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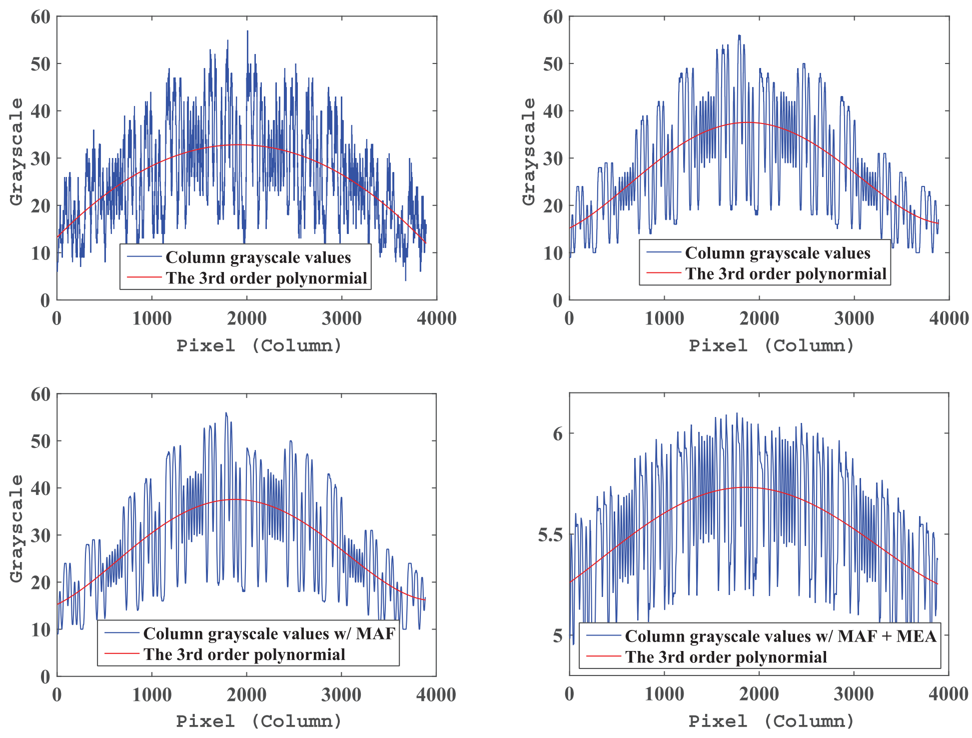
Zhenshan Zhang
Tiantian Zhang
Ji Zhou
Yaojun Qiao
Aiying Yang
Yueming Lu



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Performance Enhancement Scheme for Mobile-Phone Based VLC Using Moving Exponent Average Algorithm

Zhenshan Zhang,[1] Tiantian Zhang,[1] Ji Zhou,[1] Yaojun Qiao,[1] Aiying Yang,[2] and Yueming Lu[3]

[1]State Key Laboratory of Information Photonics and Optical Communications, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]School of Opto-electronics, Beijing Institute of Technology, Beijing 100081, China
[3]Key Laboratory of Trustworthy Distributed Computing and Service, Ministry of Education, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

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Corresponding author: Yaojun Qiao (e-mail: qiao@bupt.edu.cn).

Abstract: With the popularity of mobile phone, the mobile-phone camera used as visible light communication (VLC) receiver is attractive. However, a mobile-phone-based VLC system suffers from a high extinction ratio (ER) fluctuation for high data rate, which effects the bit error rate (BER) performance, transmission distance, and data rate. In this paper, we propose and demonstrate using the moving exponent average (MEA) algorithm to decrease the ER fluctuation and enhance the performance of the mobile-phone-based VLC system. Through the proposed MEA algorithm, not only the ER fluctuation can be decreased, but blooming can be eliminated as well. In order to demonstrate that the MEA algorithm can enhance the performance of the mobile-phone-based VLC system, we evaluated the BER performance as changing transmission distance and data rate. From the experimental results, a 7% forward error correction (BER $= 3.8 \times 10^{-3}$) requirement can be satisfied at 50 cm when the data rate is 4.8 kb/s and at 100 cm when the data rate is 3.6 kb/s.

Index Terms: Visible light communication (VLC), camera receiver, extinction ratio (ER), illumination, blooming effect.

