

Real-time white-light phosphor-LED visible light communication (VLC) with compact size

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Abstract: In this demonstration, we first demonstrate a real-time phosphor-LED visible light communication (VLC) system with 37 Mbit/s total throughput under a 1.5 m free space transmission length. The transmitter and receiver modules are compact size. Utilizing our proposed pre-equalization technology, the ~1 MHz bandwidth of phosphor LED could be extended to ~12 MHz without using blue filter. Thus, the increase in bandwidth would enhance the traffic data rate for VLC transmission. The maximum bit-rate achieved by the VLC system is 37 Mbit/s, and a video transmission at 28.419 Mbit/s is demonstrated using the proposed VLC system. In addition, the relationships of received power and signal performance are discussed and analyzed.

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1. Introduction

Recently, the low energy consumption, long lifetime and lower price per unit brightness enable light emitting diode (LED) to replace the conventional lighting for both in-door and out-door [1, 2]. Furthermore, the relatively high modulation speed of the LED permits a short-range communication employing visible light. Therefore, the visible light communication (VLC) can be distinguished from the radio-frequency (RF) communication to provide electromagnetic interference (EMI) free and license-free communications [3–7]. Thus, using LED lighting system for VLC has attracted more and more attentions [8]. However, the phosphor-based white-light LED has a limited modulation bandwidth of about 1 MHz. It would restrict the directly modulation rate of the VLC systems [7, 9]. In order to increase the data rate of phosphor LED, several technologies have been proposed [6, 8–11], such as using digital equalization method, utilizing high spectral-efficiency modulation, employing optical blue filtering, and using optical multi-input multi-output (MIMO).

LED VLC system is highly directional, and the received optical power is highly dependent on the "line-of-sight" (LOS) path. Hence, the distance and the offset between the LED light source and the receiver (Rx) could highly affect the received signal quality. For instance, to compensate the power drop in fiber communications, we could increase the launching optical power [12]. However, this is not beneficial for LED VLC system, since it will also influence the in-home luminance.

In this work, we propose and demonstrate a 37 Mbit/s real-time phosphor-based LED VLC system using our developed compact size LED lighting side and client side modules. Digital pre-equalization design is employed at the LED lighting module. At the client side, optical blue filter is not required to increase the effective bandwidth of phosphor LED. The measurement results show that the ~1 MHz bandwidth phosphor LED could be increased to nearly 12 MHz by our proposed technique (discussed in next section). Here, we integrate an orthogonal frequency division multiplexing (OFDM)-based digital signal processing (DSP) chip and analog front end (AFE) for real-time VLC transmission. There are several studies of real-time LED VLC systems [13–15]. In ref [13], they demonstrated a real-time discrete multitone (DMT)-based 100 Mbit/s VLC system, and used the Tx- and Rx-field-programmable gate array (FPGA) for the digital signal processing (DSP) processing in one direction traffic through a 1.4 m transmission length. Due the use of FPAG and blue filter in the VLC system, the cost and size would be expensive and large, while the proposed system here could be compact in size and low cost. Besides, in ref [14] and ref [15], they only employed the analog-front-end (AFE) transceiver (TRx) for real-time VLC demonstrations. We utilize a network analyzer to measure the throughput of real traffic data in the proposed LED VLC system under different received luminance. In addition, a 720p MPEG-2 video signal with a maximum peak rate of 28.419 Mbit/s is also used in the proposed VLC for broadcasting to end-user under a 1.5 m free space transmission length.

2. Experiment and results

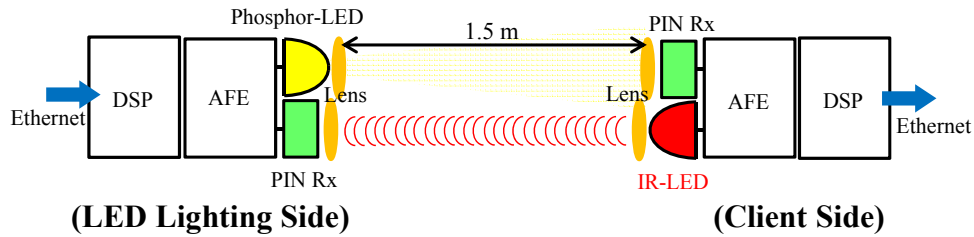


Fig. 1. Proposed bidirectional phosphor-LED-based VLC system and the design of the LED lighting and client side modules.

