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Efficient Frequency Domain Channel Equalization Methods for OFDM Visible Light Communications

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Abstract: We present efficient frequency domain channel estimation methods based on the intra-symbol frequency-domain averaging (ISFA), minimum mean squared error (MMSE) and weighted inter-frame averaging (WIFA) schemes for the orthogonal frequency division multiplexing (OFDM) visible light communications (VLC) system. OFDM-VLC with quadrature phase shift keying, 16- and 64- quadrature amplitude modulation mapping is experimentally demonstrated. Compared with the conventional least square channel estimation method, ISFA, MMSE and WIFA offer improved performance with MMSE offering the best performance in term of the error vector magnitude but at the cost of high complexity. We show that the WIFA can improve the estimation accuracy of time-varying VLC optical channel.

1. Introduction

Light-emitting diodes (LEDs) have been considered as the most promising lighting source for next-generation illumination at a global level. This is because of the high luminance efficiency, long life, low cost, and low power consumption. LED based illumination also offer additional functionalities including sensing, indoor positioning and data communications, which is very unique not seen in any other devices. LED based visible light communications (VLC) or also known as LiFi, offers a number of advantages including license free spectrum (bandwidth), free from electromagnetic interference, and inherent high security [1-5]. As a bottleneck in conventional indoor VLC systems, the bandwidth of LEDs has been increased by using post- and pre-equalization schemes [6-7]. In [6] a least mean squares (LMS) equalizer in real time with a field programmable gate array was reported. Whereas in [7] the multilayer perceptron (MLP) artificial neural network classifier as the equalizer due to its superior mean square error (MSE) convergence and bit error rate (BER) performance was reported, which doubled the bandwidth compared to [6].

The orthogonal frequency division multiplexing (OFDM) scheme widely and successfully used in RF systems [8, 9] has also been adopted in VLC systems to combat multipath distortion and boost the data rate without any bandwidth or power expansion [10-14]. In OFDM-VLC systems, the received signal is usually distorted by the wireless channel. In order to recover the transmitted bits, the channel effect must be estimated and compensated [15]. The least square (LS) scheme is one of the simplest methods to estimate the channel frequency response (CFR) by means of inserting a training sequence at the transmitter (Tx). To improve the OFDM-VLC system performance, a post-processing discrete Fourier transformation (DFT) channel estimation method [16] and an adaptive channel estimation algorithm were proposed [17]. In addition, the correlation method, the LS and the minimum mean square error (MMSE) methods based on the training sequence were also investigated for OFDM-VLC [18]. However, these above works were mainly simulation based with no experimental verifications. In [19] a specific and adaptive arrangement of the grid-type pilot scheme was proposed with improved BER performance and enhanced transmission capacity compared with the method using a training-symbol scheme.

In this paper, we experimentally demonstrate efficient channel estimation methods based on intra-symbol frequency-domain averaging (ISFA), MMSE and weighted inter-frame averaging (WIFA) for OFDM VLC. The ISFA, LMMSE and WIFA estimators are based on the channel matrix, which is estimated by LS. In ISFA estimator, averaging is carried out over the estimated matrix for multiple adjacent frequency subcarriers (SCs) [20]. In MMSE estimator, additional information such as the signal to noise ratio (SNR) and statistical characteristics of the channel are required in order to perform the best linear estimation but at the cost of increased complexity [21]. In WIFA estimator, the channel estimation results of the adjacent frames are averaged. WIFA can increase the accuracy of channel estimation provided the channel responses estimated by adjacent frames are strongly correlated with each other [22].

The rest of the paper is organised as follow: Section 2 briefly describes the channel estimation algorithm. Section 3 presents the experiment setup for OFDM-VLC. The obtained experiment results are discussed in Section 4 followed by the concluding remarks in Section 5.