1. Introduction

Visible light communication (VLC) is a short-range optical wireless communication utilizing LED lighting, so that the LED lights can provide both illumination and communication [1]. It is expected to become an important part of the future fifth-generation (5G) wireless communications because of its unique features in supporting of high data rate, unlicensed spectrum, immunity to electromagnetic interference, harmless for human body, low power consumption and long lifetime [2]–[8]. The transmitter (Tx) of VLC system transmits data information via high-speed switching between on and off of the lighting sources. The receiver (Rx) uses photoelectric components such as PIN, APD, or image sensor to detect signals from light sources [9]–[13].

With the popularity of mobile phones, cameras have become an indispensable part of them. Today, most of the mobile phones have built-in complementary metal-oxide-semiconductor (CMOS) sensor and offer rolling shutter mode. While rolling shutter is disadvantage for imaging moving objects, it is advantage for VLC which can achieve higher data rate than the image sensors frame rate [14], [15]. Hence, it has been attracted people's attention that mobile-phone camera be used as the VLC Rx.

Due to the blooming effect, some grayscale values are invalid. It's essential to select effective grayscale values for signal demodulation. In order to mitigate the blooming effect, in [20] reported every 60 rows of pixels are grouped and selecting a column matrix of grayscale values from each grouped pixels to form a column matrix for signal demodulation. Ref. [21] demonstrated using a second-order polynomial fitting for each row pixels and selecting effective grayscale values for signal demodulation. Besides, using mobile phone camera as the Rx is facing the high extinction ratio (ER) fluctuation for high data rate [16]–[19]. The high data will cause high ER fluctuation which result in the data logic can't be recovered correctly by a threshold. Refs. [16]–[18] reported using polynomial fitting for two times and adaptive thresholding to reduce the high ER fluctuation. In order to evaluate the performance of mobile-phone camera based VLC system, the bit error rate (BER) versus illuminance is measured in many works [17]–[22].

In this paper, we propose and demonstrate performance enhancement scheme for mobile-phone based visible light communication using the proposed moving exponent average algorithm (MEA). First, we sort the elements of each row matrix of grayscale values in descending order. A proper column matrix of grayscale values can be selected from the sorted grayscale image. The approach not only can reduce the grayscale values jump and the computational complexity, but also decrease the random noise interference of adjacent pixels. Then, we propose a low computational complexity MEA algorithm to reduce the ER fluctuation and blooming. After MEA algorithm processing, a 3rd order polynomial fitting can be applied to distinguish data logic without need for complicated thresholding scheme. Finally, we evaluate the BER of VLC system for different distances (50 cm, 100 cm, 150 cm, 200 cm) and data rates (2.4 kbps, 3.6 kbps and 4.8 kbps) which are real-world tests. Experimental results show that the proposed MEA algorithm can significantly enhance system performance and shows great potential for application in mobile-phone camera based VLC system.

2. Experimental Setup

Fig. 1 shows the experimental setup of the VLC system using mobile phone camera as Rx. The block diagram of the VLC system is shown in Fig. 1(a). The transmitting data signal is programmed by Tektronix ArbExpress in a computer. The transmitted data signal is generated by an arbitrary waveform generator (AWG, Tektronix, AFG3102C) to perform the digit-to-analog (DAC) conversions. The AWG have the sampling rate and bandwith of 1 GSample/s and 100 MHz. The transmitted signal is packet-based and each packet is composed of a 12-bit header and a 48-bit on-off keying (OOK) payload data in non-return-to-zero (NRZ) format. The data logic of the 12-bit header data is $\{1010\ 1010\ 1010\}$ which is enough for clock recovery and signal synchronization. The data signal is superimposed onto the LEDs driver circuit to driver a LED array with 15 white-light LEDs (Cree XPGR5) to emit modulated white light. In order to increase transmission distance of the VLC system, we use a LED array (see Fig. 1(b2)) with 15 LEDs, and the emitted light is significantly enhanced by a LED lens module (see Fig. 1(b4)). After free-space transmission, the modulated white light signal is received by mobile phone (Huawei Honor 7) rear camera (see Fig. 1(b3)) whose pixels 3888×5152 (Row $\times$ Column). With the rolling shutter effect, bright and dark fringes will be recorded by different rows of pixels with LED light source on and off. The bright and dark fringes will be recorded in an image frame which can be demodulated by computer via off-line processing.