Figure 1 shows our proposed bidirectional phosphor-LED-based VLC system and the design of the LED lighting and client side modules. In the LED lighting side, we use five commercial available phosphor white-light LEDs (fabricated by *Edison*, Taiwan) serving as illumination and VLC. And an Infra-red (IR) PIN Rx is also located at the center of the module to receive the upstream signal sent from the client. In the client side, we utilize a single 850 nm IR-LED to act as the transmitter (Tx) for upstream signal. A PIN Rx with 50 MHz bandwidth in the client side is used to receive the downstream VLC signal. Besides, we also add lenses in front of each Tx and Rx for better light focusing, as seen in Fig. 1. The diameters of lens are 2.0 and 3.2 cm in the LED lighting and client sides, respectively. In the proposed VLC, a free space transmission length of 1.5 m is performed for downstream and upstream signal traffics. The LEDs in the Tx carry the same information. According to the VLC channel analysis reported in ref [16], as the data rate of this demonstration is low, the crosstalk is negligible. In the LED Tx module, if some LEDs are operated in DC mode or in AC mode (60 Hz from the mains), they could be the background noises affecting the performance of the VLC system as discussed in ref [17]. Advanced modulation formats [17, 18] could be used to reduce the spectral overlap of the VLC signal and these background noises to restore the VLC performance.

There are two major designs of the LED lighting side and client side. One is the analog front end (AFE), and the other is digital signal processing (DSP), as also illustrated in Fig. 1. In AFE part, it can combine the DC power and modulation data and receive optical signal in Tx and Rx for VLC links, respectively. Furthermore, to increase the ~ 1 MHz bandwidth of phosphor LED to >11 MHz, an optimal pre-equalization technology is also designed and performed in the AFE part. Besides, we do not employ the blue filter to enhance the modulation bandwidth in the client side.

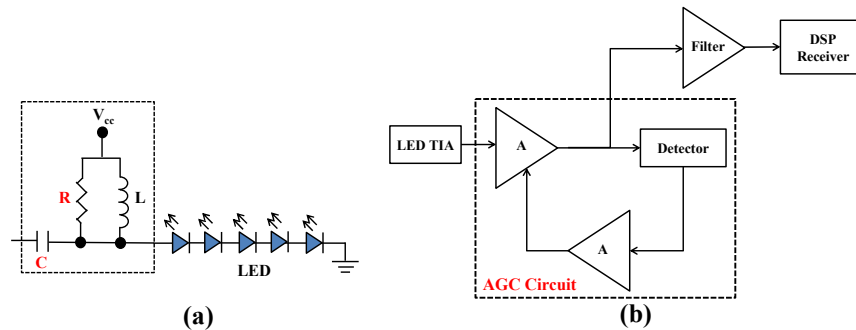


Fig. 2. (a) RLC circuit design for pre-equalization in lighting side. (b) The AGC design in Rx side for enhancing signal sensitivity. R: resistance; C: capacitance; L: inductance; A: amplifier; TIA: trans-impedance amplifier.

In the DSP system, we integrate a commercial OFDM-based DSP chip and Ethernet port for data signal processing and connecting, respectively. Furthermore, the modulation bandwidth of DSP chip is between 2 and 30 MHz also with the adaptive OFDM modulation formats from QPSK to 16-QAM.

In the lighting side, we design the RLC circuit, as shown in Fig. 2(a), for the analog pre-equalization to compensate the impedance matching of LED. The pre-equalization technique could enhance the modulation bandwidth and reduce the distortion. According to the different impedances of types of LEDs, we need to adjust the resistance (R) and capacitance (C) to achieve the optimal pre-equalization characteristic. Besides, to achieve the proposed real-time VLC system, the LED lighting and client sides must having the good digital modulation/demodulation function and sufficient modulation bandwidth. Hence we also need to improve the interference noise of power supply to avoid the signal distortion. In the Rx side, we also utilize the automatic gain control (AGC) circuit, as illustrated in Fig. 2(b), to increase the signal sensitivity to maintain and enhance the linearity of OFDM signal.