2. Channel estimation algorithm

Fig. 1 shows the schematic of digital signal processing (DSP) for the transmitter (Tx) and the receiver (Rx), which describes the OFDM framework with frequency domain equalization. At the Tx side, the transmission data blocks $d_i(t)$ are encoded into the baseband symbols (i.e., QAM) and then converted into parallel data stream prior to pilot insertion and inverse discrete Fourier transform (IDFT). This is followed by insertion of the cyclic prefix (CP) in order to mitigate multipath induced intersymbol interference (ISI) between OFDM symbols. The training symbols are required at the starting position of each OFDM frame for the purpose of channel estimation and synchronization. The generated digital OFDM signals are converted to analog signals by a digital-to-analog converter (D/A). After adding a direct current (DC), the LED intensity is modulated with the DC-OFDM signals. After free space transmission, the OFDM signal is detected by an optical receiver. Then the electrical OFDM signal is converted to digital signal by an analog-to-digital converter (A/D). The regenerated electrical OFDM signal is first passed through a frame synchronization module prior to removing CP. The rest of the Rx functions are opposite that of the Tx. The LS method is used to determine the channel matrix. The CFR of the i th frame can be calculated as [20]:

$$\hat{H}_{i,LS}(k) = \frac{Y_i(k)}{X_i(k)}, \tag{1}$$

where $\mathbf{Y}_i$, $\mathbf{X}_i$ are the frequency-domain representations of received and transmitted training symbols in i th frame, respectively. k is the subcarrier index. Based on $\hat{\mathbf{H}}_{i,LS}$, ISFA, MMSE and WIFA methods are used to increase the channel estimation accuracy. For the link with ISFA, MMSE and WIFA the CFRs are given by, respectively：

$$\hat{H}_{i,ISFA}(k) = \frac{1}{\max(k_{\max}, k+m) - \min(k_{\min}, k-m) + 1} \sum_{p=k-m}^{k+m} \hat{H}_{i,LS}(p), \tag{2}$$

$$\hat{\mathbf{H}}_{i,MMSE} = \mathbf{R}_{hh}(\mathbf{R}_{hh} + \sigma_n^2 (diag(\mathbf{X}_i) diag(\mathbf{X}_i)^H)^{-1})^{-1} \hat{\mathbf{H}}_{i,LS}, \tag{3}$$

$$\hat{\mathbf{H}}_{i,WIFA} = (1-\delta)\hat{\mathbf{H}}_{i-1,WIFA} + \delta \hat{\mathbf{H}}_{i,LS}, \tag{4}$$

where m is the number of the left and right adjacent SCs that are employed for averaging in the frequency-domain, $k_{\max}$ and $k_{\min}$ are the maximum and minimum modulated subcarrier indexes, respectively. In Eq. (2), the elements of the estimated channel matrix for p outside $[k_{\min}, k_{\max}]$ are not available and thus are set to zero in the averaging process. $\mathbf{R}_{hh}$ is the auto-covariance matrix of $\hat{\mathbf{H}}_{i,MMSE}$, σ_n^2 is the noise variance, δ is the weighted factor between 0 and 1, and $\hat{\mathbf{H}}_{i-1,WIFA}$ is the CFR of the i-1th frame. $\hat{\mathbf{H}}_{i,LS}$ is the CFR of i th frame calculated using the LS method. The accuracy of CFR estimation for WIFA highly depends on δ, which is high for lower values of improves δ. However, δ should not be two small to ensure tracking under changing channel conditions. Here, δ is determined as:

$$\delta = \begin{cases} \frac{1}{i}, & i < \frac{1}{\delta_0} \\ \delta_0, & i \geq \frac{1}{\delta_0} \end{cases}, \tag{5}$$

where i is the frame index and δ_0 is a constant value. With the CFR calculated using ISFA, MMSE and WIFA, the OFDM signal is equalized in the frequency-domain for further QAM demodulation.

