On Channel Estimation in DC Biased optical OFDM systems over VLC Channels

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***Abstract*—Visible Light Communication(VLC) has been considered as a potential access option for 5G wireless systems to solve performance limitation due to bandwidth shortage at radio frequency (RF) band. In (VLC) system, illumination infrastructure has dual usage at the same time namely illumination and wireless data transmission. DC Biased optical (DCO)-OFDM has been proposed for VLC systems to provide optically power efficient solution and easy implementation. Wireless communication systems generally require estimating and tracking the fading channel in order to detect transmitted data coherently. In this work, comb type pilot arrangement with interpolation and block type pilot arrangement are proposed for the DCO-OFDM systems over visible light channels. Simulation results have verified that the proposed block type pilot arrangement based channel estimation has clear BER performance advantages compared with comb type pilot arrangement based channel estimation.**

***Index Terms*—visible light communication (VLC), DC biased optical orthogonal frequency division multiplexing (DCO-OFDM), comb type, block type, channel estimation, interpolation.**

I. INTRODUCTION

Due to the rapidly growing demand for bandwidth by the end-users, the spectrum congestion has become a serious issue in RF technologies. One of the alternative complementary technology that could be exploited in number of applications is the emerging VLC technology due to their broad bandwidths, license free spectrum, human friendly nature and inherent security [1]. Therefore, VLC will play an important role in the future wireless systems [2]. DC biased optical OFDM (DCO-OFDM) is proposed for VLC systems as a modification of OFDM due to its easy implementation.

Pilot symbol assisted channel estimation is commonly used modern communication system. There are two different pilot arrangements for pilot symbol assisted channel estimation (PSA-CE): block-type and comb-type. To increase spectral efficiency, comb type pilot based channel estimation with various interpolation techniques are extensively used in current wireless communication systems [3], [4]. Hence, it is easily utilized for VLC systems.

In literature, uniformly inserted pilot based channel estimation with linear interpolation is offered for VLC systems in [5]. Different interpolation methods performances are investigated for asymmetrically clipped optical (ACO)-OFDM system in [6], [7]. For DCO-OFDM systems, DFT post-processing channel estimation is offered in [8] to improve the channel least square estimation performance while assuming number of channel taps is known. Furthermore, the minimum mean square error (MMSE) is considered for the indoor VLC systems while accepting covariance of wireless channel coefficient matrix is known at the receiver [9].

Inserted pilot symbols over subcarriers have caused to the spectral and/or power efficiency losses. Optimization of the total number of pilot symbol can compensate some of these losses without performance degradation. To get balance between accuracy and complexity, comb type and block type one-dimensional channel estimations are generally considered in OFDM base systems.

In this paper, we applied block type pilot arrangement based channel estimation and comb type pilot arrangement based channel estimation with interpolation for DCO-OFDM systems over VLC channels. Our simulation results show that block type pilot arrangement outperform comb type pilot arrangement for DCO-OFDM systems.

The rest of this paper is organized as follows: In Section II, basic system model of the DCO-OFDM is given. In Section III, VLC channel model is given. In Section IV, we develop DCO-OFDM with PSA-CE for block-type and comb-type pilot arrangement and introduce interpolation methods. Simulation results are presented in Section V. Finally, section VI contains conclusions.

Notation: Throughout the paper, bold and capital letters '**A**' denote frequency domain matrices and bold and small letters '**a**' denote time domain matrices. The notations, $(.)^*$ and $(.)^T$ denote conjugate and transpose of a matrix or a vector respectively.

