On Performance Analysis of LS and MMSE for Channel Estimation in VLC Systems

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***Abstract*—Channel estimation is a key feature for wireless optical communication systems. This paper presents an evaluation of channel estimation techniques for indoor visible light communication (VLC) systems using a direct current-biased optical orthogonal frequency division multiplexing (DCO-OFDM) scheme. The VLC system can simultaneously provide illumination and wireless communication at a high data rate. However, the coverage area is limited and the distance is about 3 m. In this paper, performance analysis of two channel estimation methods is presented, one using the least squares (LS) algorithm and the other the minimum mean square error (MMSE) algorithm, to estimate channel response by applying them to various M-QAM modulations. The performance of these two methods is compared by mathematical analysis and by simulation by measuring bit error rate (BER) and mean square error (MSE) versus signal-to-noise ratio (SNR). The results shown that, at higher SNR, the MMSE algorithm outperforms the LS for both BER and MSE.**

Keywords-component; visible light communication (VLC); OFDM; channel estimation; LS; MMSE

I. INTRODUCTION

In visible light communication (VLC), light-emitting diodes (LEDs) are used to illuminate and at the same time to transmit data using intensity modulation (the power of light) [1]. VLC refers to short-range optical wireless communication (OWC) using the visible light spectrum from 380 to 780 nanometers [2]. It is a viable technology that has many attractive features such as unlicensed bandwidth, worldwide availability of unused bandwidth, non-interference with radio frequency (RF) bands, very high data rates and secure communication [3].

LEDs have a limited operating voltage range and coverage, and the voltage-current characteristic shows nonlinear behavior [4]. Each LED in a VLC system works as a small cell (i.e. base station). A large number of LEDs are used to overcome the shadowing effects without health risks. Some other propagation effects such as multipath and inter-symbol interference (ISI) can be mitigated by implementing orthogonal frequency division multiplexing (OFDM). Moreover, OFDM is a promising technique as it can provide a higher data rate and combat ISI. Several studies [5-8] have implemented OFDM in VLC systems. The fast fading effects obviously do not affect the VLC system as the wavelength is significantly smaller than the detector area [1].

However, OFDM has one major disadvantage is that the high peak to average power ratio (PAPR) causes nonlinearities in the transmitted signal and increases the complexity in retrieving the original signal at the receiver. This problem is beyond the scope of this paper. However, channel estimation at the receiver is used to compensate for the variations in the communication channel in order to reduce the probability of error in the detected signal [9].

In VLC systems, channel estimation is required for synchronization and equalization, which mainly can be achieved in the frequency domain and time domain. Channel estimation techniques can be classified into: 1) training sequence based, also know pilot block-type, where pilots are used to perform channel estimation; 2) blind channel estimation, which exploits the statistical or structural properties of communication signals such as the frequency correlation and cyclic prefix (it does not use a training sequence); and 3) semi-blind channel estimation, which is a hybrid of the blind and training sequence based methods that uses pilots and the structural properties of the signals [10].

Several techniques [6, 7, 10, 11] have been proposed to enhance the channel estimation performance of VLC systems and reduce the bit error rate (BER). In [6], the authors discovered that the channel response of the white-light LED-based OWC was smooth and stable. Hence they proposed and demonstrated a specific and adaptive arrangement of a grid-type pilot rather than a comb or block-type pilot scheme to estimate the LED OWC channel response. A theoretical analysis of the benefit of discrete multi-tone (DMT) modulation in a nonlinear VLC system is presented in [11]. The authors show that DMT modulation is a better choice than pulse-amplitude modulation (PAM) for the VLC system as DMT modulation is more robust against nonlinearity. Also, it has been shown that the post-distortion nonlinear elimination method, which is applied at the receiver, can be a reliable solution for the nonlinear VLC system.

