Adaptive 84.44–190 Mbit/s phosphor-LED wireless communication utilizing no blue filter at practical transmission distance

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Abstract: We propose and experimentally demonstrate a white-light phosphor-LED visible light communication (VLC) system with an adaptive 84.44 to 190 Mbit/s 16 quadrature-amplitude-modulation (QAM) orthogonal-frequency-division-multiplexing (OFDM) signal utilizing bit-loading method. Here, the optimal analogy pre-equalization design is performed at LED transmitter (Tx) side and no blue filter is used at the Rx side. Hence, the ~1 MHz modulation bandwidth of phosphor-LED could be extended to 30 MHz. In addition, the measured bit error rates (BERs) of < 3.8×10^{-3} [forward error correction (FEC) threshold] at different measured data rates can be achieved at practical transmission distances of 0.75 to 2 m.

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

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1. Introduction

Nowadays, white-light phosphor light-emitting diode (LED) would be a practical component for the future solid-state lighting market [1]. Furthermore, using LED for visible light communications (VLC) provides many attractive advantages, such as no electromagnetic interference (EMI), integration with indoor lighting, network security, worldwide available and unlicensed bandwidth, and non-interference with radio bands etc. Due to the ubiquitous lighting and signaling infrastructure, LED VLC can offer an additional service at comparably low extra cost [2, 3]. In addition, an overview of the technical restrictions and challenges for VLC can be found in ref [4].

The commercially available white-light LED used for lighting is mainly based on a blue LED covered by a phosphor layer. However, the slow response of phosphorescent component would restrict the modulation bandwidth of phosphor-LED to around 1 MHz [5]. In order to resolve the limited bandwidth (1 MHz) of phosphor effect, several technologies of LED VLC system have been proposed, such as using analogy equalization at the transmitter (Tx) and receiver (Rx) sides, and utilizing a blue filter at client (user) side to increase the modulation bandwidth. In past studies, their experimental results showed the 40 Mbit/s on-off-keying (OOK) and 100 Mbit/s discrete multi-tone (DMT) phosphor-LED VLC systems [6, 7]. Furthermore the most recent demonstrations using OOK modulation employed a combination of “blue-filtering” and analogue equalization at the Rx to achieve transmission data rates of 100 Mbit/s, 125 Mbit/s and even 230 Mbit/s [8–10]. However, they could only accomplish the free space transmission length of < 0.45 m utilizing an avalanche photodiode (APD)-Rx. However, the APD-Rx in VLC system would result in expensive cost. If the traffic rate of phosphor-LED VLC is larger than 100 Mbit/s with blue filtering, the longest transmission length would drop to 10~30 cm long as the blue filter introduces high signal attenuation. Moreover, Gigabit VLC using wavelength-division-multiplexing (WDM) red-green-blue (RGB) LED has been also reported recently [11]; however, it requires RGB LED Tx and WDM Rx. The free space transmission distance is only 30 cm.

In this investigation, we first propose and demonstrate an adaptively 84.44 to 190 Mbit/s phosphor-LED VLC system under practical transmission distance. Here, we use the orthogonal-frequency-division-multiplexing quadrature-amplitude-modulation (OFDM-QAM) modulation with bit-loading algorithm in VLC system. In this experiment, the optimal analogy pre-equalization design is also performed at LED-Tx side and no blue filter is used at the Rx side for extending the modulation bandwidth from 1 MHz to 30 MHz. Moreover, the corresponding free space transmission lengths are between 0.75 and 2 m under various traffic rates of VLC system. And the measured bit error rates (BERs) of $< 3.8 \times 10^{-3}$ [forward error correction (FEC) threshold] at different transmission distances and measured data rates can be also obtained.

Furthermore, in European Union Project OMEGA, an indoor VLC link including a MAC layer protocol adapted to optical wireless communications systems was demonstrated [12]. It operated at 84 Mb/s and was successfully used to transmit three high definition video streams. Recently, HHI demonstrated few hundreds Mb/s VLC systems within a room scale [13]. We believe that our proposed scheme could be another alternative VLC implementation in practical distance, supporting > 100 Mb/s, using commercially available LED and PD (without blue filtering) and compact size.

2. Experiment and results

Figure 1(a) shows the experimental setup of proposed phosphor-LED VLC system without using blue filter at Rx side. In the experiment, a single white-light phosphor-LED (Edison, EDEW 3LS5) was used in the VLC system to act as the Tx. The LED was driven at ~310 mA (~3.3V) with nearly 168 lm output power. And the LED was modulated by an arbitrary waveform generator (AWG) to generate OFMD-QAM format for signal traffic. In Fig. 1(a), the white-light was emitted from the LED and received by a silicon-based PIN Rx (Hamamatsu, S6968). The Rx has the detection wavelength range from 350 to 1100 nm with responsivity of 0.63 A/W and active area of 150 mm^2. It has a bandwidth of 50 MHz and the root mean square (rms) noise of 530 μV. Here, a pair of lens was used in front of the Tx and Rx for focusing, respectively, as illustrated in Fig. 1. Then, the received OFDM signal was amplified by a wideband RF amplifier and detected by a real-time oscilloscope. In addition, Figs. 1(b) and 1(c) show the photos of LED-Tx and PIN-Rx modules.