3. Signal Processing Algorithm

For the signal demodulation, each image file is converted into grayscale format, in which the grayscale level from 0 to 255 represents the fringes from completely darkness to completely

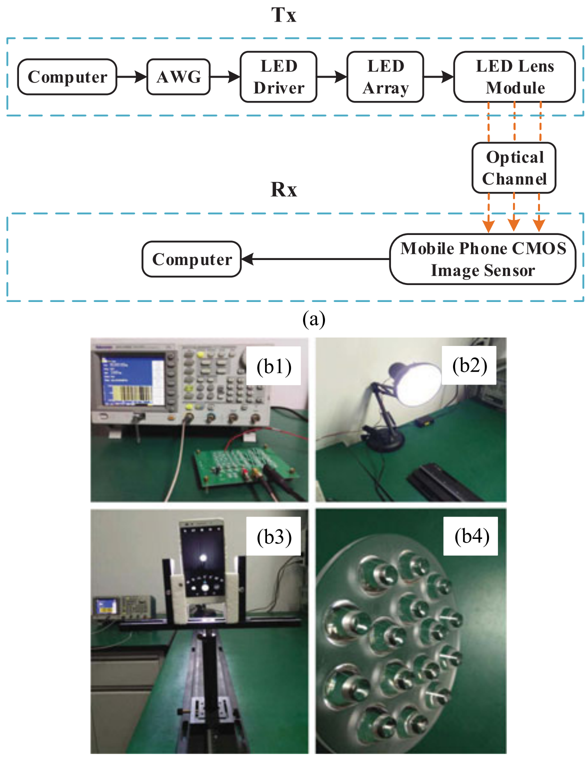

Fig. 1. (a) Block diagram of the experimental setup of the VLC system using mobile-phone camera as Rx. (b1)–(b4) Experiment pictures which are AWG and LED driver, LED array, Rx, and LED lens module, respectively.

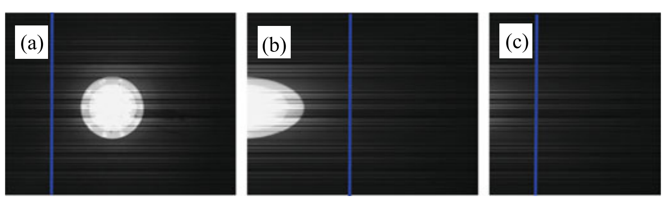

Fig. 2. (a) Raw grayscale image, (b) sorted grayscale image, and (c) selected a valid region from the sorted grayscale image.

brightness. Fig. 2(a) shows an image after the grayscale conversion. It's clearly to observe that the blooming occurs in the raw grayscale image which will result in that the bright and dark fringes can't be distinguished. Note that closing to blooming region, the contrast between bright and dark fringes is striking. In addition, due to the exposure time is very short, each row pixel is considered to record the same data signal. Hence, we only need select a proper column matrix of grayscale values just away from the blooming region from the grayscale image which contains all the information for signal demodulation. The blue line in Fig. 2(a) is the selected column matrix. The blue curve in Fig. 3(a) represents the grayscale values distribution of the selected column matrix. From Fig. 3(a), we can observe that the random noise interference of adjacent pixels is very serious, a third-order polynomial fitting (red curve) as the threshold can't distinguish the logic 1 or 0. Hence, the selected column matrix of graycale values can't be used for signal demodulation.

