Pilot Assisted Channel Estimation for Asymmetrically Clipped Optical OFDM over Visible Light Channels

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***Abstract*—The Visible Light Communication(VLC) has drawn significant attention recently for wireless communication in addressing the performance limitations of wireless systems due to the scarcity of bandwidth. In VLC system, the visible lights is used not only for illuminating rooms but also for an optical data transmission. Asymmetrically clipped optical orthogonal frequency-division multiplexing (ACO-OFDM) has been proposed for VLC systems to provide optically power efficient solution in the optical domain. The estimation of wireless channel is crucial in order to detect the transmitted data coherently. In this work, different interpolation based channel estimations for comb-type pilot distribution are proposed over visible light channels. Computer simulation results have confirmed that the proposed spline and low pass interpolation based channel estimation techniques have a clear BER performance advantages compared with linear and pchip interpolation based channel estimations for higher order modulations.**

***Index Terms*—visible light communication, asymmetrically-clipped optical orthogonal frequency division multiplexing, channel estimation, interpolation.**

I. Introduction

Visible light communication (VLC) research increased tremendously since its spectrum is not regulated and it has much wider bandwidth then conventional other communication systems [1]. Also for VLC systems, there are no health regulations to restrict the transmit power and VLC provides higher security. Therefore VLC will play a crucial role in the future wireless systems [2]. Asymmetrically clipped optical OFDM (ACO-OFDM) is proposed to be more power efficient for optical communication in [3]. It is shown that the ACO-OFDM requires less power than the DC biased optical (DCO)-OFDM for a given normalized bandwidth [4].

The channel estimation based on pilot symbols is generally employed for frequency selective channels. Its application with interpolation techniques is widely used for current radio frequency wireless systems [5]. Therefore, it is also applied for VLC systems. In [6], the channel estimation based on uniformly inserted pilot symbols and linear interpolation is proposed for VLC systems. To enhance the channel least square estimation performance, in [7], the DFT post-processing channel estimation is proposed for DCO-OFDM systems while assuming the total number of channel taps is known. Moreover, the minimum mean square error (MMSE) method is to minimize the mean square errors (MSE) is also proposed for the indoor visible light communication system while assuming the channel coefficient covariance is available at the receiver [8].

The one-dimensional(1D) channel estimations are usually preferred in OFDM based systems to accomplish the trade-off between complexity and accuracy. In this paper, we investigate least square with 1D interpolation channel estimations for the comb-type pilot arrangement. Inserted pilot symbols over subcarriers has disadvantage of a loss in spectral and/or power efficiency. It is desirable to reduce/optimize the number of total pilot symbols by using better interpolations. Therefore, in this paper, we applied the spline based channel estimation for ACO-OFDM systems over VLC channels.

The rest of this paper is organized as follows: In Section II,basic system model of the ACO-OFDM is given. In Section III, we develop ACO-OFDM with pilot symbol assisted channel estimation (PSA-CE) and introduce interpolation methods. Simulation results are presented in Section IV. Finally, section V contains conclusions.

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

II. Signal Model

The block diagram of an ACO-OFDM system is depicted in Fig. 1. First, the information stream is divided into a block of $N/4$ complex data symbols denoted by

$$\mathbf{X}_d = [X_1 \ X_2 \ X_3 \ \cdots \ X_{N/4}]^T \tag{1}$$

where the symbols are drawn from M-ary quadrature amplitude modulation (M-QAM) constellations. To ensure a real

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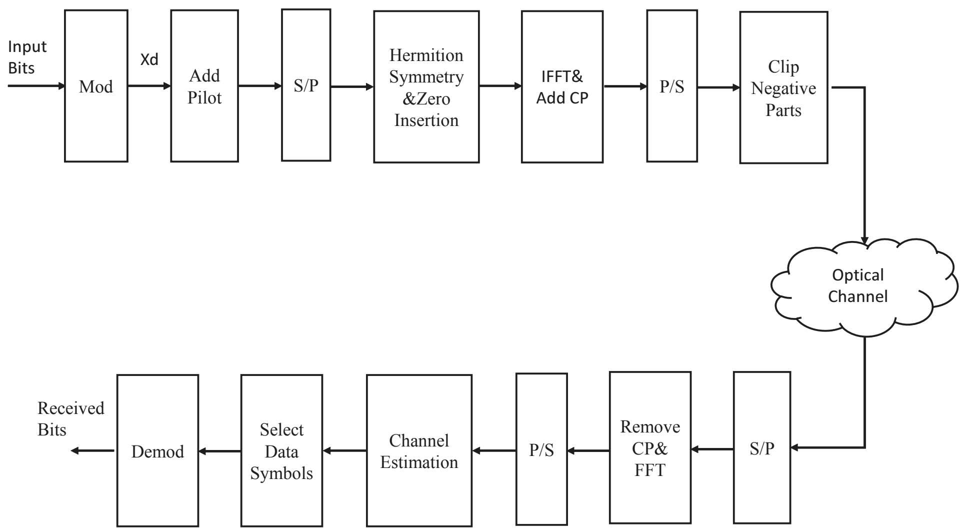

