Investigation of 4-ASK modulation with digital filtering to increase 20 times of direct modulation speed of white-light LED visible light communication system

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Abstract: In this demonstration, we propose and experimentally investigate the quaternary-amplitude-shift-keying (4-ASK) modulation with digital filtering to enhance the direct modulation speed of white-light light-emitting-diode (LED) in visible light communication (VLC) system. Here, an ordinary LED commercially available for lighting application with a direct modulation speed of 1 MHz is used. Data rate of 20 Mbit/s can be achieved in a 1 m free space transmission without using optical blue filter. In the previous studies, the transmission rate of LED VLC could only be increased by 2 to 10 times of the direct modulation speed of the white-light LED if using electrical equalization only. Moreover, the adaptive-controlled FIR filter makes the system closer to the matched filtering condition for reducing the inter-symbol-interference (ISI) for the LED VLC. A recorded 20 times enhancement of the direct modulation speed of white-light LED VLC system is demonstrated by using digital filter only and without using optical blue filter.

OCIS codes: (230.3670) Light-emitting diodes; (060.4510) Optical communications; (060.4080) Modulation.

References and links

1. J. J. D. McKendry, R. P. Green, A. E. Kelly, Z. Gong, B. Guilhabert, D. Massoubre, E. Gu, and M. D. Dawson, "High-speed visible light communications using individual pixels in a micro light-emitting diode array," IEEE Photon. Technol. Lett. **22**(18), 1346–1348 (2010).
2. Z. Wang, C. Yu, W.-D. Zhong, and J. Chen, "Performance improvement by tilting receiver plane in M-QAM OFDM visible light communications," Opt. Express **19**(14), 13418–13427 (2011).
3. W.-Y. Lin, C.-Y. Chen, H. H. Lu, C.-H. Chang, Y.-P. Lin, H.-C. Lin, and H.-W. Wu, "10m/500Mbps WDM visible light communication systems," Opt. Express **20**(9), 9919–9924 (2012).
4. Z. Wang, C. Yu, W.-D. Zhong, J. Chen, and W. Chen, "Performance of a novel LED lamp arrangement to reduce SNR fluctuation for multi-user visible light communication systems," Opt. Express **20**(4), 4564–4573 (2012).
5. K.-D. Langer, J. Vucic, C. Kottke, L. Fernández, K. Habel, A. Paraskevopoulos, M. Wendl, and V. Markov, "Exploring the potentials of optical-wireless communication using white LEDs," *Proc. ICTON*, (2011), paper Tu.D5.2.
6. H. L. Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "High-speed visible light communications using multiple-resonant equalization," IEEE Photon. Technol. Lett. **20**(14), 1243–1245 (2008).
7. Y. F. Liu, Y. C. Chang, C. W. Chow, and C. H. Yeh, "Equalization and pre-distorted schemes for increasing data rate in in-door visible light communication system," *Proc. of OFC* (2011), paper JWA083.
8. C. W. Chow, C. H. Yeh, Y. F. Liu, and Y. Liu, "Improved modulation speed of LED visible light communication system integrated to main electricity network," Electron. Lett. **47**(15), 867–868 (2011).
9. T. Komiyama, K. Kobayashi, K. Watanabe, T. Ohkubo, and Y. Kurihara, "Study of visible light communication system using RGB LED lights," *Proc. of SICE* (2011), pp. 1926–1928.

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10. H. L. Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, Y. Oh, and E. T. Wo, "100-Mb/s NRZ visible light communications using a postequalized white LED," IEEE Photon. Technol. Lett. **21**(15), 1063–1065 (2009).
11. J. Vucic, C. Kottke, S. Nerreter, A. Büttner, K.-D. Langer, and J. W. Walewski, "White light wireless transmission at 200+ Mbit/s net data rate by use of discrete-multitone modulation," IEEE Photon. Technol. Lett. **21**(20), 1511–1513 (2009).
12. T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Trans. Consum. Electron. **50**(1), 100–107 (2004).
13. J. G. Proakis and M. Salehi, *Digital Communications* (McGraw-Hill, 2007), Chap. 9.