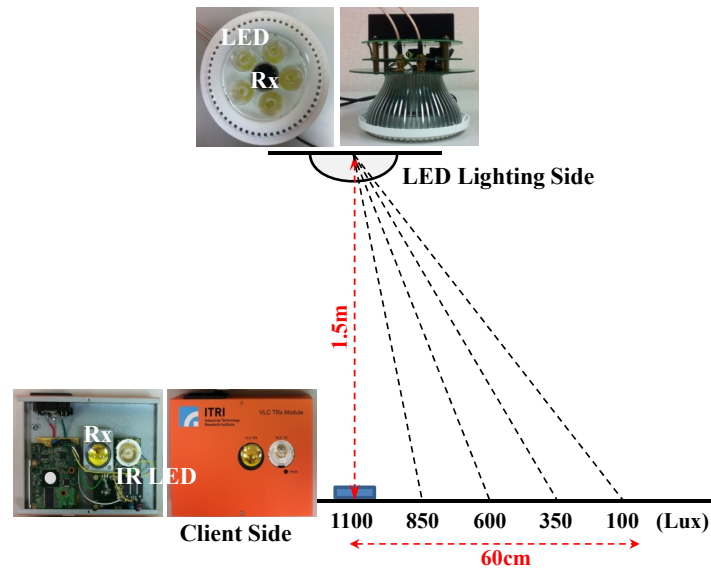


Fig. 3. The VLC vertical transmission length is setup at 1.5 m long in central point, and the client side can move outward from the central point under the horizontal positions.

To realize the relationship of received power and horizontal position in the client side, the VLC vertical transmission length is setup at 1.5 m long in central point, as shown in Fig. 3. And the client side can move outward from the central point under the horizontal positions. Here, the maximum and minimum optical powers of 1100 and 100 Lux are measured under the horizontal position of 0 and 60 cm in the client side, respectively. Besides, the photographs of LED lighting side and client side modules are also illustrated in Fig. 3. Here, the developed client side module has a compact size of $17 \times 13 \times 3 \text{ cm}^3$.

First we measure the 3 dB bandwidth of phosphor-LED under different optical illuminances. Here, if the LED lighting side is without using the proposed pre-equalization, its 3 dB bandwidth of $\sim 1.2 \text{ MHz}$ can be measured, as seen in Fig. 4(a). When the client side gradually moves outward from central point (as seen in Fig. 3), the different optical illuminances could be also measured from 1100 to 100 Lux. Hence, we can obtain the effective modulation bandwidth (after using the analog pre-equalization) of the phosphor LED are nearly 11.6 to 12.8 MHz, under different observed horizontal positions. However, when the received optical power is decreasing gradually, the maximum RF power would also be decreasing, as shown in Figs. 4(b)-4(f) respectively. And the corresponding received optical

powers are obtained at 1100, 900, 700, 500, and 300 Lux, respectively. The power difference of 15.4 dB is also produced in the Rx range of different illuminances (1100 to 300 Lux).

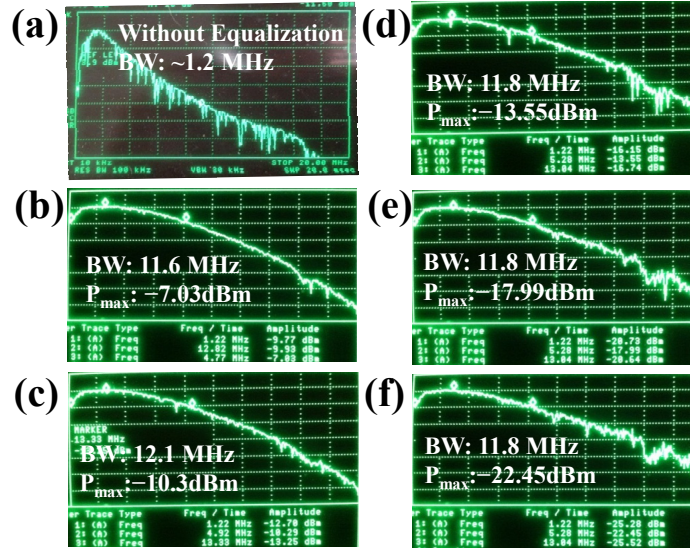


Fig. 4. (a) Effective bandwidth of phosphor-LED is without pre-equalization. The 3 dB bandwidth of phosphor-LED is with pre-equalization under the received power of (b) 1100, (c) 900, (d) 700, (e) 500 and (f) 300 Lux, respectively.