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A post-processing discrete Fourier transformation (DFT) for channel estimation has also been proposed for VLC [7]. This method is based on eliminating the noise outside the maximum channel delay to improve system performance. After linear interpolation, the least squares (LS) algorithm combined with a comb-type pilot scheme is used for channel estimation in the frequency domain. A review of the channel estimation techniques for various OFDM systems is provided in [10] for short-range wireless communication devices. Generally, all these works propose optimizing the LS and the minimum mean square error (MMSE) to perform estimation in a slow fading channel in which a one-dimensional model is used to extract channel information on the data subcarriers. However, the authors in [10] do not presented any results.

This paper investigates the performance analysis of the two channel estimation algorithms LS and MMSE in OFDM-based VLC systems. The remainder of this paper is organized as follows: Section II presents the system models, while Section III presents the simulation setup and results. Finally, a conclusion is drawn in Section IV.

II. System Models

A. Channel Model

A generic block diagram of a VLC using an OFDM transceiver is shown in Fig. 1. Unlike RF systems, VLC systems send data via light. The light cannot penetrate through opaque objects. However, this apparent drawback is an advantage in terms of security. Generally, there are two main propagation drawbacks fast fading and slow fading. The VLC channel is not subject to fast fading effects because it uses a very small wavelength compared to the detector area [1]. However, it is subject to slow fading, which is the result of shadowing from furnishings or other indoor objects.

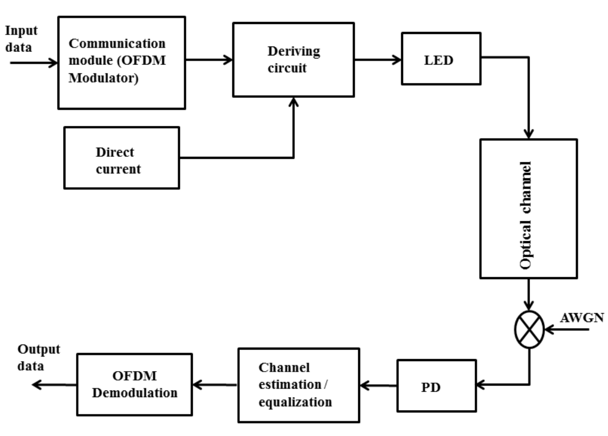

Fig. 1. Block diagram of visible light OFDM transceiver

In a VLC system, the number of multipath components is large and the propagation channel varies temporarily due to the movement of users and other nature propagation process of light such as reflection and diffraction. However, the noise due to background light can be modeled as additive white Gaussian noise (AWGN). There is no interference with other RF communication systems [12].

B. VLC using OFDM

OFDM for VLC is different from OFDM used in RF communication because in OWC intense modulation/direct detection (IM/DD) is always adopted. The OFDM signal needs to be real and positive before being transmitted. This can be achieved by adding Hermitian symmetry in the inverse fast Fourier transform (IFFT) and adding a DC-bias current are needed to make the signal real and positive, respectively. This is known as the DC-biased optical OFDM (DCO-OFDM) scheme[13]. A single OFDM frame (sometimes also referred to as an OFDM symbol) carries a set of data symbols, X, in the frequency domain. The OFDM symbol is a vector that consists of a set of N subcarriers. The IFFT algorithm outputs the discrete OFDM symbol vector, x, in the time domain, as in (1) [14]:

$$x_m = \frac{1}{N}\sum_{k=0}^{N-1} X_k\, e^{j\frac{2\pi km}{N}} \qquad for\; 0 \le m \le N-1 \qquad (1)$$

where N is the size of the IFFT and X_k is the k^{th} subcarrier symbol. The corresponding FFT conversion pair to (1) can be expressed as:

$$X_k = \frac{1}{N}\sum_{m=0}^{N-1} x_m\, e^{-j\frac{2\pi km}{N}} \qquad for\; 0 \le k \le N-1 \qquad (2)$$

It should be noted that the output of (1) is a complex signal and cannot be used in an IM/DD system such as LED-based VLC. Hermitian symmetry is used to achieve a real-valued IFFT output. The elements of the new IFFT input vector, X_H, are expressed in (3) [10] and the DC component, $X_0 = X_N = 0$.