II. SIGNAL MODEL

We will consider DCO-OFDM system shown in Fig. 1. First, in the transmitter the data stream is divided into a block of $N/2-1$ complex data symbols presented as

$$\mathbf{Xd} = [X_1\ X_2\ X_3\ \cdots\ X_{N/2-1}]^T \tag{1}$$

where the symbols are taken from M-QAM constellations where M is the constellation size. To get a real output signal

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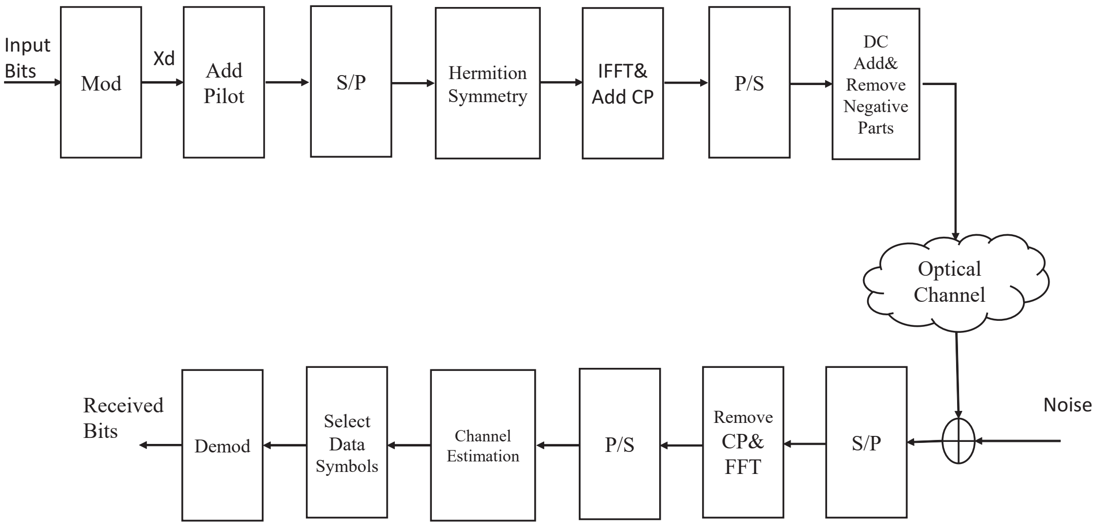

Fig. 1: DCO-OFDM Transmitter and Receiver configuration

required by intensity modulation direct detection (IM/DD) system, DCO-OFDM subcarriers must have Hermitian symmetry. In DCO-OFDM, only half of the subcarriers are carrying data symbol and other subcarriers set to conjugate mirror of first half to get real-valued time domain OFDM symbol. As a result, the complex data symbols are mapped onto a N-by-1 vector as shown below

$$\mathbf{X} = [0\ X_1\ X_2 \cdots\ X_{N/2-1}\ 0\ X^*_{N/2-1} \cdots\ X^*_2\ X^*_1]^T \quad (2)$$

An N-by-1 point IFFT is then applied on the vector **X** to build the time domain signal **x** as follows;

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j\frac{2\pi kn}{N}}. \quad (3)$$

After IFFT, last N_g sample whose length chosen longer than expected delay spread of the VLC channel is added as a cyclic extension (CP) to time domain signal **x** to avoid inter-symbol interference(ISI) as follows;

$$\tilde{x}[n] = x[N - N_g + n] \mod (N) \qquad 1 \le n \le N + N_g - 1 \quad (4)$$

This time domain bipolar signal $\tilde{x}[n]$ can be expressed in continuous domain as follows:

$$x_u(t) = \sum_{n=0}^{N_{tot}-1} \tilde{x}[n]\delta(t - nT_s) \quad (5)$$

where T_s is the sampling interval, $\delta(t)$ is the Dirac delta function and N_{tot} is the total length of the OFDM symbol $N_{tot} = N + N_g$.

