficiency than DCO-OFDM and ADO-OFDM counterparts, but only 1 dB less optical power efficiency than 16-QAM ACO-OFDM. So, for low data rates where R/B value is around 2, both ASCO-OFDM and ACO-OFDM are suitable. On the other hand, at a R/B value around 4, 64-QAM ASCO-OFDM has 12.5% more data rate, but greater optical power efficiency than 256-QAM ACO-OFDM, 16-QAM DCO-OFDM and 64/4QAM ADO-OFDM. So, for higher data rate where R/B value is around 4, ASCO-OFDM and ADO-OFDM are good choices. Results also indicate that 4-QAM ASCO-OFDM is the best choice when dimming level is increased that is when signal illumination is decreased. The results in this paper are presented for AWGN channel. In future, multipath channels should also be considered for a PWM based ASCO-OFDM scheme.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Shahfida Amjad Munni conducted the study, performed the analysis and simulations under the supervision of M. Rubaiyat Hossain Mondal. Shahfida Amjad Munni and Rashed Islam wrote the first draft of the manuscript. M. Rubaiyat Hossain Mondal edited the manuscript. All authors reviewed and approved the final version of the manuscript.

#### REFERENCES

- [1] I. Stefan, H. Elgala, and H. Haas, "Study of dimming and LED nonlinearity for ACO-OFDM Based VLC systems" in *Proc. Wireless Communications and Networking Conference (WCNC)*, 2012.
- [2] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" Journal of Light Wave Technology, vol. 34, pp. 1533-1544, 2016.
- [3] J. Armstrong, "OFDM for optical communications," J Lightw Technol. 2009, vo. 27, no. 3, pp. 189-204.
- [4] N. Wu and Y. Bar-Ness, "A novel power-efficient scheme asymmetrically and symmetrically clipping optical (ASCO)-OFDM for IM/DD optical systems," *EURASIP Journal on Advances in Signal Processing*, 2015.
- [5] M. R. H. Mondal, "Impact of spatial sampling frequency offset and motion blur on optical wireless systems using spatial OFDM," *Journal on Wireless Communications and Networking*, vol. 1, no. 238, 2016.
- [6] M. R. H. Mondal and K. Panta, "Performance analysis of spatial OFDM for pixelated optical wireless systems," *Transactions on Emerging Telecommunications Technologies*, vol. 28, no. 2, 2017.
- [7] M. R. H. Mondal and J. Armstrong, "Analysis of the effect of vignetting on MIMO optical wireless systems using spatial OFDM," *J Lightw Technol*, vol. 32, no. 5, pp. 922-929, 2014.
- [8] M. I. Khan and M. R. H. Mondal, "Effectiveness of LED index modulation and non DC biased OFDM for optical wireless communication," in Proc. 2017 IEEE International Conference on Telecommunications and Photonics (ICTP), 2017.
- [9] M. A. Kabir and M. R. H. Mondal, "Edge-based transformation and entropy coding for lossless image compression," in *Proc. the International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 2017, pp. 717–722.

- [10] S. Bęczkowski and S. Munk-Nielsen, "Led spectral and power characteristics under hybrid PWM/AM dimming strategy," in *Proc. IEEE Energy Conversion Congress and Exposition*, 2010.
- [11] Q. Wang, Wang Z., and L. Dai, "Asymmetrical hybrid optical OFDM for visible light communications with dimming control," *IEEE Photonics Technology Letters*, vol. 27, no. 9, pp. 974-977, 2015.
- [12] Y. Namei, C. Guo, Y. Yang, P. Luo, and C. Feng, "Asymmetrical and direct current biased optical OFDM for visible light communication with dimming control," in *Proc. 2017 IEEE International Conference* on Communications Workshops (ICC Workshops), Paris, 2017, pp. 23-28.
- [13] R. Islam and M. R. H. Mondal, "Hybrid DCO-OFDM, ACO-OFDM and PAM-DMT for dimmable LiFi," *Optik, Elsevier*, vol. 180, pp. 939-952, 2019.
- [14] S. B. Cihan, E. Başar, and E. Panayırcı. "Optical spatial modulation OFDM system design," in *Proc. 24th Signal Processing and Communication Application Conference (SIU)*. 2016.
- [15] H. Elgala and T. Little, "Reverse polarity optical-OFDM (RPO-OFDM): Dimming compatible OFDM for gigabit VLC links," *Opt. Express*, vol. 21, pp. 24288-24299, 2013.
- [16] A. J. Lowery, "Enhanced asymmetrically clipped optical ODFM for high spectral efficiency and sensitivity," in *Proc. Optical Fiber Communications Conference and Exhibition (OFC)*, 2016.
- [17] Y. Sun, F. Yang, and J. Gao, "Novel dimmable visible light communication approach based on hybrid LACO-OFDM," *Journal of Lightwave Technology*, vol. 36, no. 20, pp. 4942-4951, 2018.
- [18] T. Q. Wang and X. Huang, "Fractional reverse polarity optical OFDM for high speed dimmable visible light communications," in *Proc. IEEE Transactions on Communications*, vol. 66, no. 4, pp. 1565-1578, April 2018.
- [19] Z. Yang, M. Jiang, L. Zhang, and H. Tan, "Enhanced multiple pulse position modulation aided reverse polarity optical OFDM system with extended dimming control," *IEEE Photonics Journal*, vol. 10, no. 3, pp. 1-17, June 2018.
- [20] Y. Gu, N. Narendran, T. Dong, and H. Dong, "Spectral and luminous efficacy change of high-power LEDs under different dimming methods," in *Proc. SPIE 6337, 6th International Conference on Solid State Lighting*, San Diego, USA, 2006.
- [21] M. Dyble, N. Narendran, A. Bierman, and T. Klein, "Impact of dimming white LEDs: Chromaticity shifts due to different dimming method," in *Proc. SPIE 5941, 5th International Conference on Solid State Lighting*, Bellingham, WA, 2005, pp. 291–299.
- [22] G. Ntogari, T. Kamalakis, J. Walewski, and T. Sphicopoulos, "Combining illumination dimming based on pulse-width modulation with visible-light communications based on discrete multitone," *Journal of Optical Communications and Networking*, vol. 3, pp. 56-65, 2011.
- [23] S. Rajagopal and R. D. Roberts, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Communications Magazine*, pp. 72-83, 2012.
- [24] S. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems," J Lightw Technol., vol. 31, no. 7, pp. 1063-1072, 2013.
- [25] J. Armstrong and A. J. Lowery, "Power efficient optical OFDM," *Electron Letter*, vol. 42, no. 6, pp. 370-372, 2006.
- [26] H. Elgala and T. D. C. Little, "Reverse polarity optical-OFDM (RPO OFDM): dimming compatible OFDM for gigabit VLC links," *Opt Express*, Aug. 2014.
- [27] M. R. H. Mondal, "Comparison of DCO-OFDM, ADO-OFDM, HDC-OFDM and HNC-OFDM for optical wireless communications," *Journal of Optical Communications*, Nov. 2018.

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