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1. Introduction

Recently, using high brightness light emitting diode (LED) for the lighting and visible light communication (VLC) simultaneously has attracted much attenuation, since this is cost-effective, and can provide electromagnetic-interference (EMI) free, license-free and high signal-to-noise ratio (SNR) link with high security [1–9]. Using separated red, green, blue (RGB) LEDs [9] and using blue LED with phosphor [10, 11] are the two main methods to implement the white-light LED. Using the blue LED with phosphor is attractive because it does not require three separate LEDs. Hence it is simple and low cost. However, when this type of LED is used in the VLC system, the direct modulation speed would be limited to about 1 MHz by the relaxation time of the phosphor. This means that by using on-off keying (OOK) direct modulation, the maximum achievable transmission data rate is only up to 1 Mbit/s. And this transmission data rate is not enough for the future in-door communication. To enhance the direct modulation speed of the white-light LED, several methods have been proposed and investigated, such as using a blue filter at the receiver (Rx) to remove the slow response from yellow light [10, 11], employing multiple-resonant and post-equalizations [6, 10], or using spectral efficient advanced modulation formats (like the discrete multi-tone) [11]. According to the previous studies, the transmission data rate of LED VLC could only be increased by 2 to 10 times [6–8] of the direct modulation speed of the white-light LED if using electrical equalization only. An important modeling of VLC channel was also done in [12].

In this investigation, we propose and experimentally demonstrate for the first time using quaternary-amplitude-shift-keying (4-ASK) modulation and digital filtering to enhance the transmission rate of white-light LED VLC system. Here, an ordinary LED commercially available for lighting application with a direct modulation speed of 1 MHz is used in the demonstration. A recorded 20 times enhancement of the direct modulation speed of white-light LED VLC system is demonstrated by using digital filter only and without using optical blue filter. A digital filter and square root raised cosine (SRRC) filter are used for signal equalization. The bit-error-rate (BER) of $< 10^{-10}$ is measured in a free space transmission length of > 1 m.

2. Experimental setup

Figure 1 shows the experimental setup of LED communication. Here, a single white-light LED (Cree, XLamp XR-E LED), was used in the VLC system acting as the signal transmitter

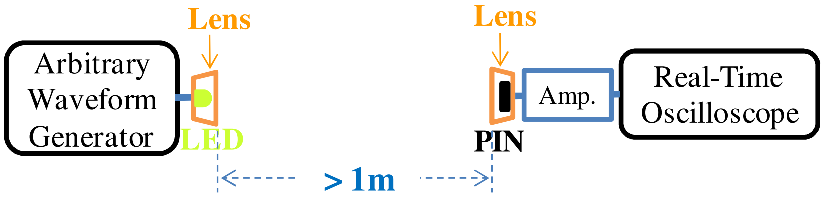

Fig. 1. Experiment setup of the proposed LED communication.

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(Tx). And the LED was driven at 350 mA with nearly 100 lm output. The LED was modulated by an arbitrary waveform generator (AWG, Agilent 33220A) to generate 4-ASK modulation optical signal.

The AWG with the maximum operation bandwidth of 20 MHz was connected the LED. The AWG provided DC bias as well as 4-ASK modulation signal to the LED. In Fig. 1, the white-light emitted from the LED was received by a silicon-based PIN Rx. The Rx had the detection wavelength range of 350–1100 nm with responsivity of 0.65 A/W and active area of 13 mm^2. It had a bandwidth of 17 MHz and the root mean square (rms) noise of 530 µV. Besides, in this experiment, a pair of lens at the Tx and Rx were used for focusing. Finally, the received signal was then amplified by a wideband coaxial amplifier, and connected by a real-time oscilloscope (*Tektronix*, TDS2022B).