Next, the bipolar OFDM signal is transformed to a unipolar signal by adding a DC bias B_{DC}. In practice an OFDM signal has a large peak to average power ratio (PAPR). Therefore, if B_{DC} is not to be excessive, the peaks of the negative going signal must first be clipped. This adds a clipping noise component to the transmitted signal [10]. After clipping process, transmitted symbol $x(t) \ge 0$ can be expressed in continuous domain as follows:

$$x(t) = x_u(t) + B_{DC} + n_c(B_{DC}) \quad (6)$$

where B_{DC} DC bias and $n_c(B_{DC})$ clipping noise. Clipping noise is inversely proportional with B_{DC}. Also, optimum clipping level changes with constellation size. For higher constellation size like 64 and 256 QAM need high SNR, so $n_c(B_{DC})$ must be small and as a consequence B_{DC} must be large. In literature, B_{DC} is generally determined relatively the power of $x_u(t)$ as follow:

$$B_{DC} = k\sqrt{E\{x_u^2(t)\}}. \quad (7)$$

This is defined as a bias of $10log10(k^2 + 1)$ dB, because it lifts the power of the DCO-OFDM signal relative to $x_u(t)$ [11].

If the impulse response, describing the multipath propagation in an indoor optical wireless channel, is $h(t)$, the received electrical signal for the baseband channel model is given by

$$r(t) = \alpha\psi\left(x(t) \otimes h(t)\right) + w(t) \quad (8)$$

where α is the responsivity of the photodetector (A/W), ψ is the gain of an LED (W/A), $w(t)$ is total noise consist of the ambient light shot noise and thermal noise and it is modeled as the additive white Gaussian noise (AWGN).

Overall channel impulse response in electrical domain $h(t)$ is defined as

$$h(t) = p(t) \otimes c(t) \otimes p(-t) \quad (9)$$

where $p(t)$ is the impulse response of the pulse shaping filter and $c(t)$ is the optical power delay profile (PDP). The discrete received signal for $h[n] = h(nT_s)$ and $r[n] = y(nT_s)$ then can be written as

$$r[n] = \sum_{l=0}^{L} h(l)x(n-l) + w(n) \tag{10}$$

where L is the total number of paths of the VLC channel and $\alpha\psi = 1$ is assumed.

At the receiver, DCO-OFDM symbols first passed through the serial to parallel converter. Once the received signal is parallelized, the cyclic prefix is removed and passed to the FFT operator. Therefore, the channel is diagonalized by the FFT.

The FFT output at the kth subcarrier can be written as

$$R[k] = X[k]H[k] + W[k] \tag{11}$$

where

$$H[k] = \sum_{n=0}^{N-1} h[n]e^{\frac{-j2\pi nk}{N}} \tag{12}$$

The FFT operation reproduces the mirrored frame structure designed in the transmitter. The upper half (elements 2 to N/2) of each frame is retained as the valid result. The complex data is then passed through the QAM demodulator to recover the binary data.

The FFT output received signal can be expressed in vector form as

$$\mathbf{R} = \mathcal{X}\mathbf{H} + \mathbf{W} \tag{13}$$

where $\mathbf{R} = [R(0), R(1), \cdots, R(N-1)]^T$, $\mathbf{H} = [H(0), H(1), \cdots, H(N-1)]^T$, $\mathbf{W} = [W(0), W(1), \cdots, W(N-1)]^T$ and $\mathcal{X}$ is $N \times N$ diagonal matrice whose elements are $X[k]$

III. CHANNEL MODEL

For computer simulations, a typical office place with dimensions of $5 \times 5 \times 3$ m is considered with one light source at the ceiling of the room. The optical power delay profile $c(t)$ is obtained by the received optical power and the delays of direct/indirect rays and corresponding delays [12]. By the usage of PDP, the discrete multi-path channel impulse response $h[n]$ between the transmitter and the receiver is shown in Fig. 2 while $\sum_{l=0}^{L-1} h[l]^2 = 1$.

IV. CHANNEL ESTIMATION

In VLC system, knowledge of channel state information at receiver is crucial for proper detection of modulated symbols. Thus, the channel estimation is the essential part of receiver design for DCO-OFDM systems.

