Pilot-Assisted Direct-Current Biased Optical Orthogonal Frequency Division Multiplexing Visible Light Communication System

Ayad A. Abdulkafi, Shahir F. Nawaf, Mohammed K. Hussein, Ibrahim K. Sileh, Fouad A. Abdulkafi

***Abstract*—**Visible light communication (VLC) is a new approach of optical wireless communication proposed to support the congested radio frequency (RF) spectrum. VLC systems are combined with orthogonal frequency division multiplexing (OFDM) to achieve high rate transmission and high spectral efficiency. In this paper, we investigate the Pilot-Assisted Channel Estimation for DC biased Optical OFDM (PACE-DCO-OFDM) systems to reduce the effects of the distortion on the transmitted signal. Least-square (LS) and linear minimum mean-squared error (LMMSE) estimators are implemented in MATLAB/Simulink to enhance the bit-error-rate (BER) of PACE-DCO-OFDM. Results show that DCO-OFDM system based on PACE scheme has achieved better BER performance compared to conventional system without pilot assisted channel estimation. Simulation results show that the proposed PACE-DCO-OFDM based on LMMSE algorithm can more accurately estimate the channel and achieves better BER performance when compared to the LS based PACE-DCO-OFDM and the traditional system without PACE. For the same signal to noise ratio (SNR) of 25 dB, the achieved BER is about 5×10^{-4} for LMMSE-PACE and 4.2×10^{-3} with LS-PACE while it is about 2×10^{-1} for system without PACE scheme.

***Keywords*—**Channel estimation, OFDM, pilot-assist, VLC.

I. Introduction

THE future wireless networks are obliged to provide ubiquitous high data rate in order to meet the broadband multimedia services to a large number of users. As a consequence, the RF is becoming scarce and getting more and more crowded. Therefore, new communications mediums are required to meet the increase in these future demands [1]. VLC has been emerging as an effective alternative and ideal complement technology to the RF system to overcome the spectrum limitations, especially for indoor wireless communications. In VLC technology, a low-cost and simple light-emitting diode (LED) can be used as transmitters by converting and translating the modulated electrical signal into an optical form. In reverse process, the VLC receiver allows a photodiode (PD) to detect the signal and demodulate it via simple digital signal processing [2]. Along with that, OFDM has also been utilized in VLC system because its ability of providing a higher data rate, reducing multipath effects and combating inter symbol interference (ISI) [3]. Since the intensity modulation/direct detection (IM/DD) mechanism is used by VLC systems; the transmitted signal has to be positive and real values. Moreover, the nonlinearities of transmitted signal using OFDM and the nature of wireless optical propagation results in higher complexity involved in retrieving the source data at the receiver [4]. As a consequent for this, sufficient techniques for channel estimation are required. The process of channel estimation attempts to estimate the channel effect on the transmitted signal as well to reduce it in order to perform the recovering of the transmitted signal at receiver.

Several channel estimation methods [5]-[7] have been suggested to improve the channel estimation performance of VLC systems and reduce its BER. However, these algorithms have been introduced for optical wireless communication systems rather than optical OFDM based systems. Furthermore, some techniques have been proposed for purposes other than channel estimation could also be used for channel estimation. For examples, the methods proposed in [8] and [9], have been dedicated to solve the nonlinearities of OFDM in VLC systems and to reduce the peak to average power ratio (PAPR) in such systems. In comparison to the RF systems scenario, there have been limited considerations on channel estimation for the OFDM VLC system. However, the principles of conventional channel estimation technologies, for example the pilot-aided channel estimation (PACE) schemes [10], [11], maybe also applicable to VLC scenarios. However, as a typical VLC system operates in indoor optical wireless channels [12] that differ from conventional wireless radio channels, a direct migration of channel estimation methods from RF to VLC may not be optimal. Motivated by this, the present work aims to implement the PACE scheme OFDM based VLC system and evaluates the system performances.

