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Simple digital FIR equalizer design for improving the phosphor LED modulation bandwidth in visible light communication

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Abstract We propose and demonstrate a simple digital post-equalization technique to improve the bandwidth-limitation of light-emitting-diode (LED) visible-light-communication (VLC) channel. The design of finite-impulse-response equalizer according to the channel response is presented to improve the bandwidth limitation of LED VLC channel. Here, no optical blue filter is used. The simulation and experimental results show ∼10 times enhancement of the direct modulation speed of white-light LED VLC system. When compares with the previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor, the proposed scheme shows an improvement in signal quality and transmission distance, and a 10 Mbit/s error-free free-space transmission over 1 m can be achieved under the bit error rate of $< 10^{-9}$.

Keywords Visible light communication (VLC) · FIR filter · Access network · LED

1 Introduction

Recently, light emitting diode (LED) lighting is gradually replacing the traditional incandescent or fluorescent lighting since LED is more power-efficient and becoming more

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cost-effective. The LED lighting system can be integrated with the communication system to provide optical wireless visible light communication (VLC) link with little extra cost. This optical wireless communication system is license-free and electromagnetic interference (EMI) free, and thus it is more advantageous than radio frequency (RF) communication. Directivity of the visible light beam can also provide secure communication link (Lin et al. 2012; Wang et al. 2012; Liu et al. 2011; Minh et al. 2008, 2009).

White-light VLC lighting system using blue LED with phosphors is cost-effective when compared with the red-green-blue (RGB) white-light LED; however the slow response of the phosphor limits the available channel bandwidth (Yang et al. 2011; Shrestha et al. 2010). According to previous studies, the phosphor-based white-light LED VLC system only had a 3-dB bandwidth of about 1 MHz (Liu et al. 2011; Minh et al. 2009); hence the transmission data rate was limited to about 1 Mbit/s without inter-symbol interference and the transmission distance was limited to 10 cm (Liu et al. 2011) if signal pre-distortion or post-equalization was not used.

In this paper, we propose and demonstrate using a simple digital post-equalization finite impulse response (FIR) equalizer to improve the bandwidth limitation of LED VLC channel. No optical blue filter is used. The simulation and experimental results show ∼10 times enhancement of the direct modulation speed of white-light LED VLC system. When compared with the previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor (Liu et al. 2011), the proposed scheme shows an improvement in signal quality and transmission distance, and a 10 Mbit/s error-free free-space transmission over 1 m is achieved under the bit error rate (BER) of $< 10^{-9}$.

2 Simulation

In this demonstration, we first simulate using the simple FIR equalizer to correct the VLC channel effect and to improve the bandwidth limitation of the LED VLC system. The electrical-to-optical-to-electrical (E-O-E) channel of the VLC system can be modelled as a first-order RC low-pass circuit as shown in Fig. 1a. The corresponding impulse response (time domain) of an analogue low-pass RC system can be written as

$$H_1(t) = \exp\left(-\frac{t}{RC}\right) \tag{1}$$

Then the equalizer (modelled as a first-order high-pass circuit) can be used to correct and equalize the channel response as shown in Fig. 1b (Minh et al. 2009, 2008). The transfer function of this equalizer can be written as follow (H is in bold to represent the frequency domain):

$$\mathbf{H}_2(\omega) = \frac{R_2}{\frac{R_1}{j\omega CR_1} + R_2} \tag{2}$$

Equation (1) was used to model the E-O-E channel of the LED VLC system, where 1/RC was set to 1.28 MHz, which was the measured 3 dB bandwidth of the system. Equation (2) was used to model the equalizer, and the filter parameters were obtained as described in Liu et al. (2011). The sampling rate in our simulation was $F_s = 100$ MHz. Equation (2) was sampled in frequency domain with 128 points with each step size of "$F_s/128$" from DC to both positive and negative "$F_s/2$". The simulations were performed using MATLAB program.