Pilot based channel estimation is commonly used for OFDM based wireless communication systems. There are two different pilot arrangements for pilot symbol assisted channel estimation (PSA-CE), namely block-type pilot arrangement and comb-type pilot arrangement. (see Fig. 3)

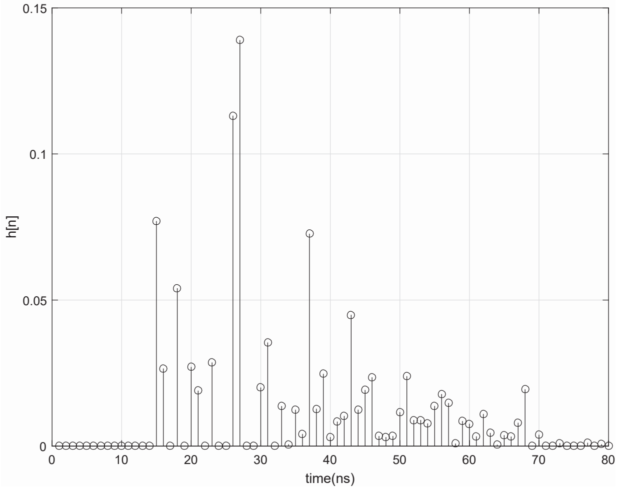

Fig. 2: Impulse response of the VLC channel

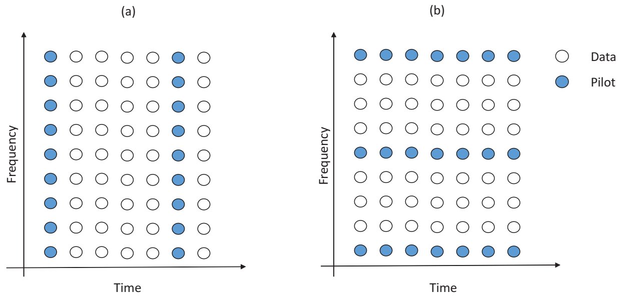

Fig. 3: Plot arrangement a) Block-type b) Comb-type

The received signals at pilot subcarier (k_p) can be expressed for each DCO-OFDM as follows:

$$R[k_p] = H[k_p]x_p + W[k_p] \tag{14}$$

where x_p is the pilot symbol and $W(k_p)$ is additive white Gaussian noise at pilot destination. Then, the received signal at pilot symbols are processed with known pilot blocks for estimation of channel frequency response at pilot destinations [9].

A. Comb Type Pilot Arrangement

In the comb-type arrangement, pilot symbols are replaced with selected subcarriers in each OFDM symbol. After the channel frequency responses at pilots are estimated by the least square (LS) then channel parameters at the positions of data symbols are determined by interpolation [5]. The piecewise linear interpolation is commonly used with pilot symbol assisted channel estimation techniques since it is simple and easy to implement. In this study, piecewise linear interpolation (PLI) is used as an interpolation techniques. The least square solution of the channel estimate can be written as follows [9] ;

$$\hat{H}[k_p] = R[k_p]/\mathcal{P}[k], \tag{15}$$

where $k_p = 2 : PIR : (N/2)$ and PIR is the pilot insertion rate for the comp-type pilot distribution. In VLC, the wireless channel is quasi-static so that estimated channel coefficients in the DCO-OFDM pilot symbols can be employed as the channel response of the other OFDM symbols in the same frame. Therefore, the block type channel estimation is also considered.

B. Block Type Pilot Arrangement

In block type, pilot tones are inserted into all subcarriers in the first OFDM symbol of the block. The channel frequency response estimated for the first OFDM symbols is then used for equalization of the rest of the symbols in the block. Block-type pilot arrangement is preferred for slow time-varying channels. The block type interpolation could be considered where PIR=1 is selected and no interpolation is applied. As a summary, the received signal at pilot symbols is processed with known pilot blocks for estimation of channel frequency response.

V. SIMULATION RESULTS

Channel estimation performance of proposed pilot arrangements is verified by computer simulation for VLC channel model. The DCO-OFDM system parameters for both pilot arrangements are chosen as follows: the number of subcarriers 2048, pilot insertion ratio =1/8. To evaluate solely channel estimation performance, perfect synchronization is considered. Linear interpolation method is used for comb-type pilot arrangement.