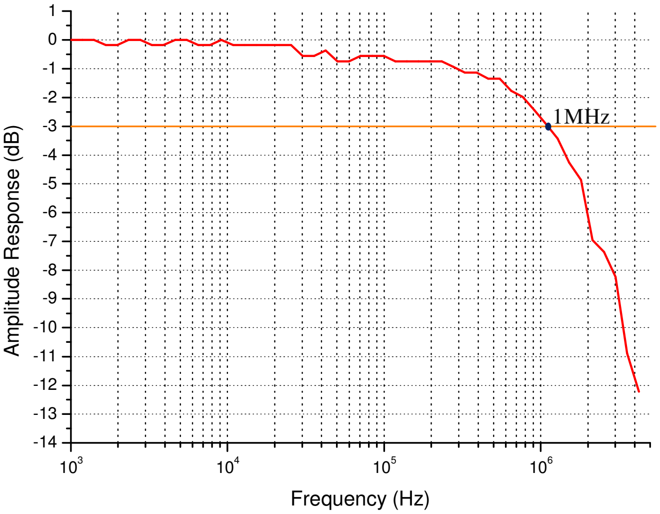

Fig. 2. Measured normalized frequency response spectrum of the white phosphor-based LED used in the experiment.

We first estimated the direct modulation speed of the white-light LED by using a similar experimental setup in Fig. 1 with back-to-back transmission distance. A sweep driving frequency from 1 kHz to 10 MHz was employed to the LED, and the frequency response spectrum of the LED was measured. Figure 2 shows the measured normalized frequency response of the white-light phosphor-based LED used in this experiment. As shown in Fig. 2, the measured 3 dB bandwidth of the LED is about 1 MHz. The limited bandwidth would result in a lower transmission data rate in VLC.

Figure 3 shows the signal flow of 4-ASK modulation generation using digital filtering. The binary sequence is first mapped to 4-ASK symbol which contains 4 different amplitude levels to represent 2 bit/symbol. The up-sampling increases the sampling rate by inserting zeros between the original sample points; for example, up-sampling by a factor 2 is to insert a zero between the adjacent samples (shown in Fig. 3). The digital finite impulse response (FIR) filter is a filter in time domain (time domain convolution), which equivalently creates a frequency domain compensation for the system channel response. A square-root raised cosine (SRRC) filter (roll of factor 0.25) is used after Rx. The adaptation process of adaptively-controlled FIR filter is to transmit a known series of training symbols, and the received pattern is analyzed (“Error Analysis” block in Fig. 3) and then the result is used for adjusting the FIR coefficients in the next transmission using post-processing. The estimation is based on FFT (Fast Fourier transform) to estimate the zero forcing equalizer (ZFE) which is the updated FIR coefficients to invert the channel response. The FIR filter has 13-taps denoted as h[t], with the initial setting of h[0] = 3.5, h [1] = 3.5, h [2] = –2.5, h [3] = –2.5, and otherwise

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h is zero. After 10 iterations, the filter coefficients converged to fixed numbers and the system is stabilized.

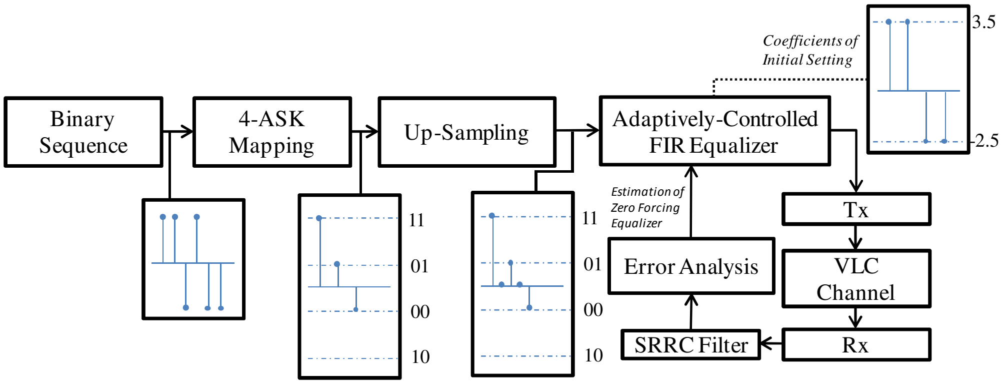

Fig. 3. The digital filtering scheme for 4-level ASK modulation.

