Modulation Format Shifting Scheme for Optical Camera Communication

Jin Shi, Jing He, Zhongwei Jiang, and Gee-Kung Chang, *Life Fellow, IEEE*

***Abstract*— We propose and experimentally demonstrate a simple and elegant modulation format shifting (MFS) scheme by continuously changing the modulation formats between OOK and Manchester signal for optical camera communication (OCC) using a commercially available mobile phone. Leveraging the MFS scheme, extra data bits are delivered without reducing the pixel width of each bit, resulting in higher transmitted data rate. Meanwhile, multi-thresholding scheme is proposed for modulation format identification and signal decoding at the receiver. The experimental results demonstrate that the proposed MFS scheme can achieve a data rate of 8.16 Kbps with the bit error rate (BER) of 2.9×10^{-3} at the illuminance of 400 lux. In addition, compared with conventional OOK modulation, MFS scheme can remarkably improve the BER performance at the same data rate.**

***Index Terms*— Visible light communications (VLC), optical camera communication (OCC), light emitting diode.**

I. Introduction

VISIBLE light communication (VLC) has attracted increasing attention as a supplement for future wireless communications [1]. VLC using light-emitting diodes (LEDs) can realize both data transmission and illumination simultaneously, thus becoming a promising indoor wireless transmission scheme. Most of VLC systems use the positive-intrinsic-negative (PIN) and the avalanche photodiode (APD) to detect the received signal. Recently, optical camera communication (OCC) has received extensive attention by using Complementary Metal-Oxide-Semiconductor (CMOS) camera to detect the received signal in VLC system since it has better flexibility and lower cost [2]–[4]. By using the rolling-shutter mode in CMOS camera [5], the camera will exposure line by line subsequently in each image frame rather than capturing all pixel values at the same time in the global shutter mode. Though using rolling shutter mode will result in blooming effect (saturation of pixels) of CMOS cameras, there are some research works available for mitigating the issue [6], [7]. The bright and dark stripes in the image reflect the corresponding bit information, resulting in higher throughput than the frame rate. Camera on-off keying (OOK) using run-length limited (RLL) is an alternative scheme to maintain an average brightness and to avoid severe flickering issue as opposed that without RLL based on IEEE 802.15.7-2018… [8]. However, it will further decrease the throughput owing to the presence of bit redundancy.[1]

To increase system throughput, several technologies have been proposed. The multiplexing scheme using red-green-blue LEDs… [9], [10] and advanced thresholding scheme [11] have been investigated to enhance the system throughput. In addition, to make a stipe can represent more bits, multilevel modulation scheme is proposed to remarkably increase the system throughput. In our previous work [12], the multilevel modulation realized by the overlapping of two light sources is proposed without the requirement of multi-level voltage amplitudes. In [13], pulse width modulation (PWM) based multilevel modulation is utilized to achieve high data rate. However, these schemes require multiple LED sources or high luminance to clearly judge different levels at the receivers, which will severely limit the real application and transmission distance.

In this paper, we propose and experimentally demonstrate a novel modulation format shifting (MFS) scheme using OOK and Manchester signal to achieve higher data rate for OCC system only using one LED. It can remarkably enhance the data rate while mitigating the flickering issue as opposed to conventional OOK without RLL. Moreover, a multi-thresholding scheme is proposed for identifying the modulation formats and signal decoding at the receiver. In addition to conventional signal decoding, we gain an extra bit of information through identifying OOK and Manchester signal. Experimental results show that compared to conventional OOK scheme, the proposed MFS scheme can achieve significant bit error rate (BER) performance improvement, meanwhile realizing higher system throughput of 8.16 Kbps at the low illuminance of 400 lux.

II. The Proposed MFS Scheme

A. The Principle of MFS Scheme

The principle of proposed MFS scheme is shown in Fig. 1. The incoming bit stream is divided into odd-index group and even-index group. The odd-index bits are used for modulation format selection, wherein bit “0” denotes that following even index bit is modulated by OOK and bit “1” stands for Manchester modulation for the following even-index bit. OOK

Manuscript received January 13, 2020; revised July 19, 2020; accepted July 26, 2020. Date of publication July 29, 2020; date of current version August 18, 2020. This work was supported in part by the National Natural Science Foundation of China under Grant 61775054; in part by the Science and Technology Project of Hunan Province under Grant 2016GK2011; and in part by the China Scholarship Council (CSC) under Grant 201906130124. *(Corresponding author: Jing He.)*

Jin Shi is with the College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China, and also with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308 USA.

Jing He and Zhongwei Jiang are with the College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China (e-mail: jhe@hnu.edu.cn).