In order to select a proper column matrix for signal demodulation, we sort elements of each row matrix of grayscale values in raw grayscale image frame in descending order. Fig. 2(b) is generated by sorting elements of each row matrix of grayscale values in descending order. Due to the data

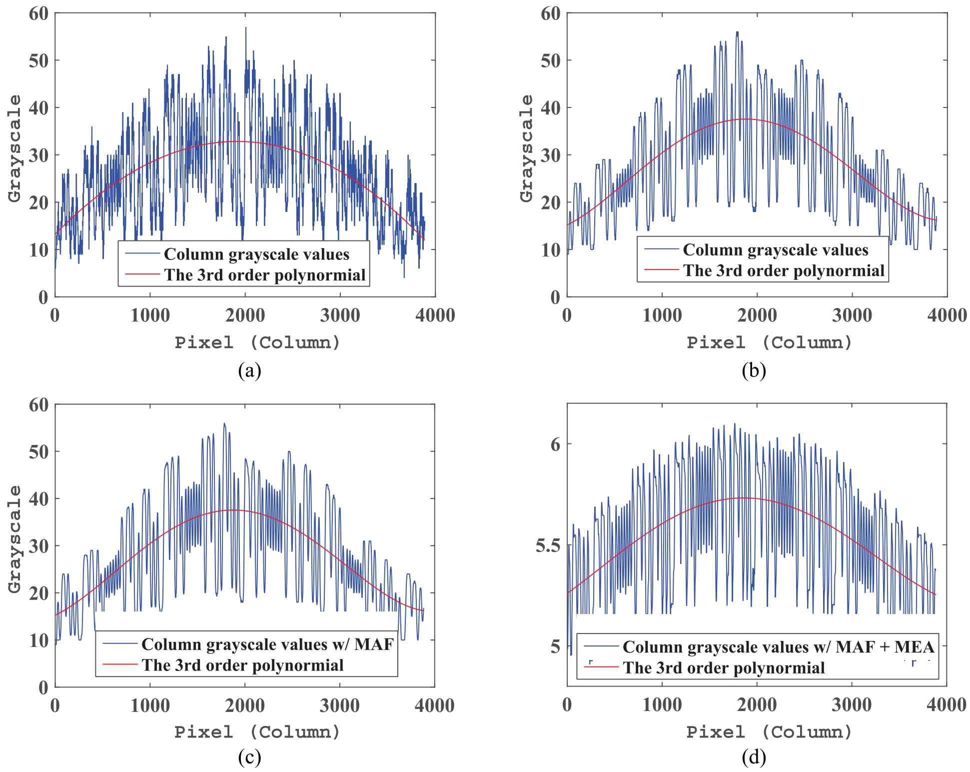

Fig. 3. Column matrix of grayscale values of (a) raw signal, (b) raw sorted signal, (c) after moving average filter, and (d) after moving average filter + moving exponent average.

signal can be affected or lost owing to pixels saturation caused by the higher intensity optical signal or the grayscale values of pixels approach to zero caused by the lower intensity optical signal. We select a valid region from the sorted grayscale image to avoid the booming region and the too dark region. The valid grayscale region is determined by the following method.

Checking each element value of column matrix of grayscale values from the first column in the sorted grayscale image every 100 column interval, such as the 1st, 101th, 201th $\cdots$ column, until each element value of k_1th column matrix of grayscale values is less than 200. With the same method, we check each element value of column matrix of grayscale values from the last column in the sorted grayscale image every 100 column interval, such as 3888th, 3788th, 3688th $\cdots$, until each element value of k_2th column matrix of grayscale values is greater than 3. The selected valid region is from k_1th column to k_2th column of the sorted grayscale image. Fig. 2(c) shows the selected valid region where the booming region and the too dark region are removed. Finally, we select the nth ($n = [(k_1 * 3 + k_2)/4]$) column of the sorted grayscale image (see the blue line in Fig. 2(b) and (c)) for signal demodulation, where $[\cdot]$ is rounding symbol. For example, $[2.3] = 2$, $[2.6] = 3$.

Fig. 3(b) shows the grayscale values distribution of the selected column matrix. We can clearly observe that after sorting elements of row matrix of grayscale values in ascending order, the random noise interference of adjacent pixels has been reduced. As all known, the moving average filter (MAF) can decrease the amplitude of the random noise, but also reduces the the sharpness of the edges [23]. In order to further decrease the amplitude of the random noise, the selected column matrix grayscale values are processed by the MAF. Equation (2), shown below, shows the theory of MAF.