3. Experimental Setup

The experimental setup for the proposed system is shown in Fig. 2 and Fig. 3. At the Tx, a 1.7 Mbaud baseband OFDM signal is three times up-sampled and then up-converted to 1.25 MHz by means of digital

I-Q modulation. The total SCs employed are 1024, of which 724 SCs are used for data transmission, and the CP size is 16. The generated waveform in the Matlab domain is uploaded into an arbitrary waveform generator (AWG) operating at 5-MS/s, the output of which (i.e., the electrical OFDM signal) is converted into an analog stream and then DC-level shifted using the bias Tee prior to intensity modulation of a commercially available phosphorescent white LED (Cree XLamp XHP50). The *P-I* characteristics of the LED is shown in Fig. 4, where the most linear part is at the lower current range. And the key system parameters are provided in Table I. At the Rx, a commercial optical Rx (THORLABS PDA10A) composed of a Si photodetector and an amplifier is used to convert the optical signal back into the electrical signal. The optical Rx output is passed through DAC and captured using a real-time digital oscilloscope for offline signal processing in the Matalb domain in order to recover the transmitted data. Note that the OFDM decoder is exactly the opposite of the OFDM coder. In order to achieve synchronization between the transmitter and the receiver, a reference clock signal generated by the AWG is sent into the scope.

To assess the link performance we have used both the error vector magnitude (EVM) and the bit error rate (BER) metrics, which is in line what has been reported in the literature. The EVM describes link performance in the presence of channel impairments and noise. In an additive white Gaussian noise (AWGN) channel with a high level of noise, the ideal EVM can be expressed as [23]:

$$EVM_{RMS} = \sqrt{\frac{1}{SNR}} \,. \tag{6}$$

However, for cases with lower levels of SNR the measured EVM < the ideal value [23].

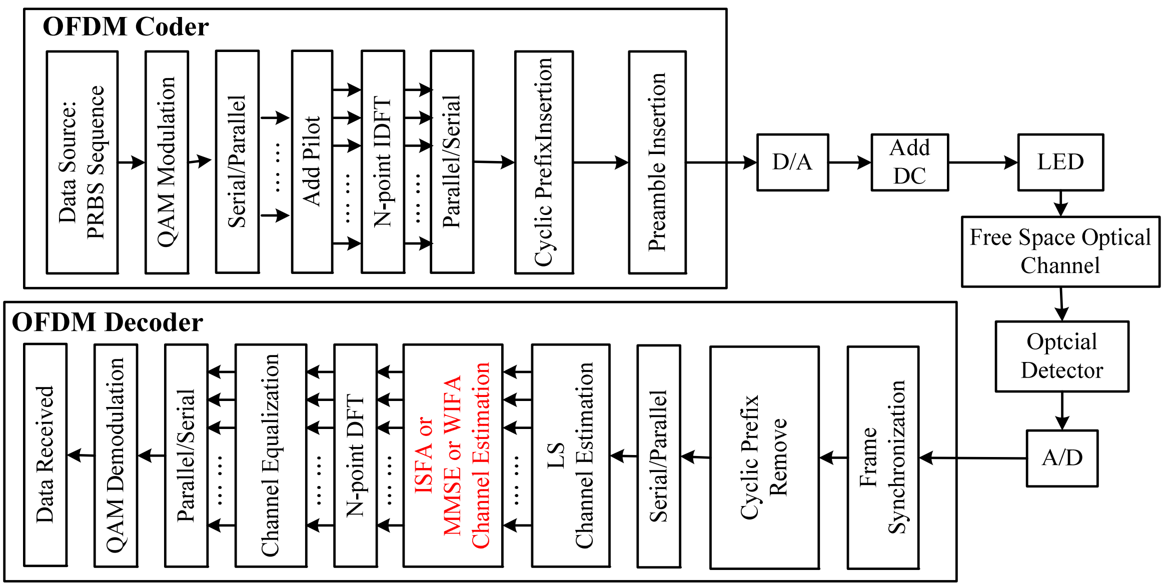

Fig. 1. *Block diagram for OFDM visible light communication with frequency domain channel estimation methods*