$$X_H = [X_0,\, X_1, X_2 \ldots X_{N-1}, X_N,\, X^*_{N-1},\, X^*_{N-2} \ldots X^*_2,\, X^*_1] \quad (3)$$

This results in a 2N-point IFFT output of the OFDM symbol. Equation (1) is modified to (4).

$$x_m = \frac{1}{N}\sum_{h=0}^{2N-1} X_{H,h}\, e^{j\frac{2\pi hm}{N}} \qquad for\; 0 \le m \le 2N-1 \qquad (4)$$

where h is the h^{th}-subcarrier symbol of X_H. The OFDM symbol is a periodic function with a period, T_P=1/ Δf, and Δf is the subcarrier spacing, which is given by Δf=$B/(N-1)$, where B is the signal modulation bandwidth.

III. Channel Estimation

Channel estimation based on the training sequence (TS) technique can be further categorized into two schemes according to the arrangement of the pilots. The first scheme is known as the block-type pilot scheme. The idea of this scheme, based on the TS, is to insert subcarriers that are already known by the receiver into a symbol to estimate the channel response. All subcarriers are reserved for pilots with a specific period of TS. The instantaneous channel impulse response can be estimated by analyzing the relationship between the known TS and the received symbols. The LS channel estimation is used when the channel and noise distribution are unknown, while MMSE is used when the channel and noise distribution are known. At the receiver, the obtained parameters from the channel estimation are used for equalization [15].

The second scheme of channel estimation is called the comb-type pilot scheme. In this scheme, some subcarriers are reserved for pilots for each symbol. Fig. 2(a) and (b) illustrates the two types of channel estimation scheme, block-type and comb-type, respectively. Note that a hybrid pilot arrangement was implemented as a grid-type pilot in [6].

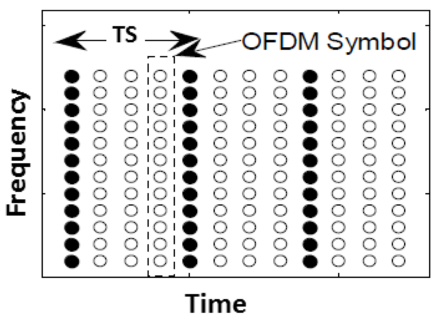

Fig. 2(a). Block-type pilot scheme

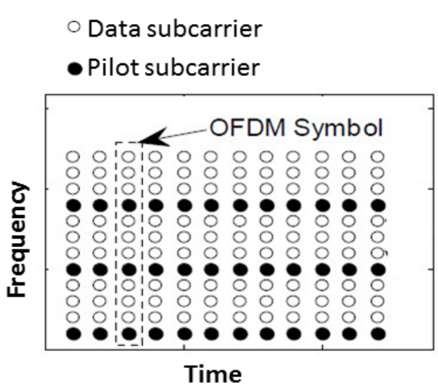

Fig. 2(b). Comb-type pilot scheme

A. Least Squares

Channel estimation accuracy has a significant impact on overall VLC system performance. When many LEDs are used, the shadowing effects can be alleviated. On the other hand, a large number of LEDs increases the multipath effect, which leads to ISI. The ISI is a severe problem in VLC as it can degrade the data rate of the system as well as BER performance [4]. That is why channel estimation is a crucial and challenging issue to overcome to achieve coherent demodulation.

At the receiver, a reverse methodology is used. The modulated and attenuated optical signal is detected by a photodiode (PD). The output received signal of the channel can be expressed as:

$$y'(n) = x'(n) \otimes h(n) + w(n) \qquad for\, 0 \le n \le 2N-1 \qquad (5)$$

where $h(n)$ is the impulse response of the channel. It is assumed that the channel is linear and $2N$ is the received time-domain signal length. An AWGN channel is represented by $w(n)$. After removing the cyclic prefix (CP), (5) can be rewrite as below:

$$y(n) = x(n) \otimes h(n) + w(n) \qquad (6)$$

In the frequency domain, (6) can be written as follows:

$$Y(k) = X(k)\,H(k) + W(k) \qquad k = 0,....,N-1 \qquad (7)$$

where $H(k)$ and $W(K)$ are the FFTs of $h(n)$ and $w(n)$ in (6), respectively.