Then, to evaluate the performance of proposed real-time LED VLC system, we utilize a network analyzer (IXIA 1600T) to test and measure the IP-based throughput for real data traffic. Thus, a 40 Mbit/s traffic rate of network analyzer is used in our proposed VLC system. Figure 5 presents the observed throughput of proposed VLC system under different illuminances from 100 to 2100 Lux after a 1.5 m free space transmission length. As shown in Fig. 5, if the illuminance is 100 Lux measuring at the client side, the obtained throughput is only 1.8 Mbit/s. It means that the received optical power is not high enough to produce the required signal to noise ratio (SNR) for supporting the high speed VLC. With the increase of illuminance gradually, the measured throughputs are 18, 26, 31, 35, 36 and 37 Mbit/s, respectively, while the corresponding illuminances are 300, 500, 700, 900, 1100, and 2000 Lux. To achieve >30 Mbit/s traffic rate in the proposed VLC system, the received illuminance must be greater than 700 Lux, as shown in Fig. 5. As a result, the maximum traffic throughput of VLC system depends on the illuminance, which affects the received SNR.

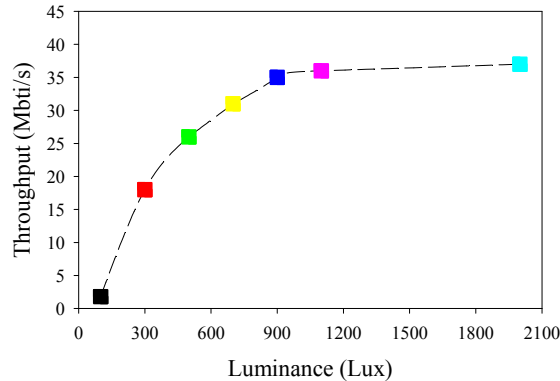


Fig. 5. Observed throughput of proposed LED VLC system under the different received illuminances from 100 to 2100 Lux.



Fig. 6. Observed throughput of proposed LED VLC system under the different received illuminances from 100 to 2100 Lux.

Next, in order to demonstrate the real-time performance of the proposed LED VLC system, a 720p MPEG-2 video is used to broadcast from the LED lighting side to the client through 1.5 m free space transmission. The video is sent from a personal computer (PC) to the LED lighting module via a typical Cat-5 Ethernet cable for real-time broadcasting. Then the video signal is received at a client, which is connected to another PC via Ethernet cable to decode and display the video by the “VLC streaming software”. Here, the IR-LED of client side is employed to return upstream signal for synchronization. The received video in client side is shown in Fig. 6. In the measurement, the maximum peak traffic of nearly 28.419 Mbit/s is measured at client side, and the average traffic of the transmitted video in LED VLC system is around 17 Mbit/s. In addition, during four hours observation, the broadcasting video is very clear and smooth.

4. Conclusion

In summary, we have proposed and demonstrated a up to 37 Mbit/s real-time phosphor-LED-based VLC system using our developed compact size LED lighting module and client module ($17 \times 13 \times 3 \text{ cm}^3$). Here, $\sim 1 \text{ MHz}$ bandwidth of phosphor-LED could be increased to $\sim 12 \text{ MHz}$ by our proposed analog pre-equalization technique without using blue filter. And, we integrate an OFDM-based DSP chip for real-time operation in VLC system. Moreover, we utilized a network analyzer to measure and test the throughput of real traffic data in the proposed LED VLC system. A 720p Mpeg-2 video signal transmission at 28.419 Mbit/s is demonstrated using the proposed VLC system under a 1.5 m free space transmission length.