DCO-OFDM signal is generated within the 1 GHz bandwidth with $N = 2048$ subcarriers and CP is selected as $G = 256$ samples. The uncorrelated random data symbols are generated and the M-level quadrature amplitude modulation (QAM) formats chosen such as 4-QAM, 16-QAM.

The computer simulation results for the DCO-OFDM based VLC systems to show the BER performance of the proposed pilot based channel estimation are in Fig. 4 and Fig. 5. In figures, the legends *block-type, comb-type* denote different pilot arrangements.

Fig. 4 shows the BER performances of different channel estimation methods and DC biased levels for 4-QAM modulation. We also included the performance of receiver for the case of perfect CSI. To demonstrate the effect of a moderate and large DC bias values, 13 dB and 21 dB are chosen in this paper.

As can be seen from Fig. 4, the BER performance of the channel estimation employing the block-type pilot arrangement is nearly the same as compare to BER performance of the channel estimation employing comb-type pilot arrangement in both biased level.

The performance of the higher order modulation scheme namely 16-QAM is also investigated in Fig. 5. It is observed that the block-type pilot arrangement outperforms the comb type pilot arrangement in both biased levels.

In Fig. 5, it is also shown that the comb-type pilot arrangement has an irreducible error floor at high SNR values for 16-QAM. Because clipping negative part of transmitted signal corrupts pilot symbols and degrades channel estimation performance.

Our result showed that the block type pilot arrangement is robust for both higher SNRs and higher order modulations.

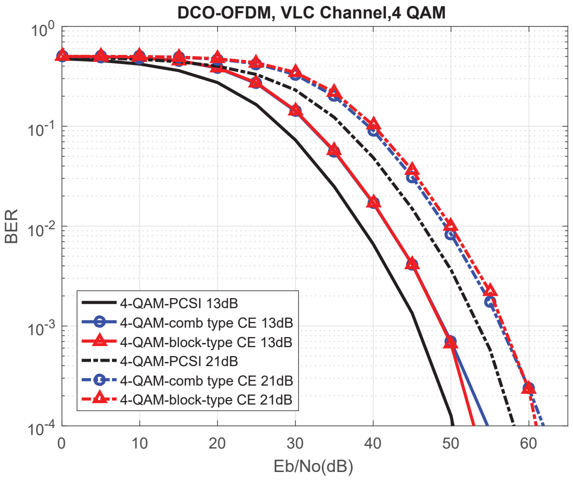

Fig. 4: BER Performance of 4-QAM DCO-OFDM with different channel estimation

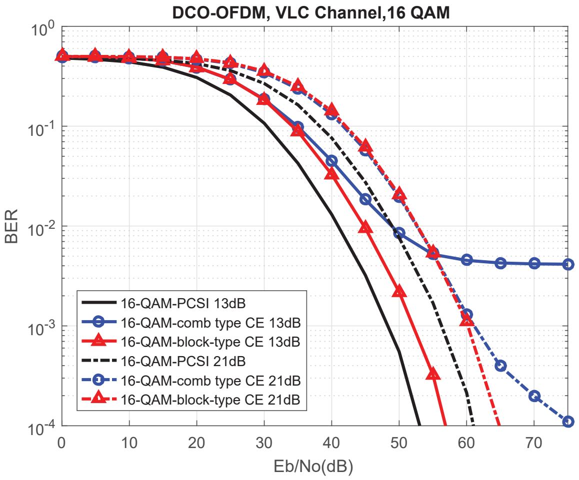

Fig. 5: BER Performance of 16-QAM DCO-OFDM with different channel estimation

VI. CONCLUSION

The comb-type pilot channel estimation are generally preferred to satisfy the need for equalizing when the channel changes even in one OFDM block. However, we showed that its performance is significantly degraded for DCO-OFDM systems because of clipping noise. Therefore, block-type pilot arrangement more suitable for DCO-OFDM system over VLC channels.

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