Assuming that the N point of the DFT of the received signal samples is $Y=[Y_0,Y_1,\dots, Y_{N-1}]^T$, $H=[H_0,H_1,\dots, H_{N-1}]^T$ and $W=[W_0,W_1,\dots, W_{N-1}]^T$ is the Gaussian noise with variance σ^2, then the input matrix $\overline{X}$ = diag($\{X_k\}$), so the channel statistical model in the frequency domain for the VLC system can be modeled as:

$$Y = \overline{X}H + W \qquad (8)$$

The optimality criterion of the LS method is to minimize the least square errors to find an optimal estimator for the unknown parameters [16].

To find the LS channel estimation, the sum of square errors $\varepsilon(\bullet)$ of channel estimation in the frequency domain using (8) can be defined as:

$$\varepsilon(H) = \left\| Y - \overline{X}H \right\|^2 = (Y - \overline{X}H)^H (Y - \overline{X}H) \qquad (9)$$

where $\|\bullet\|$ denotes a non-negative norm of a vector and $(\bullet)^H$ is the Hermitian transposition. The normalized value can be written as:

$$\widehat{H}_{LS} = \arg\min_{H} \varepsilon(H) \qquad (10)$$

Using differentiating with respect to channel coefficient and setting to zero with each channel coefficient H, as below:

$$\frac{\partial}{\partial H}(Y - \overline{X}H)^H (Y - \overline{X}H) = 0 \qquad (11)$$

In the frequency domain, LS channel estimation can be obtained as follows:

$$\widehat{H}_{LS} = \frac{Y}{X} \qquad (12)$$

The channel estimation objective and estimation error can be found by substituting (8) into (12):

$$\widehat{H}_{LS} = H + \frac{W}{X} \qquad (13)$$

where *W/X* is the estimated error and *H* is the objective of channel estimation.

B. Minimum Mean Square Error Estimation

The second channel estimation method is the MMSE. The main idea of MMSE is to find the unknown parameters by minimizing the mean square error (MSE). Defining the linear estimator operator *L* [17] finds the MMSE as:

$$\widehat{H}_{MMSE} = LY \qquad (14)$$

From (14), the MSE of the channel estimation for the VLC system can be modeled as:

$$\partial(L) = \mathrm{E}\left[\left\|(H - \widehat{H}_{MMSE})\right\|^2\right] \qquad (15)$$

where $E\,[\bullet]$ denotes the expectations operator. First, is to determine the estimator value *L* to obtain the MMSE channel estimation. Therefore the value of *L* must be satisfied by (16) below:

$$\widehat{L} = \arg\min_{L} \partial(L) \qquad (16)$$

In a similar manner to LS, using differentiating and setting the result to zero with respect to each channel coefficient *L*, as below:

$$\frac{\partial}{\partial L}\mathrm{E}\left[(H - LY)(H - LY)^H\right] = 0 \qquad (17)$$

By solving (17), the value of operator *L* can be calculated as:

$$\widehat{L} = \frac{R_H \overline{X}^H}{\overline{X} R_H \overline{X}^H + R_W} \qquad (18)$$

where R_W=E[WW^H] is the covariance matrix of noise and R_H=E[HH^H] is the covariance matrix of the channel coefficient in the frequency domain. The noise variance is denoted by σ^2.