The rest of this paper is organized as following. Section II introduces the system models with detailed descriptions. The discussion analysis and performance evaluation is presented in Section III. Finally, the conclusion is drawn in Section IV.

II. System Descriptions

A. System Model

Fig. 1 shows the structure of the Simulink model implemented for the pilot-assisted based on direct-current-biased optical OFDM (DCO-OFDM) system. The DCO-OFDM type of O-OFDM technique is selected in this

Ayad A Abdulkafi is with the Electrical Engineering Department, Tikrit University, Salahaddin,34, Iraq (corresponding author, phone: 0096477-040-66660; e-mail: ayad_atiyah@ tu.edu.iq).

I. K. Sileh, Mohammed K. Hussein and Shahir F. Nawaf are with the Electrical Engineering Department, Tikrit University, Salahaddin, 34, Iraq.

Fouad A.Abdulkafi is with the Electric and Computer Engineering Department, Graduate School of Science and Engineering, Altinbas University, Istanbul, Turkey.

proposed VLC system. At the transmitter, the data are generated and modulated using M-ary quadrature amplitude modulation (QAM) and then appended with pilot symbols for the purpose of estimating the channel at receiver side. To ensure the real valued signal, a Hermitian symmetry is applied on the combined pilot and data symbols before transferring them to time domain with the inverse fast Fourier transform (IFFT). A cyclic prefix (CP) is appended to the result signal to prevent any inter symbol interference. A digital to analog converter (DAC) is used to obtain the analog form. Although, the real valued signal is ensured but still have negative parts which cannot be used for the IM/DD system. The DCO-OFDM scheme is employed here to satisfy the non-negative constrain of VLC system [3].