After the system is stabilized, the FIR filter at Tx and the SRRC filter at Rx reach the condition of matched filtering. Each of the transmitted optical 4-ASK symbol is shaped with the filter response of FIR filter and the transfer function of the physical electrical-optical-electrical (E-O-E) channel. The importance of matched filtering is that if the resultant optical signal is matched with the response of the SRRC filter at the Rx, the SNR of the received signal is enhanced and the transmitted signal has a spectral profile between rectangular function (time-limited) and Sinc function (band-limited). The mathematical expression for SRRC filters are described in [13]. The FIR filter plays a role for balancing SNR in different frequency range and for matching the filter at the Rx.

In order to simplify the explanation, we use a short symbol pattern of 110100 (also shown in Fig. 3) to illustrate the working process of the adaptive FIR filter. The stem plot of applied electrical signal without any FIR filtering is shown in Fig. 4(a). With the initial FIR setting, the output of the filter is shown in Fig. 4(b). After the adaptation of FIR coefficients, the output is shown in Fig. 4(c). Throughout the adaptation process, the waveform gradually changes to the suitable form that is matched with the channel, hence the SNR is increased.

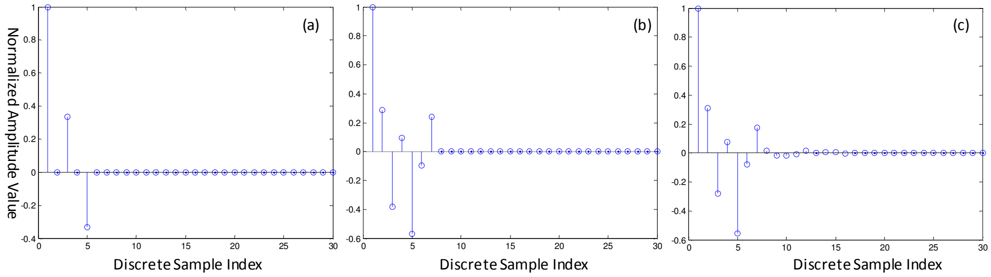

Fig. 4. The stem plot of electrical waveform at Tx (a) Without FIR filter (b) With initial setting of FIR filter (c) With the converged setting of FIR filter.

In this experiment, the proposed scheme with initial pre-distorted setting of 4-ASK format, adaptively-controlled filter and SRRC filter were verified simultaneously. Here, the SRRC filter had a spectral efficiency of about 2 bit/Hz, and 4-ASK format had a spectral efficiency of 2 bit/Hz. Thus, the total spectral efficiency is about 4. As a result, the 20 Mbit/s signal can be transmitted with most of the power located within 5 MHz bandwidth. As shown in Fig. 5, the width of received signal spectrum with matched filtering varies with the changes of roll-off factors β. For a system with 1/T symbol rate, the spectral width ranges from 1/T to 1/2T as the roll-off factors changes from 1 to 0, and the corresponding spectral efficiency changes from 1 to 2. That is to say, the matched filtering using SRRC filters can ideally reduce width of the signal spectrum while maintaining zero ISI [13].

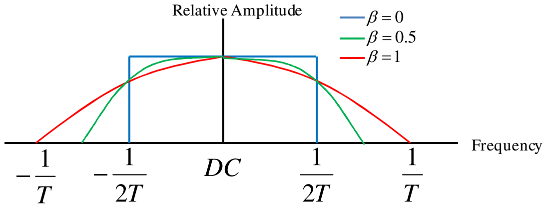

Fig. 5. The spectral efficiency of matched filtering with different roll-off factors β.

3. Experimental results

First of all, a control experimental without using the proposed scheme was performed. When the 4-ASK modulation format with 20 Mbit/s traffic rate was applied to the 1 MHz white-light LED, the measured eye-diagram is completely closed, as illustrated in Fig. 6(a). Since the data rate of the applied signal is much beyond the direct modulation bandwidth of the white-light phosphor-based LED. Without using the proposed scheme, the bit error rate (BER) cannot be measured, and the eye-diagram is completely closed. A clear and wide open 4-ASK eye diagram can be obtained by using the proposed scheme, as shown in Fig. 6(b), when total transmission data rate of 20 Mbit/s. Furthermore, Fig. 7(a) shows the measured BER performance of the proposed LED communication at different electrical data peak-to-peak driving voltages under 1 m free space transmission. And BER of $< 10^{-10}$ can be achieved.