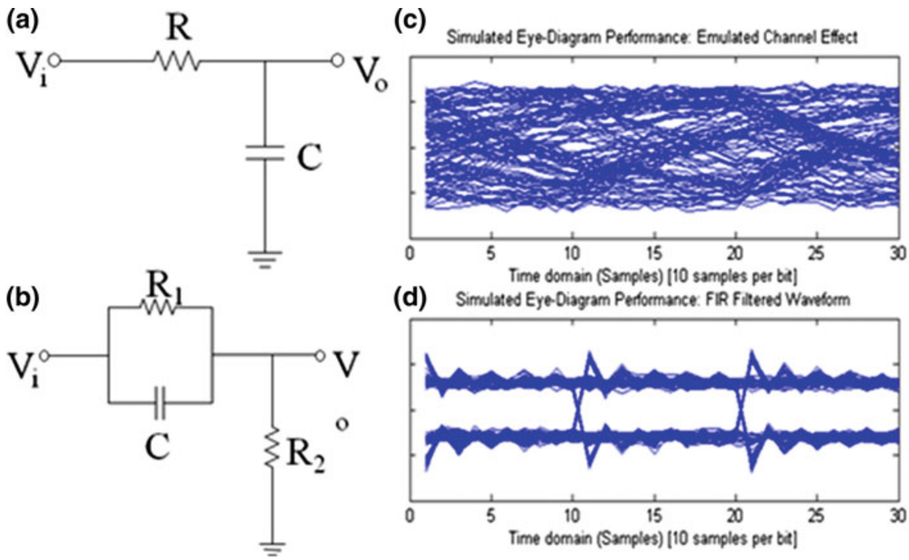

Fig. 1 Circuit models and the simulation results. **a** VLC channel modelled as a low-pass circuit. **b** proposed equalizer modeled as a first-order high-pass circuit. **c** simulated eye-diagram without using the FIR equalizer. **d** simulated eye-diagram using the FIR equalizer

The finite impulse response of the FIR filter can be designed to achieve the equalization in frequency domain, so that it can eliminate inter-symbol interference. The tap-number and the estimation algorithm for the coefficients affect the performance of the filter. The following simulation was used to verify the filter design. The FIR filter has several taps to cancel the impulse response. The increasing number of taps may increase the performance but it is also limited by the resources available for FIR filter in the transceiver. Besides, the noise in the analogue channel could also limit the system performance. Moreover, the improvement may be the use of advanced algorithm to implement the filter, or to use more computational-complex formats such as OFDM to equalize the signal. In addition, the coding techniques may be implemented as well.

Pseudorandom binary sequence (PRBS) $2^{10} - 1$, 10 Mbit/s NRZ data was used in the simulation. Since the $F_s = 100$ MHz, each bit contained 10 digital samples. Figure 1c, d show the simulated eye-diagrams of a 10 Mbit/s non-return-to-zero (NRZ) signals without and with the FIR equalizer respectively. We can clearly observe that by using the simple FIR post-equalizer, the inter-symbol interference (ISI) due to the limited modulation bandwidth (1.28 MHz) can be significantly eliminated and a clear widely opened 10 Mbit/s NRZ eye-diagram can be obtained (Fig. 1d).

3 Experiment

Then, a LED VLC experiment was performed. The experimental setup is shown in Fig. 2a. MATLAB generated 10 Mb/s, PRBS $2^{10} - 1$ signal was sent to an arbitrary waveform generator (AWG, Agilent 33220A), which was used to drive a single phosphor-based LED. The LED was from Cree (XLamp XR-E LED). LED was DC-biased at 2V with peak-to-peak signal modulation voltage from 100 to 500 mV. A lens was used to enhance directivity

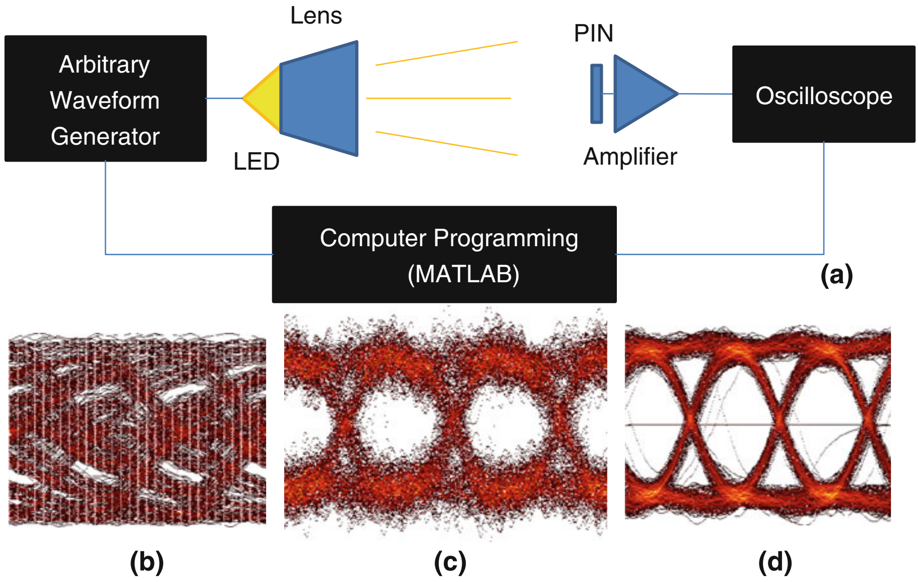

Fig. 2 Experimental setup and experimental results. **a** LED VLC experimental setup. **b** experimental eye-diagram without using the FIR equalizer. **c** experimental eye-diagram using the FIR equalizer. **d** experimental eye-diagram with further high frequency noise removal