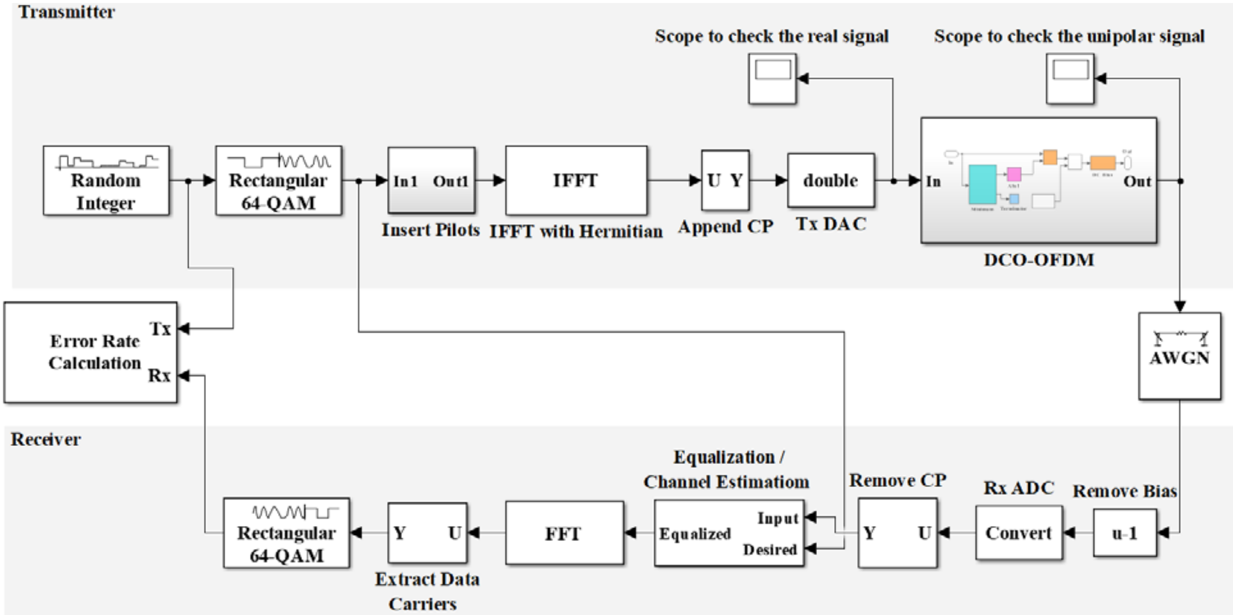

Fig. 1 Pilot-Assisted DCO-OFDM Simulink Model

The resulting signal is then converted to optical form by using LED and transmitted through optical wireless channel with additive white Gaussian noise (AWGN) model. At receiver side, the reverse operations are performed after optical to electrical conversion done by the PD (LED and PD component are not shown for simplicity). The implementation of receiver is an inversion of all functions of transmitter with addition of equalization and channel estimation parts. The DC bias is removed and the digital form is achieved using the analog to digital converter (ADC) to remove the CP appended at transmitter. The fast Fourier transform (FFT) operation is performed and data subcarriers are extracted with the help of channel estimation and equalization processes. The QAM demodulator estimates the original data. The BER performance is evaluated by calculating the bit error between the source data generated at transmitter and the estimated data at receiver as demonstrated in the system block diagram shown in Fig. 1.

B. DCO-OFDM Scheme

DCO-OFDM form is used here to obtain the non-negative signal. To do this, the IFFT output should be modified to guarantee the optical intensity modulation of positive signal. This can be achieved by following the steps shown in Fig. 2. First, the absolute of the minimum value of the bipolar signal is added to the bipolar signal. The output of this operation should be scaled (multiplying by a pre-defined constant) to be compatible with the LED's dynamic range. The resulting signal is shifted up/down to adjust the minimum value of the scaled signal to turn on voltage (TOV) of the LED by adding a TOV value to the scaled version of signal [13].

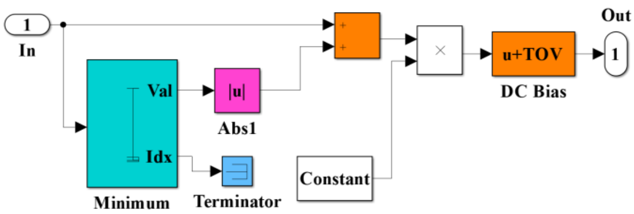

Fig. 2 DCO- OFDM Structure

C. Channel Estimation

Channel estimation is basically used in OFDM VLC system to extract the optical signal coherently, with a low BER by reducing the effect of noise and signal distortion [14]. The best way of estimating the channel in fading environment is to multiplex the known pilots' symbols into the transmitted signal. The pilot symbol pattern is known by both the receiver and the transmitter. From these pilot symbols, all channel attenuations are estimated with an equalizer. This method is called pilot symbol assisted modulation. Pilot symbols are transmitted in certain positions in the time and frequency grid of OFDM and the channel estimation is then performed by interpolation to decide and estimate the original data as shown in Fig. 3. Previous works proposed different algorithms for channel estimation. In this research paper, we have used the commonly methods, namely, LS and LMMSE estimators.

These channel estimators provide a low BER in short range data transmission wirelessly and improving the quality of transmission by reducing the effect of inter-channel interference in VLC systems [14]. However, the difficulties in implementing of these algorithms are considered the main problems. For instance, the LMMSE algorithm offers a very low BER but has a high complexity rate [4] which is not the case of the LS estimator. The full details and description of mentioned algorithms can be found in [14, and references therein].

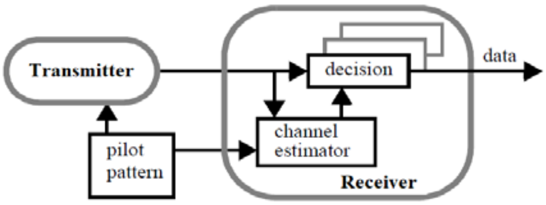

Fig. 3 Channel Estimation Approach

III. Discussion and Results Analysis

This section discusses the performance of proposed PACE-DCO-OFDM scheme based VLC system. The simulation results of the described approach with LS channel estimation and LMMSE channel estimation algorithms are evaluated and compared to the system without employing the PACE scheme to provide insights into different methods used in terms BER performance. The used parameters for simulation are listed in Table I.

