Optical Channel Estimation Based on Kalman Filtering for VLC Systems Adopting DCO-OFDM

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ABSTRACT

We propose the use of a Kalman filter method for estimating the response of the visible-light communication channel adopting DCO-OFDM techniques. Our proposed method is shown to achieve better performance than that of traditional least-square (LS) and minimum mean square error (MMSE) estimators.

Keywords: Kalman filter, MMSE, LS, DCO-OFDM, optical channel estimation, visible light communications.

1. INTRODUCTION

Visible light communications (VLC) combined with orthogonal frequency-division multiplexing (OFDM) is a promising technology that has many attractive features suitable for high transmission rates in indoor applications. In OFDM-VLC systems, the received signal is usually distorted by the wireless channel. In order to recover the transmitted bits, the channel effects must be estimated and compensated. Several channel estimation techniques have been proposed in [1-4]. Among them is the least square (LS) scheme, which is one of the simplest methods to estimate the channel frequency response by means of inserting a training sequence at the transmitter.

In this paper, channel estimation based on Kalman filtering is proposed in order to improve the bit-error rate (BER) performance of the OFDM-based VLC system over the LS and MMSE techniques. The VLC channel model is shown in Sec. 2 and its system model is described in Sec. 3. The channel estimation methods are presented in Sec. 3. The BER performance analysis of the system is demonstrated in Sec. 4.

2. VLC Channel Model

Characterization of a communication channel is performed by its channel response which is used to analyze the effects of channel distortions. A VLC channel model depends on many factors such as the light radiation pattern, the distance between the light source and photodetector d, the receiver aperture area A_r, the received angle θ, different kinds of reflections, and the wavelength of light. In indoor application, the received signal can arrive from the line-of-sight (LOS) or non-line-of-sight (NLOS) paths. Figure 1 show the LOS channel model in the room where its response is given by [1]:

$$H_{los}(0) = \begin{cases} \frac{A_r(m_1+1)}{2\pi d^2}\cos^{m_1}(\theta)T_s(\phi)g(\phi)\cos\phi\,; & 0 \le \phi \le \phi_c \\ 0; & \text{elsewhere,} \end{cases} \tag{1}$$

Where m_1 is the Lambert's mode number that represents the directivity of the source beam, $T_s(\phi)$ is the receiver optical bandpass filter, $g(\phi)$ is the concentrator gain, ϕ is the angle with respect to the transmitter. The NLOS response is caused by a number of reflections from walls, floor, and other objects of furniture. Typically, for VLC, the LOS link always has a dominant and significant influence on the communication performance. Therefore, in this paper, the NLOS response is neglected and LOS is considered only [5, 6].

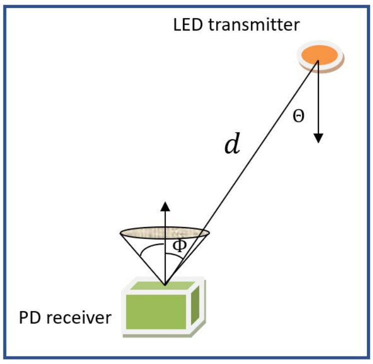

Figure 1. Geometry for a LOS propagation model.

3. VLC SYSTEM MODEL

The block diagram of the proposed VLC system is illustrated in Fig. 2. Input bits are mapped to corresponding QAM symbols. An inverse fast Fourier transform (IFFT) is applied to the modulated complex symbols $X\ (k)$ to get the time-domain OFDM signal. For intensity modulation and direct detection (IM/DD) system, the transmitted signal must be real-valued and unipolar. To satisfy these constraints, Hermitian symmetry is first applied to $X(k)$ symbols before the IFFT process, such that

$$X = (X_0, X_1, \dots, X_{N-1}, X_N, X_{N-1}^*, \dots, X_1^*) \tag{2}$$

where X is the modulated data and N is the number of subcarriers. The sub-carriers X_0 and X_N are set to zero. In addition, a DC bias is added to make the signal non-negative $x_c(n)$. Notice that a cyclic prefix (CP) is added in front of each OFDM symbol to avoid inter-symbol interference (ISI). The resultant electrical signal is converted to an optical signal using light emitting diode and then transmitted through the channel.

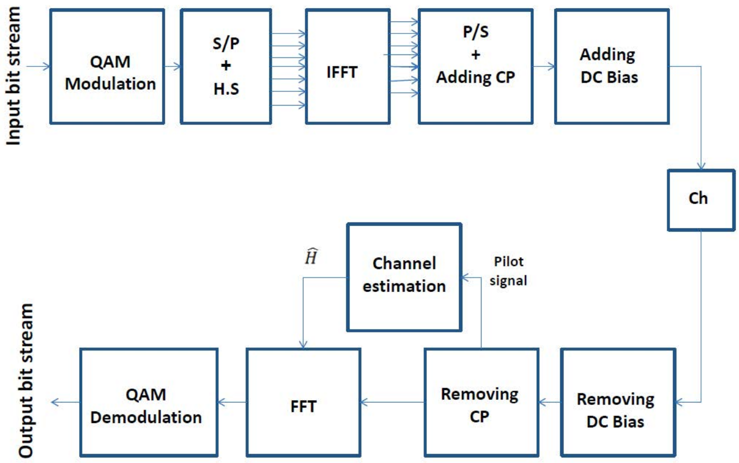

Figure 2. Block diagram of DCO-OFDM system.