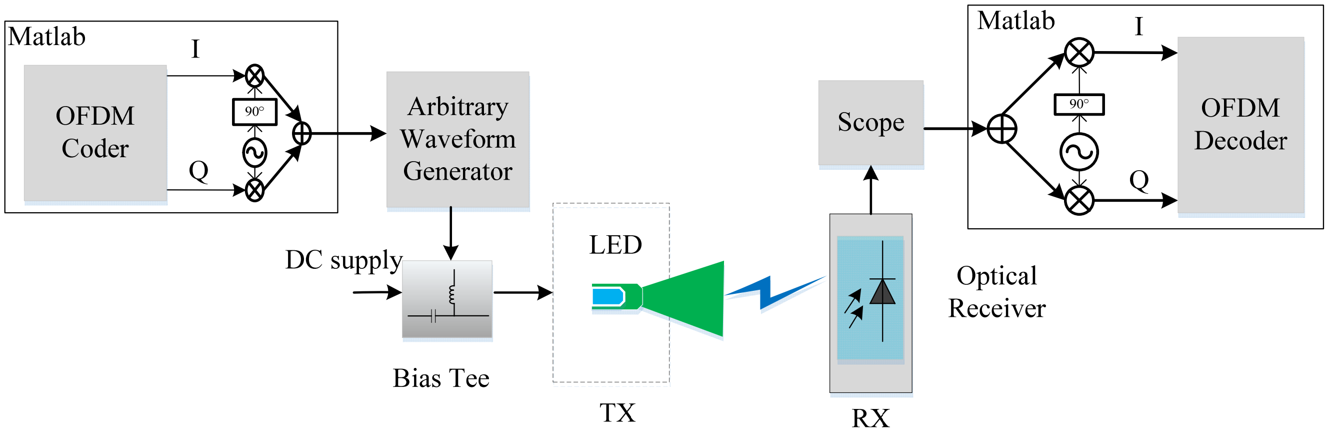

Fig. 2. *Experiment setup for OFDM visible light communications*

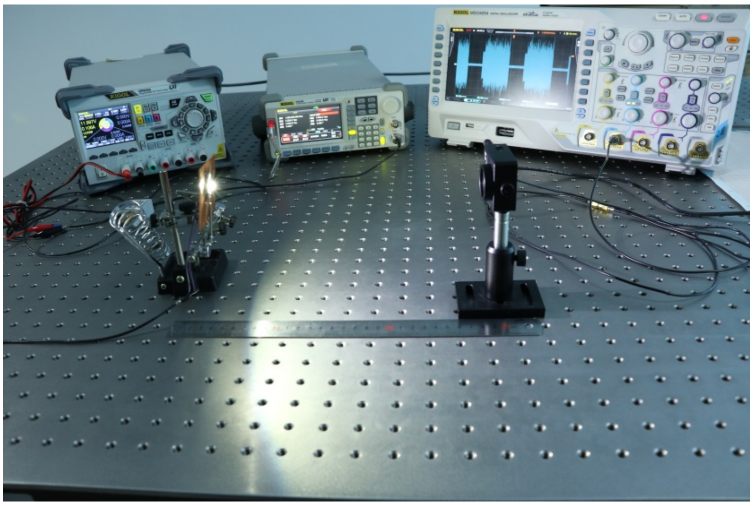

Fig. 3. *Photo of the actual experiment setup*

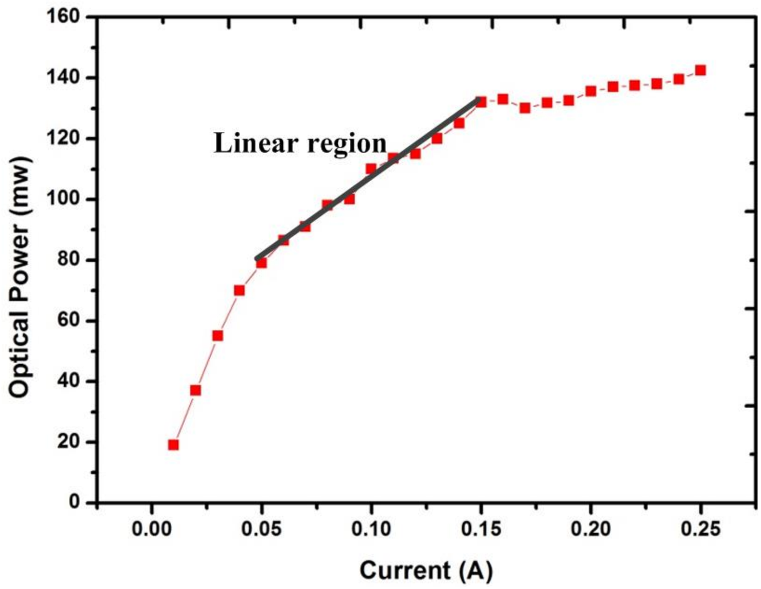

Fig. 4. *The output optical power as a function of current in our experiment.*

Table I System parameters

Parameter	Value
LED • Bandwidth • Semi-angle of half power • Transmit power	 < 5 MHz ~ 60^o 100 mw
Pin photodetector • Active area A_r • Responsivity R • Bandwidth	 0.8 mm^2 < 0.44 A/W 150 MHz
OFDM • No. of SC • CP length	 1024 16
Field of view of Receiver	90^o
DC bias	0.12 A

4. Experiment results

We recorded 25 consecutive frames for each trial in our experiment. Fig. 5 shows the captured received OFDM signal waveform using the QPSK mapping. Due to the fast timing-varying physical characteristics of optical channel, the CFR of each frame is quite different. Therefore, the EVM performance of each frame using LS, ISFA, MMSE and WIFA methods is different as shown in Fig. 6. Note that in the LS method a single training symbol is used to calculate the CFR, whereas in the ISFA method, the estimation results from LS are used along with the averaging of 5 adjacent subcarriers. In the WIFA method, δ_0 in (5) is set to 0.1. From Fig. 5, for index of frames > 5 both the MMSE and WIFA methods display higher EVM whereas ISFA followed by LS show lower values. For