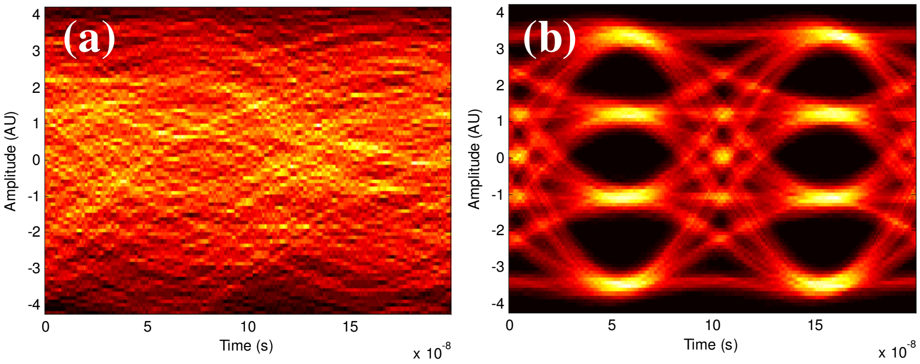

Fig. 6. Measured eye-diagrams of (a) without and (b) with the proposed scheme at 1 m transmission distance.

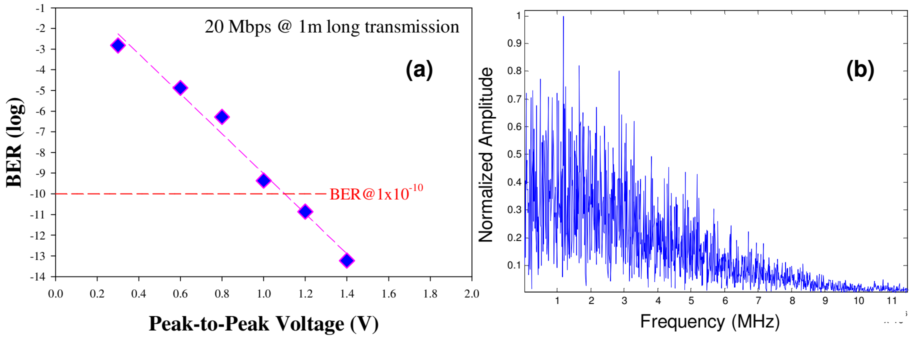

Fig. 7. (a) BER performance versus the different peak-to-peak driving voltages under 1 m free space transmission. (b) Absolute value of FFT of 10000 points from the processed waveform.

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Furthermore, Fig. 7(b) presents the absolute value of fast Fourier transform (FFT) of 10000 points from the processed waveform (containing 500 symbols, oversampling at a rate of 200MSample/s). We can observe that the signal energy is distributed from DC to 10 MHz range. Here, the SRRC filter was used to reduce the signal power from 5 MHz to 10 MHz without inter-symbol-interference (ISI) effect, and the FIR filter compensated the severe high frequency attenuation to make the 20 Mbit/s transmission possible.

4. Conclusion

The VLC system using white-light LED can provide the benefits of license-free, EMI-free, and secure wireless communication channel with low extra cost. Therefore, the in-building LED can provide not only the function of lighting but also communications. To obtain the higher transmission data rate of white LED communication within a limited direct modulation speed of the white-light LED would be an important research issue.

In this work, we proposed and experimentally demonstrated the 4-ASK modulation with FIR digital filtering to enhance the direct modulation speed of white-light LED VLC system. Here, an ordinary LED commercially available for lighting application with a direct modulation speed of 1 MHz is used. And data rate of 20 Mbit/s (BER < 10^{-10}) was achieved in a 1 m free space transmission without using optical blue filter. A recorded 20 times enhancement of the direct modulation speed of white-light LED VLC system was demonstrated by using digital filter only and without using optical blue filter. We believe that the same technique can also be applied to the VLC system when optical blue filter is used. Thus, we expected a data rate of 200Mb/s can be achieved due to the fact that optical blue filter can enhance the bandwidth of the system by about 10 times [6, 10].

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