At the receiver side, the optical signal is converted back to an electrical one using a photodiode (PD). Both the receiver noise and ambient light are modeled as additive white Gaussian noise (AWGN). Accordingly, the received noisy signal can be expressed as:

$$y[n] = x_c[n] * h[n] + n_g[n], \tag{3}$$

where $h[n]$ and $n_g[n]$ denote the discrete forms of the channel response $h(t)$ and AWGN, respectively. Here $x_c(n)$ is the signal after adding DC bias. Fast Fourier transform (FFT) is performed to recover the symbols from the sampled data. The channel estimation block is used to recover the transmitted signal at the receiver. The estimation is based on the transmission of pilot symbols that are known to the receiver. Since both real and imaginary part of a phase modulated signal is corrupted by AWGN, the statistics of received noisy signal follows a Rician distribution. Accordingly, we assume transmission through a Rician AWGN channel.

4. CHANNEL ESTIMATION METHOD

In a VLC system, knowledge of channel state information at receiver is crucial for proper detection of modulated symbols. Thus, the channel estimation is an 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, namely block-type pilot arrangement and comb-type pilot arrangement [4]. In our simulations, we use the comb-type pilot signal for channel estimation where some subcarriers are reserved for pilots for each symbol.

In this section, two classical channel estimation algorithms are discussed, followed by our proposed scheme. Specifically, we present both LS and MMSE estimation methods for VLC. Next, we introduce a Kalman Filtering (KF) estimation method as a new method of channel estimation for VLC systems to improve the performance of our system.

4.1 Least Square Channel Estimation

The LS channel estimation is the simplest one. The only catch with this estimation is that the optimal solution is only achieved when there is no noise and interference is considered in the received signal. Thus, concluding the LS estimation technique is not the best solution for this channel estimation. In this method, the estimated channel is given by:

$$H_{LS} = Y_k / X_k, \tag{4}$$

where k is a pilot index, X_k and Y_k are the transmitted and received pilot signals, respectively.

4.2 Minimum Mean Square Error Estimation

The idea of MMSE is to discover the unknown parameters by minimizing the mean square error (MSE) [4]. The solution of the MMSE is

$$H_{MMSE} = R_H \left[\frac{1}{R_H + \sigma^2 \frac{1}{\bar{X}\bar{X}^H}}\right] H_{LS}, \tag{5}$$

where $R_H = E\,[HH^H]$ is the covariance matrix of the channel coefficient in frequency domain, σ^2 is the noise variance, and $\bar{X} = diag\{X_k\}$.

4.3 Channel Estimation using a Kalman Filter

A Kalman filter (KF) is an algorithm that observes a series of measurements observed and produces an estimation of unknown variables that tend to be more accurate than those based on a single measurement alone. The Kalman filter has numerous applications in technology. The algorithm works in a two-step process: a prediction step and an updating step. In the prediction step, the Kalman filter produces estimation of the current state variables, along with their uncertainties. Once the outcome of the next measurement (probably corrupted with random noise) is observed, these estimates are updated in an updating step to estimate with higher certainty. The algorithm is recursive and can run using only the present input measurements and the previously calculated state and its uncertainty matrix; no additional past information is required.

4.3.1 Proposed Estimator and Algorithm

Usually, the autoregressive (AR) model is used to approach Rayleigh and Rician fading channel models and facilitate their manipulations. Moreover, it has been shown that a first-order model is enough to capture most of the channel tap dynamics [7,8]. This approximation has been widely used to track the true Jakes's spectrum channel by a KF in various wireless communication systems [9]. Here, we propose the KF based on the autoregressive (AR) predictive model for our system [10] in order to improve the accuracy of the estimation. The Kalman filtering algorithms can be stated as: Given the matrix X_k of known transmitted pilot symbols and received signal Y_k at kth OFDM symbol, It is easy to verify that the channel coefficients h_k can be modeled by the following dynamic AR process: $h_{k+1,n} = a_n\, h_{k,n} + v_{k,n}$, where $n \in \{1,2,\ldots,N\}$. Here, a_n represents the time correlation of the channel response between k^{th} and $(k+1)^{\text{th}}$ OFDM symbols at the nth subcarrier an $v_{k,n}$ is a process noise. In this paper we consider only the first order of AR model. The channel tracking algorithm works as follows:

1. Initialize the variables and matrices.
2. Generate input data.
3. Modulate the data using QAM modulator using HS, and add CP and DC bias.
4. Assume transmission through a Rician AWGN channel.
5. Obtain the a priori estimate of the current state $\hat{h}_{k/k-1} = A_k \hat{h}_{k-1|k-1}$.
6. Obtain the a priori estimate of the state covariance matrix $p_{k/k-1} = A_k P_{k-1|k-1}\, A_k^T + Q_k$.
7. Compute a measurement equation for the output $z_k = h_k^T + v_k$.
8. Compute the Kalman gain $K_k = P_{k|k-1}\, H_k^T\, \left[H_k\, P_{k|k-1}\, H_k^T + R_k\right]^{-1}$.
9. Compute the updated estimate $\hat{h}_{k|k} = \hat{h}_{k|k-1} + K_k\left[z_k - H_k \hat{h}_{k|k-1}\right]$.
10. Compute the updated state covariance matrix $P_{k|k} = [I - K_k H_k] P_{k|k-1}$.
11. Demodulate the received data and plot the results.

Here, h_k is the state estimate at k^{th} sample, P_k is the error covariance matrix (a measure of the estimated accuracy of the state estimate), A_k is the state transition model, H_k is the observation model, Q_k is the covariance of the process noise, and R_k is the covariance of the observation noise.

5. SIMULATION ANALYSIS

The above mathematical model is simulated using MATLAB. The simulation parameters and room geometry are given in Table 1.

Table 1. System parameters.

Parameter	Value
Number of subcarriers	1024
Number of pilots	N/8
Distribution of pilot	Comb-type
Modulation formats	64,128, 256 QAM
Channel estimation scheme	LS, MMSE, KF
Transmitted optical power by individual LED	20 mW

Room size	(5 5 3) m
Locations of transmitters	(1. 25, 1.25, 3), (1.25, 3.75,3), (3.75, 1.25, 3), (3.75, 3.75, 3)
FOV	70°
Filter gain	1
Number of LEDs per array	60, 60
Active area of PD	1cm^2
Concentrator gain	25

Our simulation results are plotted in Figs. 3 and 4. In Fig. 3, we compare the bit-error rate (BER) performance of our scheme with that of other algorithms under same channel conditions. Four transmitters located in a room with dimensions (5,5,3) are used in our simulations. A DCO-OFDM system with $N = 1024$ subcarriers is used. The simulated system is modulated by 64,128,256 QAM levels. It is configured with a cyclic prefix of $N/8$. We use the comb-type pilot with number of pilots of $N/8$. From the figure, it can be seen that with 64-QAM the KF channel estimation method performs better than that of both the LS and MMSE channel estimation methods. Specifically, KF performs better than the MMSE channel estimation method by about 1.5 dB. In addition, KF has the least value for BER for different mapping. At different high constellation orders, the results show that all types of estimators have a higher BER. Nevertheless, the KF method maintains a lower BER than both methods for all QAM orders. Figure 4 shows the Kalman filter response for all subcarriers.

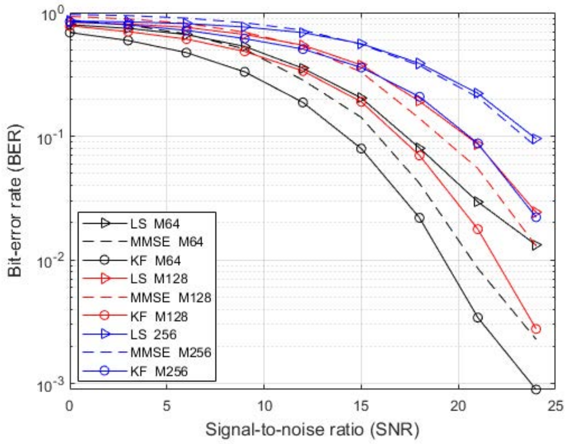

Figure 3. Comparison of BER performance for KF, LS, and MMSE.

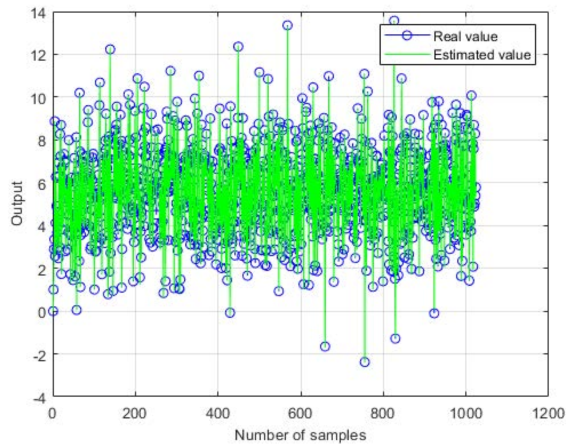

Figure 4. Kalman filter response.

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