the index of frames < 5 all schemes display lower values of EVM. With the increased number of received frames, the WIFA display a more accurate CFR estimation by inter-frame averaging. After the 7th frame, the CFR estimated by WIFA is converged.

Fig. 7 shows the EVM performance as a function of transmission distance for QPSK-OFDM. Figs. 8, 9 and 10 depict the BER performances for QPSK-OFDM, 16QAM-OFDM and 64QAM-OFDM, respectively. Each BER is determined from the average of 25 frames. In Fig. 7, the constellation is captured with LS for the link of 17 cm long. The EVM gains are 2.7 dB, 3.7 dB and 3.5 dB for ISFA, MMSE and WIFA, respectively compared with the conventional LS method, see Fig. 7. Additionally, at a BER of 10^{-3} the increased transmission spans are about 1 cm, 3 cm and 3 cm for ISFA, MMSE and WIFA, respectively as depicted in Fig. 8. While the increased transmission spans are about 0.7 cm, 2.7 cm and 1.7 cm for ISFA, MMSE and WIFA, respectively in the case of 16QAM mapping as depicted in Fig. 9. In the case of 64QAM mapping, the increased transmission spans are about 2 cm, 3 cm and 1 cm for ISFA, MMSE and WIFA respectively at a BER of 10^{-2} as shown in Fig. 10. In all, MMSE always performs the best in term of EVM but at the cost of increased complexity. The WIFA can also improve the accuracy of channel estimation, even though the VLC optical channel changes rapidly.