$$y_i = \frac{1}{M} \sum_{j=0}^{M-1} x_{i+j} \tag{1}$$

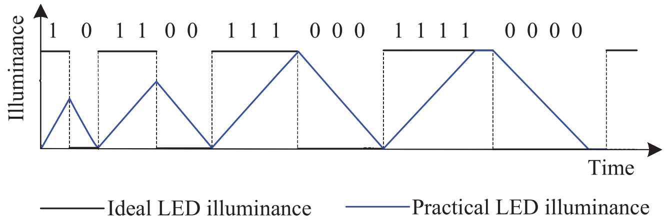

Fig. 4. Model of LED ideal and practical illuminance against different pulse duration at high data rate.

where x_i is the input signal, y_i is the output signal, and M is the number of the points used in MAF which is determined by the bit resolution (i.e., pixels per bit). In the experiment, x_i is ith element of the selected matrix of grayscale values, $M = [N/3]$, where $[\cdot]$ is rounding symbol, N is bit resolution. Fig. 3(c) is the moving average filter output signal.

In Fig. 3(b) and (c), the red curve is the third-order polynomial fitting curve which is used as the threshold to distinguish the logic 1 and 0. However, we can observe that there exist some failures where the third-order polynomial fitting curve can't distinguish the logic 1 or 0. The two main reasons are the "blooming effect" of the CMOS sensor and the high ER fluctuation. As shown in Fig. 4, ideally, the emitted light is instantly brighten or darken with the LED lights on or off. However, actually, due to the capacitive characteristics of LED, the emitted light is gradually brighten, which will result in the high ER fluctuation. Moreover, the ER fluctuation will be more significant with the increasing of data rate. In order to enhance the performance of mobile-phone camera based VLC system, we propose a MEA algorithm to reduce the ER fluctuation. The following equation shows the theory of the proposed MEA algorithm.

$$z_i = \begin{cases} \dfrac{y_i^2 + y_{i+1}^2}{y_i^\beta}, & i = 1, 2, \cdots 3887 \\ z_{i-1}, & y_{i+1} = y_i \text{ or } i = 3888 \end{cases} \tag{2}$$

where z_i is the output signal, y_i is the output of the selected column matrix of grayscale values processed by MAF, 3888 is the number of rows of mobile-phone camera pixels, and β is a constant coefficient which is used to adjust the ER fluctuation. A larger value of β will make z_i value smaller which causes error decision when a third-order polynomial fitting curve is used as the threshold to distinguish the logic 1 and 0. A smaller value of β cannot reduce the ER fluctuation. Here, a better β value is 1.9 which is obtained by a lot of experiments.

As the blue curve clearly shown in Fig. 3(d), MEA not only can reduce the ER fluctuation, but also can significantly reduce the "blooming effect" of the CMOS sensor. We use a third-order polynomial fitting (red curve) as the threshold to distinguish the logic 1 and 0. By comparing Fig. 3(c) and (d), it's easily to find that there are many incorrect decisions to data logic values without MEA while almost the data logic values can be correctly decided with MEA.

4. Results and Discussion

After grayscale conversation, sorting elements of each row matrix of grayscale values to reduce random noise interference of adjacent pixels, column matrix selection, processing by MAF and MEA, a third-order polynomial fitting for thresholding, recovering the data logic, the BER performance of the mobile phone camera based VLC system can be evaluated. As mentioned before, the VLC signal is packed-based, and each packet is composed of a 12-bit header data {1010 1010 1010} and a 48-bit OOK payload data in NRZ format. The header data is used for clock recovery and signal synchronization. In order to evaluate the performance of the mobile phone camera based VLC system, we carried out a number of experiments for different transmission distances (50 cm,