Gee-Kung Chang is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2020.3012834

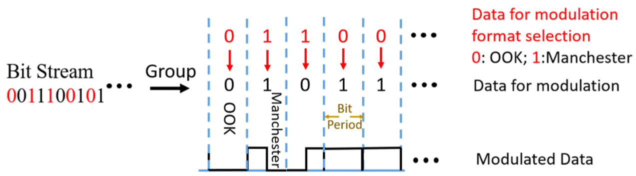

Fig. 1. Principle of the proposed MFS scheme.

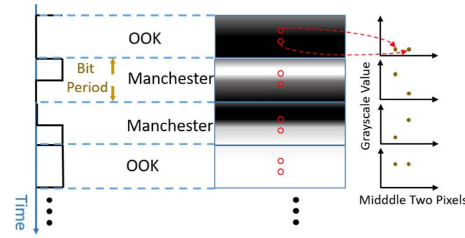

Fig. 2. Grayscale image comparison by using OOK and Manchester modulation in rolling shutter-based OCC system.

modulation is used to deliver binary data by changing on and off state of the light. The on and off states of the LED denote bit 1 and bit 0, respectively. As for the Manchester modulation, each bit period contains a transition, which means at the middle of bit period, there exists an edge. As illustrated in Fig. 1, bit 0 is represented by a falling edge and bit 1 is represented by a rising edge. Enabled by MFS scheme, in addition to the bit information obtained by conventional demodulation according to identified modulation format, identifying the modulation format at each period can additionally acquire one bit information. Therefore, by using the proposed scheme, two bits are carried at only one bit period, which remarkably enhances the throughput of optical camera communication. It is worth noting that, the identification of OOK and Manchester is very simple yet effective by using our proposed scheme, which will be explained in the following.

B. The Decoding Scheme for the Proposed MFS

Fig. 2 illustrates the grayscale image comparison by using OOK and Manchester modulation in rolling shutter-based OCC system. It can be seen than there exists edge information at the middle of each bit period for Manchester signal. While, for OOK signal, the signal intensity keeps invariant at each bit period. Thus, the middle two pixels located at each bit period can be easily used to identify the OOK and Manchester signal by judging whether the edge information exists or not. If the both middle two pixels are bright or dark, it denotes that the data bit is modulated by OOK and the corresponding transmitted data bit is 1 or 0. On the contrary, when there exists two obvious bright and dark stripes at one bit period, it represents the data bit is modulated by Manchester. If the first one of the middle two pixels is bright and the other is dark, it reveals that there is a falling edge and thus bit 0 can be attained. On the other hand, if the first one of the middle two pixels is dark and the other is bright, it represents that there is a rising edge and data bit 1 is obtained.

III. Experiment, Results, and Discussion

The experimental setup of OCC system with a conventional mobile phone camera is shown in Fig. 3(a). The modulated data enable by MFS scheme as illustrated in Fig. 1 is offline generated by personal computer (PC), then fed into a single port read-only memory (ROM) of field-programmable gate array (FPGA) from Xilinx Spartan 6 series (xc6slx45). The general-purpose input/output (GPIO) pin outputs logic high or logic low, which corresponds to symbol "1" or "0" stored in the ROM, respectively. They can be used to control the "ON" or "OFF" state of LED. In order to increase the current drive and control the brightness of LED, the LED driver circuit is used to drive the white-light LED (Cree XLamp XR-E) for data transmission. The transmitted symbol rate is about 28.8 KS/s (80 (data bits/frame)$\times$2 (symbols/data bit)$\times$60 (frames/second)$\times$3 (repeat 3 times) $=$ 28.8 KS/s). To avoid data packet loss induced by frame rate variation for a period of BER measurement, we finely tune the transmitted frequency manually so that the it can approach the real row scan frequency on average as closely as we can. After 60 cm free space transmission, a mobile phone (iPhone 6s) with camera app named ProMovie Recorder is utilized to receive the signal by video recording. It is worth noting that we physically attach a small piece of thin paper in front of the camera to scatter the received light so as to mitigate the blooming effect. The video is recorded at the frame rate of 60 fps and the resolution is 1080 $\times$ 1920. Meanwhile, the exposure time is manually fixed. Though smaller exposure time i.e., higher shutter speed has clearer stripe, the brightness of image will get lower due to shorter time letting light in. As such, the trade-off exposure time is set to 1/38400. Moreover, to increase the sensitivity to received light, the camera sensor sensitivity (ISO) is set to its maximum at 735. A digital light meter (Benetech-GM1020) is used to measure the intensity of received signal. In addition, the structure of data packet is illustrated in the inset of Fig. 3(a). Since there is frame processing time that could not capture any information, each data packet including header and payload will be transmitted three times, which is a trade-off to guarantee each frame at least contains a complete data packet and meanwhile avoid redundancy when more times are involved [12]. A 12-bit header is used for symbol synchronization and clock recovery, and each payload has 68 effective data bits. Thus, including the same amount of data bits carried by modulation formats, each image frame has total 136 effective data bits. Therefore, the net data rate is 8.16 Kbps (136 (bits per frame)$\times$60 (frames per second) $=$ 8.16 Kbps). The experimental scene is illustrated in Fig. 3(b).