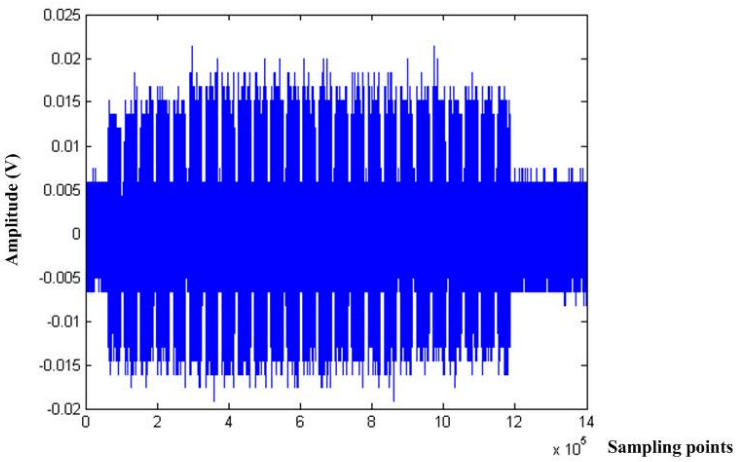

Fig. 5. *QPSK-OFDM signal waveform after 19-cm free space transmission sampled by real-time scope*

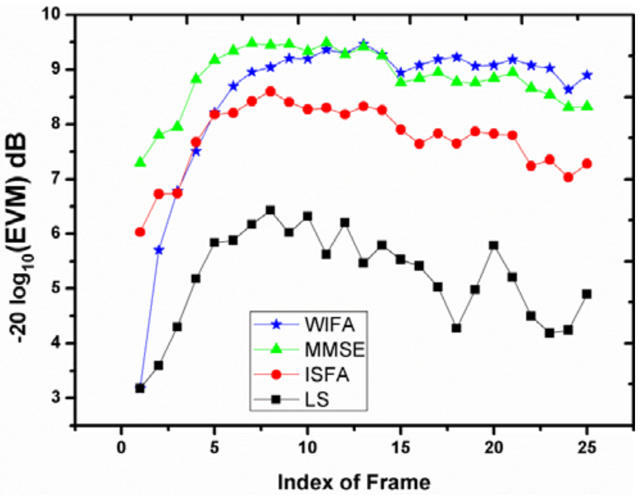

Fig. 6. *EVM against the frame index for WIFA, MMSE, ISFA and LS, for QPSK-OFDM over a 19 cm free space transmission*

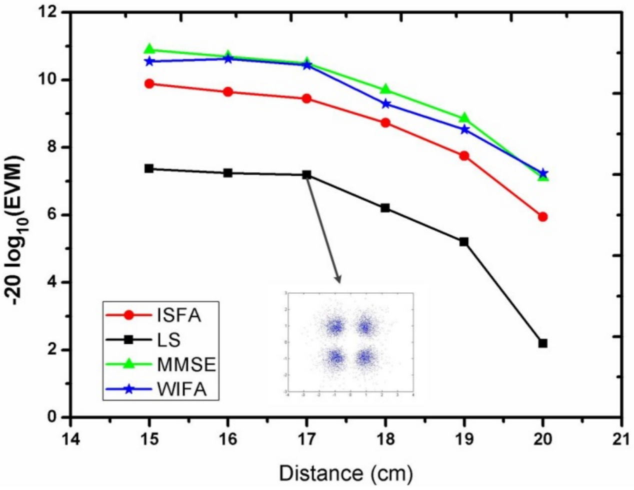

Fig. 7. *EVM as a function of transmission distance for ISFA, LS, MMSE, WIFA and for QPSK-OFDM*