Thus, the MMSE channel estimation can be expressed as:

$$\widehat{H}_{MMSE} = \widehat{L}Y = \left[\frac{R_H \overline{X}^H}{\overline{X} R_H \overline{X}^H + R_W}\right] Y$$

$$= R_H \left[\frac{1}{\left(R_H + \sigma^2\left(\frac{1}{\overline{XX}^H}\right)\right)}\right] \widehat{H}_{LS} \qquad (19)$$

From (19), it is obvious that the MMSE channel estimation method mitigates the channel noise effects relatively better than the LS method. However, in the MMSE method more prior knowledge is needed about the channel coefficient covariance matrix and noise covariance matrix R_H and R_W, respectively. Therefore, the MMSE method is higher in complexity than the LS method.

IV. Performance Analysis

A. Simulation Setup

In the simulation setup, linear scaling is adopted to make the OFDM signal work within the dynamic range constrained by the VLC system while a DC bias is added to the bipolar OFDM signal to conform with the non-negativity constraint. Data bits are randomly generated and converted from serial to parallel to form symbols for the M-ary quadrature amplitude modulation (*M*-QAM). The QAM symbols are assigned to subcarriers with perfect with the channel impulse response. The resultant signal modulates a light source and is transmitted over the OWC channel. The reverse process is carried out at the receiver after removing the DC bias. The other simulation parameters are shown in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Transmitted optical power by individual LED (P_t)	20 mW
Room Size	$(5 \times 5 \times 3)$ m^3
Location for 4 LEDs	(1. 25, 1.25, 3), (1.25, 3.75, 3), (3.75, 1.25, 3), (3.75, 3.75, 3)
Semiangle at half power ($\Phi_{1/2}$)	30, 70 degrees
Filter gain $Ts(\psi)$	1
Number of LEDs per array	60×60
Active area (A)	1 cm^2
Concentrator gain $g(\psi)$	2.5

B. Results and Discussion

The theoretical channel estimation model has been presented in section III. In this section, system is presented by means of simulation results. The received optical power distribution on the receiver plane is estimated based on the line of sight (LOS) channel model and by ignoring the reflection off the walls. Fig. 3 shows the optical power distribution.

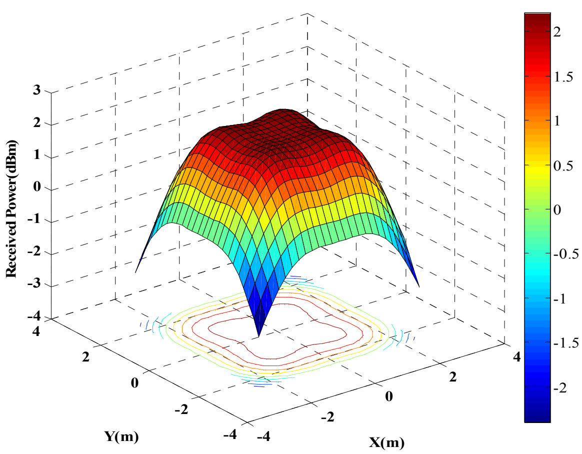

Fig. 3. Optical power distribution

The effect of ISI in VLC systems is not as severe as in RF systems because the frequency response of the VLC channel falls off relatively slowly. This is because the coverage area in the VLC system is small. Assume that a diversity system utilizes multiple lighting sources to alleviate the shadowing problem [18].

When simulating a channel estimation model, the simulation is usually based on corresponding received samples and a known pilot subcarrier. Evaluation system performance in terms of BER and MSE versus signal-to-noise ratio (SNR) is introduced. In addition, different constellation order schemes are considered such as 16-QAM, 64-QAM and 128-QAM.

Fig. 4 depicts the results of the simulation at different levels of mapping. From the figure it can be seen that, for instance, with 16-QAM the MMSE channel estimation method performs better than the LS channel estimation method. When SNR is 12 dB the LS estimator has a BER of 10^{-1}, which is higher than that of the MMSE estimator. In addition, the MMSE estimator can achieve the same BER of 10^{-1} but at lower SNR of 8 dB. Thus, the higher the SNR, the better the MMSE estimator performs in comparison to the LS estimator.