To recover the bit information from the recorded video, the processing diagram can be summarized as shown in Fig. 4. First, several image frames are extracted from the video before converted into grayscale images with pixel value ranging from 0 to 255. Since the camera scans each row at the same time by using rolling shutter mode, one column of grayscale values for each image frame are selected for signal demodulation as shown in Fig. 4(a). And then, in order to reduce the effect of noise, each column of pixel values is smoothed by a low pass filter (LPF) with filter coefficients of [1/3, 1/3, 1/3] as shown in Fig. 4(b). Meanwhile, histogram equalization is carried out to increase the extinction ratio (ER) which can be seen

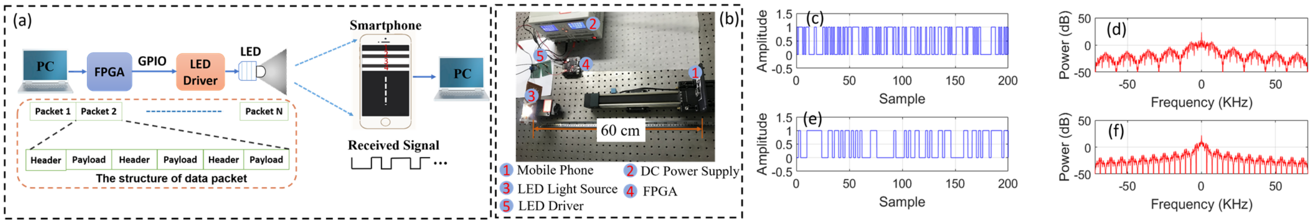

Fig. 3. (a) Experimental setup of optical camera communication system using mobile phone camera, (b) the experimental scene. (c-f) are the time domain waveforms and their spectra using MFS scheme and conventional OOK, respectively.

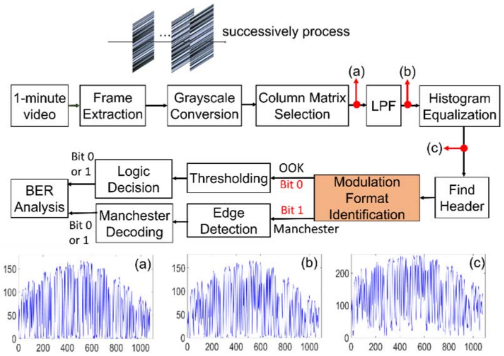

Fig. 4. The process diagram of OCC system using mobile phone with MFS scheme. The corresponding grayscale values before (a) LPF, after (b) LPF and after (c) histogram equalization.

in Fig. 4(c). After finding the header of each frame, modulation format identification is performed to recover the extra bits by distinguishing OOK and Manchester before signal decoding. As for OOK modulation, the thresholding is utilized for logic decision. While edge detection is implemented for Manchester decoding. Finally, the BER can be obtained after counting the total error bits.

The modulation format identification is essential to accurately derive the bit information carried by modulation format and the encoding information. Since there exists edge information at the middle of each bit period for Manchester signal while the intensity of OOK signal always keeps invariant at each bit period, the middle pixel values $M(i)$ and $M(i+1)$ can be easily utilized to determine which modulation format is used. In our experiment, each bit occupies six pixels, which is derived from the header of each image frame. Therefore, the 3rd and 4th pixels at each bit period are picked up for further processing. To increase the accuracy of modulation format identification, multi-thresholding scheme is proposed as shown in Fig. 5. Firstly, by applying third-order polynomial fitting to the selected column of grayscale values $p(i)$, (i = 1, 2, …1080), the thresholding curve referred to as middle threshold $Tm(i)$ is plotted. Secondly, by replacing the grayscale values smaller than middle thresholding values with the middle thresholding values as $pu1(i)=p(i)<Tm(i)?Tm(i):p(i)$, the updated grayscale values $pu1(i)$ as shown in Fig. 5(b) are obtained and then third-order polynomial fitting is used to obtain a new thresholding curve referred to as upper threshold $Tu(i)$ as illustrated in Fig. 5(d). Similarly, as shown in Fig. 5(c), letting grayscale values greater than thresholding values directly equal to the thresholding values as $pu2(i)=p(i)>Tm(i)?Tm(i):p(i)$, another new thresholding curve termed as lower threshold $Tl(i)$, as shown in Fig. 5(e), can be acquired from the updated grayscale values $pu2(i)$. If $M(i)$ and $M(i+1)$ are respectively greater than upper threshold values $Tu(i)$ and $Tu(i+1)$ or respectively smaller than lower threshold values $Tl(i)$ and $Tl(i+1)$, it can be implied that there is no symbol transition and thus OOK modulation is identified. Otherwise, large fluctuation on grayscale values of middle two pixels indicates that there exists edge transition at the middle of each bit period. Thus, the modulation format is identified as Manchester modulation. At the same time, the corresponding data bits can be obtained from the modulation formats since they are determined by the data bit 0 and 1.