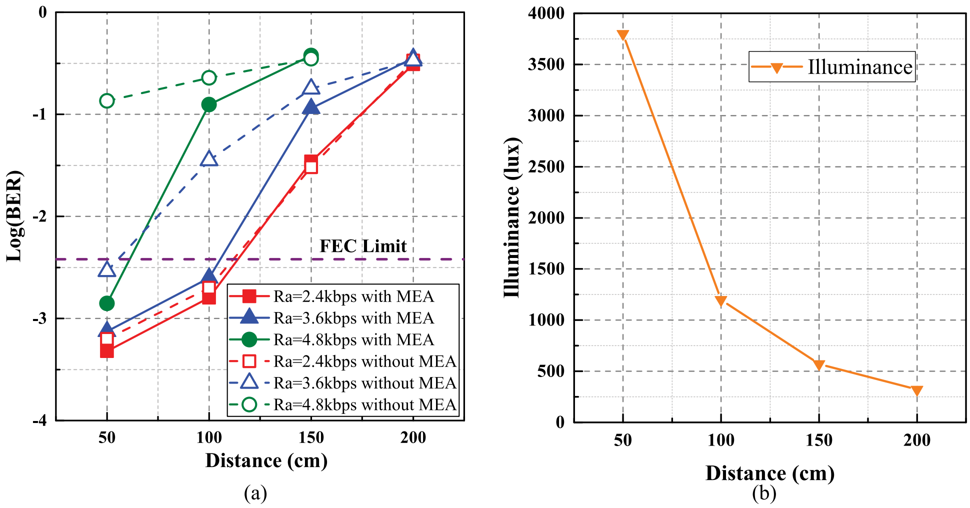

Fig. 5. (a) BER performance at different distances with and without the proposed MEA algorithm. (b) Illuminance at different distance.

100 cm, 150 cm and 200 cm) and data rates (2.4 kbps, 3.6 kbps and 4.8 kbps). We sent $\sim 2 \times 10^4$ bits for each given transmission distance and data rate.

Fig. 5(a) and 5(b) are shown the measured BER-versus-distance curves for six different cases and the illuminance-versus-distance curve, respectively. It is obviously observed that the BER performance has a substantial improvement at data rate of 3.6 kbps and 4.8 kbps when using the MEA algorithm. The reason of the phenomenon is the high ER fluctuation will be reduced by using the MEA algorithm. However, at data rate of 2.4 kbps, there is no significant improvement of BER after the MEA processing, which reason is that the ER fluctuation is lower as the pulse duration is sufficient for LED to reach its brightest and darkest at the lower data rates.

A comparison between solid line and dash line at the same distance suggests that the higher data rate can be achieved by MEA algorithm. Without MEA processing, the %7 forward error correction (FEC; BER $= 3.8 \times 10^{-3}$) requirement can be satisfied when the data rates at distances of 50 cm and 100 cm are 3.6 kbps and 2.4 kbps, respectively. By using the MEA algorithm, achievable data rates at distances of 50 cm and 100 cm are increased to 4.8 kbps and 3.6 kbps, respectively. In addition, MEA algorithm also can increase the transmission distance at the certain date rate. As shown in Fig. 5(a), for the data rate of 3.6 kbps, without MEA algorithm, the achievable distance is only 50 cm. When using MEA algorithm, the achievable distance is around 100 cm at the same condition. For the data rate of 4.8 kbps, the BER can't satisfy the FEC requirement without MEA algorithm. By using MEA algorithm the BER is still achieved at about 50 cm. Although the BER, transmission distance and data rate can be improved by increasing the illumination, the higher illumination is limited from the consideration of the human eye safety. Hence, our proposed scheme has great advantages in practical applications.

5. Conclusion

In this paper, we proposed using MEA algorithm to enhance the performance of mobile-phone based VLC. We first described our procedure of column matrix selection, including grayscale conversion, sorting the elements of each row matrix of grayscale values in descending order to reduce random noise interference of adjacent pixels, selecting a valid region from the sorted grayscale image, and locating the selected column matrix to avoid blooming. Then, the selected column matrix of grayscale values is processed by signal processing algorithms to be used for demodulation, including reducing the amplitude of the random noise by MAF, decreasing the ER fluctuation by the proposed MEA algorithm, and a third-order polynomial fitting for thresholding. Finally, we evaluate the BER of VLC system for different distances (50 cm, 100 cm, 150 cm and 200 cm) and data rates (2.4 kbps, 3.6 kbps and 4.8 kbps). The experimental results are shown that the proposed MEA algorithm not only can improve system BER performance, but also significantly increase the transmission distance and data rate. The BER can satisfy the FEC requirement at the transmission distance of 50 cm when data rate is 4.8 kbps; and at the transmission distance of 100 cm when data rate is 3.6 kbps. Our proposed scheme shows great potential for application in mobile-phone camera based VLC system.

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