Fig. 1: ACO-OFDM Transmitter and Receiver configuration

output signal for an intensity modulation and direct detection (IM/DD), subcarriers must have the Hermitian symmetry. Moreover, in ACO-OFDM, only odd subcarriers are carrying data symbol and even subcarrier set to zero to avoid performance degradation from clipping noise. As a result, the complex data symbols are mapped onto a $N \times 1$ vector as shown below

$$\mathbf{X} = [X_1 \ 0 \ X_2 \ 0 \ \cdots \ X_{N/4} \ 0 \ X^*_{N/4} \cdots \ 0 \ X^*_2 \ 0 \ X^*_1]^T \quad (2)$$

An N-point IFFT is then applied on the vector $\mathbf{X}$ to build the time domain vector $x[n]$ as follows;

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

The time-domain vector is extended as $\tilde{x}[n]$ by the cyclic prefix that contains N_g samples whose length is chosen to be longer than the expected delay spread of the VLC channel to avoid ISI.

In literature, it is proven that since only the odd subcarriers carrying useful data, the cutting negative values does not affect the data-carrying subcarriers, but only reduces their amplitude by a factor of two. Before transmission all the negative values are set to zero to get unipolar transmitted signal. The transmitted intensity waveform $x(t) \geq 0$ can be written as;

$$x(t) = \sum_{n=0}^{P-1} \tilde{x}[n] \delta(t - nT_s) \quad (4)$$

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

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

$$r(t) = \alpha\psi \left(x(t) \otimes h(t) \right) + w(t) \quad (5)$$

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 modelled as the additive white Gaussian noise (AWGN). The electrical channel impulse response $h(t)$ is defined as

$$h(t) = p(t) \otimes c(t) \otimes p(-t) \quad (6)$$

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 $r[n] = y(nT_s)$ can be written as

$$r[n] = \sum_{l=0}^{L} h(l) x(n-l) + w(n) \quad (7)$$

where assuming $\alpha\psi = 1$ without losing generality and L is the total number of paths of the frequency selective fading channel.

At the receiver, ACO-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 expressed as

$$R[k] = X[k]H[k] + W[k] \tag{8}$$

where

$$H[k] = \sum_{n=0}^{N-1} h[n] e^{\frac{-j2\pi nk}{N}} \tag{9}$$

The FFT operation reproduces the mirrored frame structure designed in the transmitter. The upper half (elements 1 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

$$\mathbf{R} = \mathcal{X}\mathbf{H} + \mathbf{W} \tag{10}$$

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

A typical office space with dimensions of $5 \times 5 \times 3$ m is considered for 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 [9]. By the usage of PDP, the discrete multipath channel impulse response $h[n]$ between the transmitter and the receiver is shown in Figure 2 while assuming the $h[n]$ is normalized as unit energy $\sum_{l=0}^{L-1} h[l]^2 = 1$.

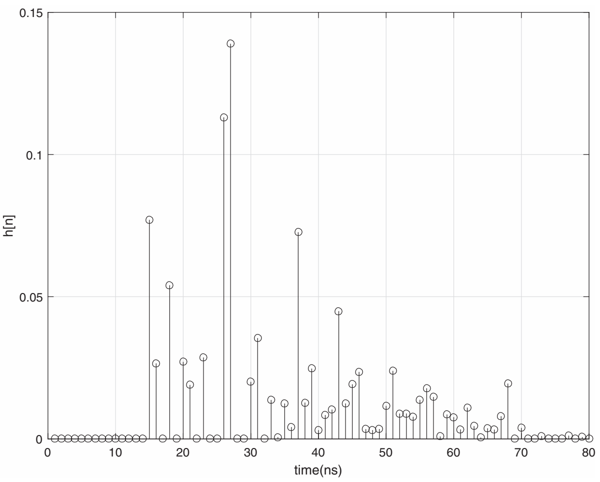

Fig. 2: Impulse response of the VLC channel

IV. Channel Estimation

In VLC system, receiver needs the channel state information (CSI) for proper detection of modulated symbols. Therefore, the channel estimation is the essential part of the receiver design for ACO-OFDM systems. Assume that each ACO-OFDM symbol has P subcarriers where pilots occupied as shown in Fig. 3.

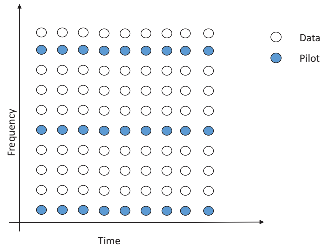

Fig. 3: Comb-type plot arrangement

The received signals at pilot subcarier (k_p) for each ACO-OFDM symbol can be written as follows:

$$R[k_p] = \mathcal{P}H[k_p] + W[k_p] \tag{11}$$

where $\mathcal{P}$ is pilot symbol and $\mathbf{W}(k_p)$ is additive white Gaussian noise at pilot symbol. Then the received blocks are serially operated with the known pilot blocks for estimating the channel frequency response at all pilot positions. From (9), the least square (LS) solution of the observation model with the pilot symbols, can be written as,

$$\hat{H}[k_p] = R[k_p]/\mathcal{P} \tag{12}$$

After estimating channel effect at pilot symbols, interpolation techniques are used for estimation of channel at data subcarriers. In VLC, channel are quasi-static so that estimated channel coefficients in the ACO-OFDM pilot symbols can be employed as the channel response of the other OFDM symbols in the same frame. The interpolation is crucial to estimate the channel variations for data subcarriers. We investigated four interpolation techniques called piecewise linear interpolation (PLI), lowpass interpolation, piecewise cubic hermite interpolating polynomial (Pchip) and cubic shape-preserving interpolation (Cubic Spline).