TABLE I
Simulation Parameters

Parameter	Specification
System	PACE-DCO-OFDM
IFFT size (N)	128
Modulation	64 QAM
Channel Model	Optical wireless with AWGN
Channel Estimation	LS, LMMSE
Pilot spacing	4
CP length	32

Fig. 4 shows the real-valued time domain signals where Hermitian symmetry is applied to the input symbols of IFFT in frequency domain to ensure the non-complex signal constrained by IM/DD system. It should be noted that the input to the IFFT represents the combined data and pilot symbols which are symmetrically expanded with complex conjugate (e.g. $X_n = X^*_{N-n}$) are used at the IFFT input to produce a real-time domain output signal. The symbols $\boldsymbol{X_0}$ and $\boldsymbol{X_{N/2}}$ are set to zero to ensure that the output consists of only real values. However, and as illustrated in Fig. 4, the resulting time-domain signal is still in bipolar form and need to be modified.

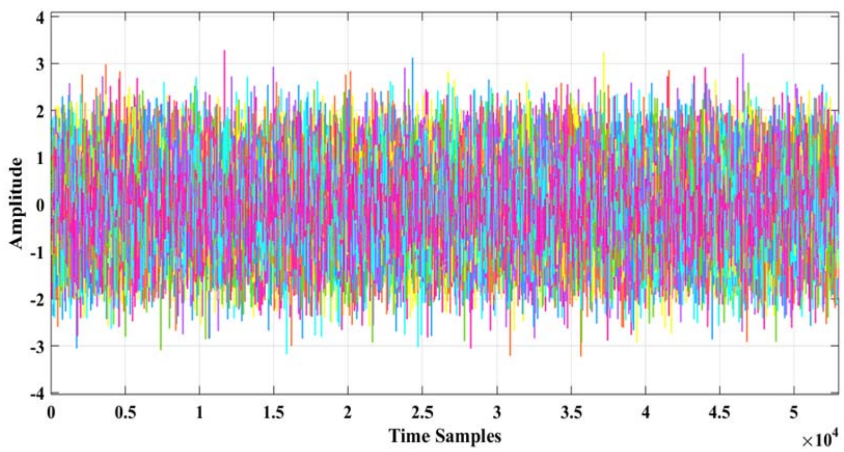

Fig. 4 Real bipolar OFDM time domain signals

DCO-OFDM scheme (explained earlier) is the used method of obtaining the unipolar signal by adding a positive DC bias and introducing the scaling operation. The unipolar real-time domain signal is demonstrated in Fig. 5. It is worth to mention that the addition of the constant biasing level leads to an increase in electrical power consumption. However, if the light source is used for illumination at the same time, the light output as a result of the DC bias is not wasted because it is utilized to fulfill the illumination function. Only in case of illumination is not required, such as in the uplink of a VLC system, the DC bias can compromise power efficiency. Moreover, it can be seen that there is no any distortion of signals and they have the same waveform as they are just scaled and shifted.

In order to demonstrate the effectiveness of the proposed PACE approach based DCO-OFDM system, the following analysis is provided along with numerical results. Fig. 6 shows comparison of the BER performances with and without PACE approach. It can be seen that the PACE -DCO-OFDM system based on LS and LMMSE algorithms has better BER performance compared to conventional system without PACE. In addition, our results demonstrate that the proposed PACE-

DCO-OFDM based on LMMSE scheme significantly outperforms the other approaches. At a SNR of 25 dB, the achieved BER values are 5×10^{-4} , 4.2×10^{-3} and 2×10^{-1} for the LMMSE-PACE , LS-PACE and system without PACE respectively. In other words, to achieve a BER of 10^{-3}, the required SNR values are 24.5 dB for LMMSE based PACE and 27.2 dB for the LS-PACE scheme while this BER target cannot be ensured without using the PACE method. This is because we have used a pilot pattern where 4% of the transmitted symbols are known (pilot spacing is 4). This pilot pattern is very sufficient to provide good estimations of the channel attenuations as well the receiver can use all these pilot symbols that are transmitted for detection.