Following the modulation format identification, the signal decoding is then performed based on the identified modulation formats. For OOK decoding, if the middle two-pixel values are greater than the upper thresholding, the modulated signal is decoded as bit 1. Otherwise, it is judged as bit 0. As for the Manchester decoding, the differential value of the middle two-pixel values i.e., $d(i) = M(i+1)\text{-}M(i)$ is used to judge the rising edge or falling edge. If the differential value is greater than 0, it indicates than there exists rising edge and thus the modulated information can be decoded as bit 0. Otherwise, bit 1 is derived.

To evaluate the system performance of our proposed MFS scheme in OCC system using mobile phone camera, the BER performance versus illuminance is firstly investigated and the experimental results are shown in Fig. 6. Since there are two bits information respectively carried by modulation format and data encoding at each bit period, the corresponding BER curves are shown in Fig. 6. It can be seen that the BER performance gradually gets improved with the increase of illuminance due to increased signal power so as to have better signal noise ratio (SNR). When the illuminance is 400 lux, the BERs obtained from the data carried by modulation format and data for modulation are 3.5×10^{-3} and 2.3×10^{-3}, respectively, which are below the HD-FEC limitation of 3.8×10^{-3}. When increasing the illuminance to 700 lux, the corresponding BERs are reduced to 6.7×10^{-4} and 5.6×10^{-4}.

In order to further demonstrate the superiority of the proposed MFS scheme, the BER performance comparison between the MFS scheme and conventional OOK scheme without RLL is implemented. To guarantee the fairness, same data rate is considered. Therefore, OOK signal is transmitted with a doubled bit rate. In this case, each bit period is represented by 3 pixels for OOK scheme while each bit period includes 6 pixels for the proposed MFS scheme. The average BER is taken as metric for MFS scheme to perform a comparison with conventional OOK scheme. As shown in Fig. 7,

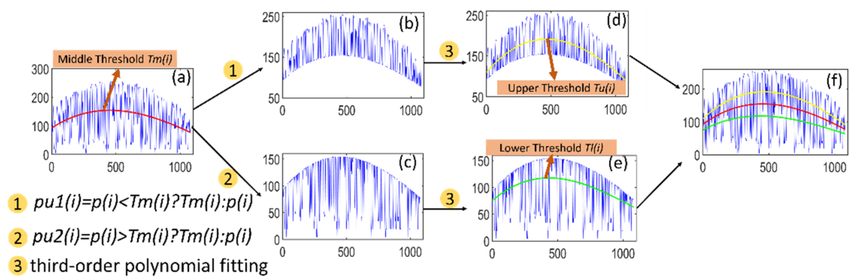

Fig. 5. Proposed multi-thresholding scheme for modulation format identification.

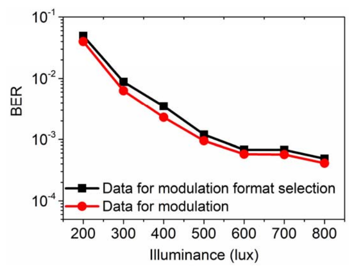

Fig. 6. BER performance versus illuminance by using MFS scheme for OCC system.