The piecewise linear interpolation is commonly used with pilot symbol assisted channel estimation techniques since it is simple and easy to implement. 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. Recently, it is also proposed for DCO-OFDM over VLC channels [6]. As an alternative, a smooth and continuous polynomial fitted to estimated channel estimation points is done by the cubic spline interpolation [10]. Other two alternative lowpass and pchip interpolations are also well known in literature [5].

V. Simulation Results

In this section, we provide computer simulation results for the ACO-OFDM based VLC systems to show the bit error rate (BER) performance of the proposed pilot based channel estimation with different interpolation techniques.

ACO-OFDM signal is generated within the 1 GHz bandwidth (T_s = 1 nsec) with $N = 2048$ subcarriers and the cyclic prefix length is selected as $N_G = 128$ samples. Pilot symbol rate is 1/16. Perfect synchronization is assumed in order to observe the channel estimation performance alone. The data symbols are generated as uncorrelated symbols and the M-QAM modulation formats chosen such as 4-QAM and 64-QAM. Square constellation is used for QAM modulations. The legends *linear, spline, pchip, lowpass* denote interpolation schemes for pilot based channel estimation at the pilot subcarriers.

Fig. 4 shows the BER performances of channel estimation methods with different interpolation methods for 4-QAM modulation. We also included the performance of receiver for the case of perfect CSI (P-CSI), which may be considered as a genie bound. As can be seen from Fig. 4, the channel estimations with different interpolation techniques show similar BER performance. Also, it is seen that the performance of the proposed channel estimations are within 2 dB of the genie bound for $BER = 10^{-4}$.

The performance of the higher order modulations scheme such as 64-QAM is also investigated in Fig. 5. The higher order QAM modulations are very sensitive to channel estimation errors. It is observed that the spline and lowpass interpolations outperform the linear and pchip interpolations.

In Fig. 5, it is also shown that the linear and pchip interpolations have irreducible error floors at high SNR values for 64-QAM. It is clear that the spline and lowpass interpolations are robust for both higher SNRs and higher order modulations. For higher SNR region, it has a better performance due partly to the fact that estimation become more insignificant.

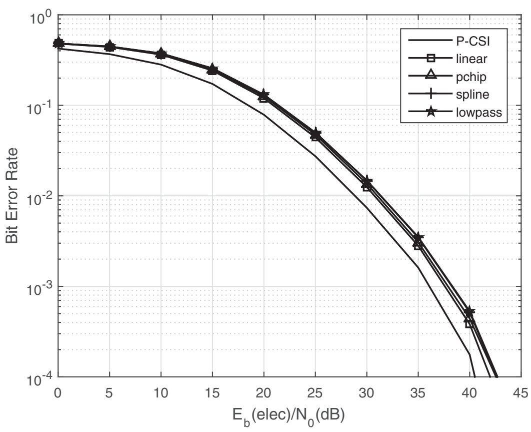

Fig. 4: BER Performance of 4-QAM ACO-OFDM with channel estimation

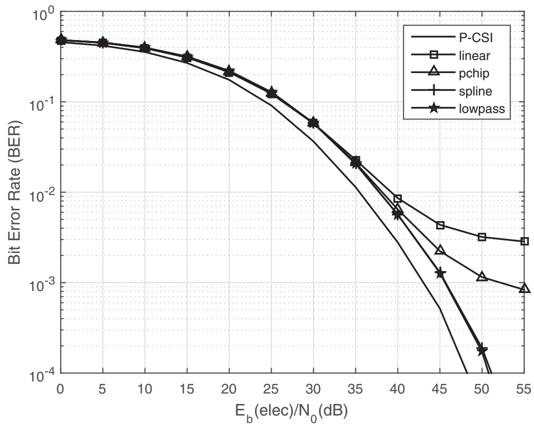

Fig. 5: BER Performance of 64-QAM ACO-OFDM with channel estimation

VI. Conclusion

The comb-type pilot arrangement based channel estimation performance is investigated by different interpolations for ACO-OFDM systems over VLC channels. It is demonstrated that channel estimations with different interpolations have similar performance for lower order modulations such as 4-QAM. However, it is shown that the the spline and lowpass based estimators yield the better performance for higher order modulations, but they have a relatively higher complexity than others.

VII. Acknowledgment

This work was supported by the European COST and Turkish Scientific and Research Council(TUBITAK) under Grant 110307.

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