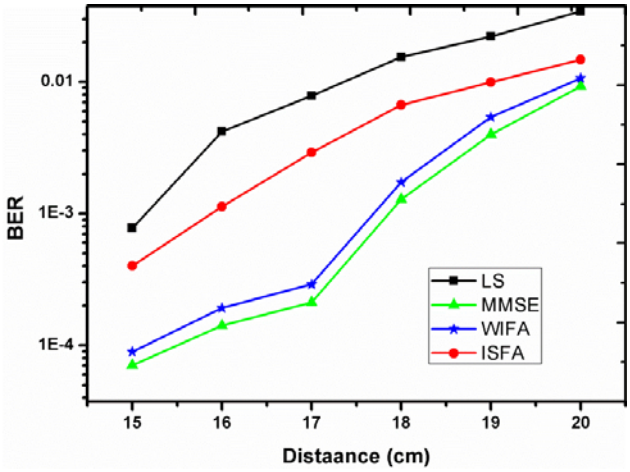

Fig. 8. *BER as a function of transmission distance for ISFA, LS, MMSE, WIFA and for QPSK-OFDM*

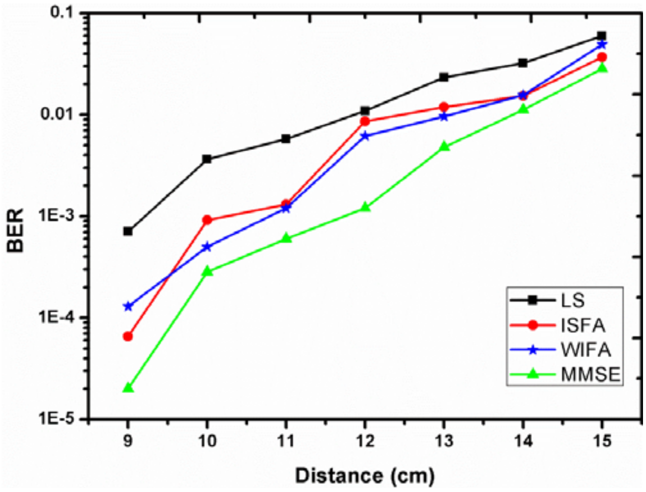

Fig. 9. *BER as a function of transmission distance for ISFA, LS, MMSE, WIFA and for 16QAM-OFDM*

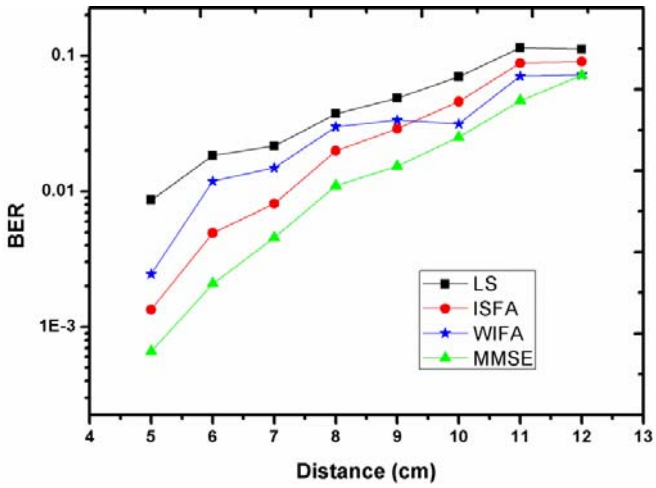

Fig. 10. *BER as a function of transmission distance for ISFA, LS, MMSE, WIFA and for 64QAM-OFDM*

5. Conclusion

In this paper, we presented efficient frequency domain channel estimation methods based on ISFA, MMSE and WIFA for OFDM-VLC system. The experiment results showed that MMSE outperforms the other two schemes in term of the EVM for QPSK-OFDM, 16- and 64-QAM-OFDM VLC systems. For QPSK-OFDM VLC transmission, the EVM gains were about 3 dB, 4 dB and 3.5 dB for ISFA, MMSE and WIFA, respectively compared to the conventional LS method. We also showed that WIFA can improve the estimation accuracy of time-varying VLC optical channel.

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