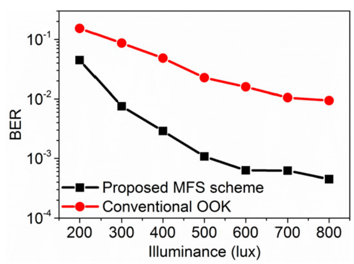

Fig. 7. BER performance comparison for MFS scheme and conventional OOK.

it can be found that our proposed MFS scheme remarkably improves the BER performance compared to conventional OOK. When the illuminance is 400 lux, the conventional OOK obtains the BER of 4.8×10^{-2}, while the MFS scheme can achieve the BER of 2.9×10^{-3}. Even when further increasing the illuminance, conventional OOK only achieves the BER of 9.4×10^{-3}, which still cannot satisfy the HD-FEC threshold. Whereas by using our proposed MFS scheme, it can attain the BER of 4.4×10^{-4}. For OOK modulation, higher data rate can be obtained by reducing the bit period, which means the reduction of pixel number for each bit. However, it will make the system less robust against sampling deviation due to the thresholding curve-based signal decoding. While for our proposed MFS scheme, the pixel number of each bit is doubled compared to OOK scheme. Consequently, MFS scheme can achieve better BER performance than conventional OOK scheme. By using our proposed scheme. When the illuminance is as low as 400 lux, the OCC system can achieve the data rate of 8.16 Kbps with a BER below HD-FEC.

IV. Conclusion

In this paper, we have proposed and experimentally demonstrated a novel MFS scheme for the OCC system using a mobile phone camera to improve the transmission performance. Without multilevel modulation, extra bits can be carried by changing the modulation formats according to incoming bit information. Moreover, at the receiver, the modulation format identification and signal decoding can be easily performed by using our proposed multi-thresholding scheme. Experimental results demonstrate that our proposed scheme can remarkably improve the BER performance, and under the regular illuminance of 400 lux, the data rate of 8.16 Kbps can be achieved with a BER below 3.8×10^{-3} using only one LED. Therefore, it can be concluded that MFS is a promising scheme for OCC system using mobile phone camera to realize higher data rate transmission without multi-level modulation.

References

[1] D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," *Opt. Express*, vol. 23, no. 2, p. 1627, Jan. 2015.

[2] J. Shi, J. He, J. He, Z. Jiang, Y. Zhou, and Y. Xiao, "Enabling user mobility for optical camera communication using mobile phone," *Opt. Express*, vol. 26, no. 17, pp. 21762–21767, Aug. 2018.

[3] J. He *et al.*, "Efficient sampling scheme based on length estimation for optical camera communication," *IEEE Photon. Technol. Lett.*, vol. 31, no. 11, pp. 841–844, Jun. 1, 2019.

[4] J. He, Z. Jiang, J. Shi, Y. Zhou, and J. He, "A novel column matrix selection scheme for VLC system with mobile phone camera," *IEEE Photon. Technol. Lett.*, vol. 31, no. 2, pp. 149–152, Jan. 15, 2019.

[5] C.-W. Chow, C.-Y. Chen, and S.-H. Chen, "Visible light communication using mobile-phone camera with data rate higher than frame rate," *Opt. Express*, vol. 23, no. 20, pp. 26080–26085, Oct. 2015.

[6] W. Guan, Y. Wu, C. Xie, L. Fang, X. Liu, and Y. Chen, "Performance analysis and enhancement for visible light communication using CMOS sensors," *Opt. Commun.*, vol. 410, pp. 531–551, Mar. 2018.

[7] C.-W. Chow, C.-Y. Chen, and S.-H. Chen, "Enhancement of signal performance in LED visible light communications using mobile phone camera," *IEEE Photon. J.*, vol. 7, no. 5, pp. 1–7, Oct. 2015.

[8] *IEEE Standard for Local and Metropolitan Area Networks-Part 15.7: Short-Range Optical Wireless Communications*, IEEE Standard 802.15.7-2018, Apr. 2019, pp. 1–670.

[9] K. Liang, C.-W. Chow, and Y. Liu, "RGB visible light communication using mobile-phone camera and multi-input multi-output," *Opt. Express*, vol. 24, no. 9, pp. 9383–9388, May 2016.

[10] R. Deng, J. He, Y. Hong, J. Shi, and L. Chen, "2.38 Kbits/frame WDM transmission over a CVLC system with sampling reconstruction for SFO mitigation," *Opt. Express*, vol. 25, no. 24, pp. 30575–30581, Nov. 2017.

[11] K. Liang, C.-W. Chow, Y. Liu, and C.-H. Yeh, "Thresholding schemes for visible light communications with CMOS camera using entropy-based algorithms," *Opt. Express*, vol. 24, no. 22, pp. 25641–25646, Oct. 2016.

[12] J. Shi *et al.*, "Multilevel modulation scheme using the overlapping of two light sources for visible light communication with mobile phone camera," *Opt. Express*, vol. 25, no. 14, pp. 15905–15912, Jul. 2017.

[13] V. P. Rachim and W.-Y. Chung, "Multilevel intensity-modulation for rolling shutter-based optical camera communication," *IEEE Photon. Technol. Lett.*, vol. 30, no. 10, pp. 903–906, May 15, 2018.