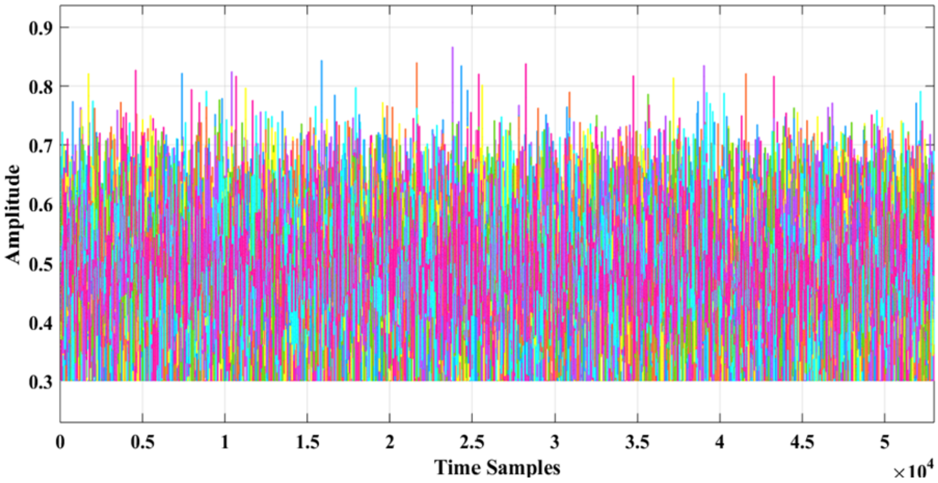

Fig. 5 Real unipolar OFDM time domain signals

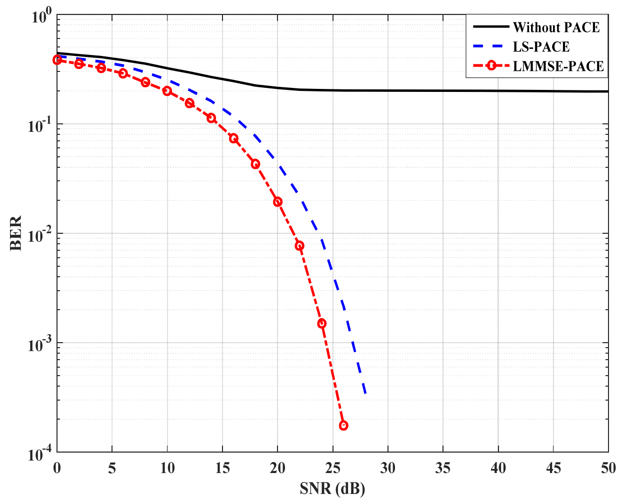

Fig. 6 BER versus SNR for different approaches

IV. Conclusion

This paper presents models for simulating a PACE-DCO-OFDM system in Simulink and subsystems in MATLAB files. Performance of system implementation in different channel conditions is tested. Different approaches for channel estimation are modeled and evaluated. BER versus SNR curves are used for comparing the results. Results confirm that the proposed PACE scheme outperforms other conventional approaches without PACE in terms of BER performances. Additionally, PACE-DCO-OFDM based on LMMSE algorithm has achieved a BER of 10^{-3} with a SNR of 24 dB, while the required SNR value is more than 27 dB for the LS algorithm proposed for PACE- DCO-OFDM system to achieve this target which cannot be obtained without using the PACE approach. The large PAPR of OFDM is another important issue which leads to signal distortion and BER performance degradations. In order to further improve the BER performance of proposed PACE-DCO-OFDM scheme, future works on PAPR reduction methods can be investigated along with their effect on BER performance.

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