At different high constellation orders, the results show that both types of estimator have a higher BER. Nevertheless, the MMSE method maintained a lower BER than the LS method for all QAM orders. Obviously, using a high order modulation will require a sufficient SNR, which can be achieved with a very small cell size such as a Pico cell of a room size or desktop size.

The LS estimator is uncorrelated properties of TS. However, LS is susceptible to channel noise and variance in the estimation error which is largely dependent on the level of noise. On the other hand, MMSE is more powerful in eliminating noise and because it uses the frequency correlation of the channel, it obtains a better estimation. Thus, in practice, depending on the application of the VLC system, a tradeoff could be made between system cost, complexity and improvement in performance to identify a suitable channel estimator.

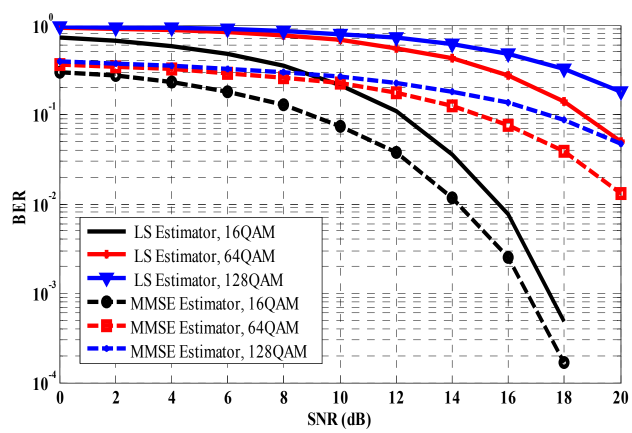

Fig. 4. Comparison of BER performance for LS and MMSE channel estimation at different M-QAM

Fig. 5 exhibits the MSE performance of both the LS and MMSE channel estimation methods. The results show that the MMSE estimator gains more than 4 dB over LS estimator with all SNR values. This is due to the ability of MMSE to eliminate outside noise. Moreover, when the SNR is increased, the MSE of the MMSE estimator is lower than that of the LS estimator.

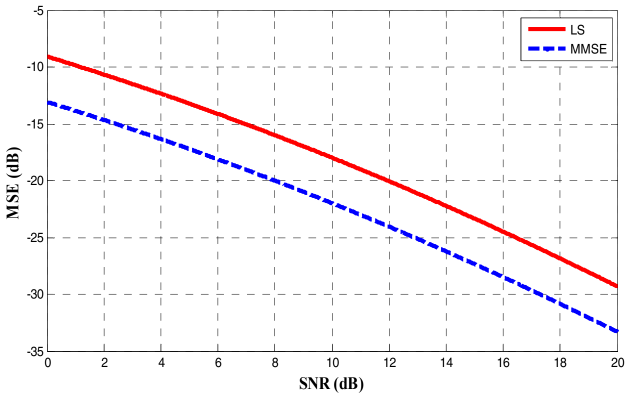

Fig. 5. Channel MSE vs SNR for LS and MMSE estimator

V. CONCLUSION

It is obvious that precise channel estimation is required for a high quality and high data rate system. In this paper, we evaluated and compared the performance of two channel estimation methods for indoor VLC systems using a DCO-OFDM scheme. The two algorithms tested were LS and MMSE in the frequency domain. They are both linear channel estimation techniques that are based on the use of a pilot-based scheme. Our theoretical analysis and simulation results were in agreement, i.e. that the MMSE channel estimation method is highly accurate and outperforms the LS channel estimation method. However, the MMSE method involves more multiplications and a matrix inversion, which increases complexity. While the LS method is less complicated and easy to implement, it is more sensitive to channel noise. Thus further work is needed to find a more sophisticated channel estimation method that can offer a good tradeoff between complexity and accuracy.

ACKNOWLEDGMENT

This work is supported by Multimedia University and Telekom Malaysia.

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