at transmitter side. The optical signal transmitted 1 m distance in free space and received by a silicon-based PIN receiver (Rx) (Thorlabs PDA36A). The received signal was further amplified using a wideband coaxial amplifier (Mini-Circuit ZHL-6A), and finally captured by using a real-time oscilloscope (Tektronix TDS3014C). The operation of the equalization process requires a short delay for initialization. The data was analyzed using 1700 bits.

Figure 2b shows the measured eye-diagram without using the proposed FIR equalizer. The eye is completely closed as agreed with our simulation results as shown in Fig. 1c due to the ISI generated by the limited modulation bandwidth of the LED. The FIR equalized eye-diagram, shown in Fig. 2c, has a significantly improved eye opening. However, high frequency noise can be observed, and this noise may come from non-ideal truncation in Eq. (2). Therefore, a low-pass filter in the form of Eq. (1) with $1/RC = 10\,\text{MHz}$ was used after the FIR equalizer for high frequency noise removal. The eye-diagram after the high frequency noise removal is shown in Fig. 2d, a clearer and sharper eye can be observed.

Bit error rate (BER) analysis were performed by using the measured Q factors of the eye-diagrams against different AC peak-to-peak signal voltage. The result was presented in Fig. 3. When the peak-to-peak driving voltage is $\geqq 500\,\text{mV}$, error-free BER $< 10^{-9}$ was achieved. When compared with our previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor (Liu et al. 2011), the proposed scheme shows an improvement in better BER performance with the same peak-to-peak driving voltage (at BER of 10^{-9}, peak-to-peak driving voltage is reduced from 1 V to 500 mV), since the digital FIR equalizer allows a more precise and flexible control of the equalizer parameters.

We believe that at higher computational complexity, the FIR equalizer could be more flexible and effective than the analogue equalizer. Since the quality of LEDs may differ from one to another, the 3 dB modulation bandwidth in Eq. (1) is not fixed; hence the design parameters in Eq. (2) can be used to adaptively enhance the channel response.

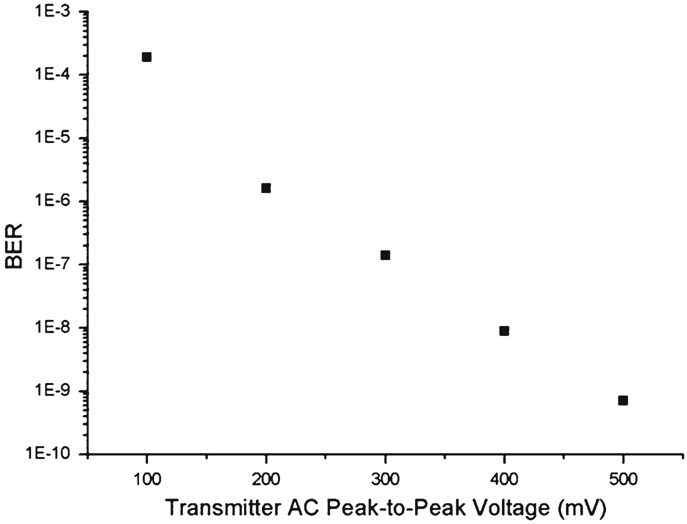

Fig. 3 BER measurement result

4 Conclusion

We proposed and demonstrated using a simple digital post-equalization FIR equalizer to improve the bandwidth limitation of LED VLC channel. No optical blue filter was used. The simulation and experimental results showed ~10 times enhancement of the direct modulation speed of white-light LED VLC system. When compared with the previous demonstration using high-pass equalization circuit constructed by lumped capacitor and resistor, the proposed scheme showed an improvement in signal quality and transmission distance, and a 10 Mb/s error-free (BER $< 10^{-9}$) free-space transmission over 1 m was achieved. The use of focusing lens on the receiver end could further be used to enhance the transmission distance.

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