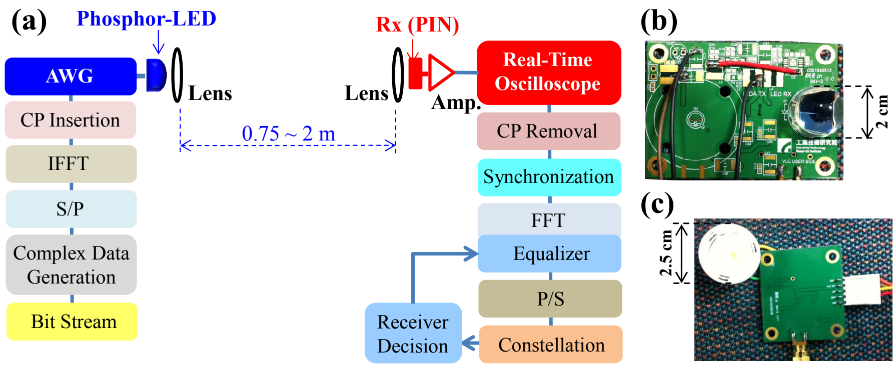

Fig. 1. (a) Experimental setup of phosphor-LED-based VLC system. (b) Designed LED-Tx module. (c) Designed PIN-Rx module.

Here, we first estimated the direct modulation speed of the phosphor-LED by using the same experimental setup in Fig. 1(a) with back-to-back (B2B) transmission distance. By sweeping the driving frequencies from 1 kHz to 10 MHz, the frequency response spectrum of the LED is measured. Hence, we obtained the 3 dB bandwidth of phosphor-LED, which was around 1 MHz, without using pre-equalization.

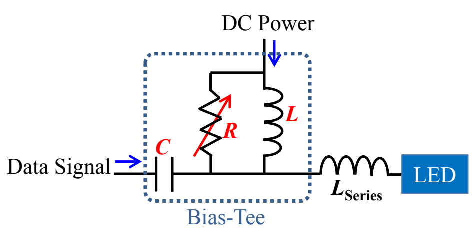

Fig. 2. Architecture of pre-equalization design in LED Tx side.

In the LED Tx side, we designed the optimal RLC circuit for the analog pre-equalization to compensate the impedance matching of phosphor-LED, as shown in Fig. 1(b). In the PIN Rx side, we also used the automatic gain control (AGC) circuit to increase the signal sensitivity to maintain and enhance the linearity of OFDM signal, as illustrated in Fig. 1(c). Here, the pre-equalization technique could enhance the modulation bandwidth and reduce the distortion. According to the different impedances of different types of LEDs, we needed to adjust the resistance (R), inductance (L), and capacitance (C) and utilized a series perking technology to accomplish the optimal pre-equalization characteristic, as illustrated in Fig. 2. Besides, the related detail specifications of pre-equalization and OFDM-QAM modulation were also analyzed and discussed in the past studies [6, 14, 15].

Then, we would measure the effective modulation bandwidth of the LED with the proposed analog pre-equalization by using different OFDM-QAM modulation signals. Here, the baseband electrical OFDM signal was generated by using Matlab® programs, and the signal processing of the OFDM Tx was constructed by serial-to-parallel conversion, QAM

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symbol encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). Then, the OFDM signal could be applied to LED for directly modulation. The visible-light wireless signal is directly detected by a PIN Rx. The received downstream OFDM signal was captured by using Matlab® programs for signal demodulation. To demodulate the vector signal, the off-line DSP program was utilized. The demodulation process included the synchronization, FFT, one-tap equalization, and QAM symbol decoding. Besides, the BER could be calculated according to the observed signal-to-noise ratio (SNR) of each OFDM subcarrier.

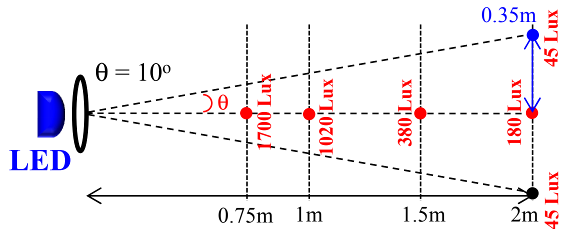

Fig. 3. Received illumination versus transmission distance in the field of view (FOV) of proposed LED VLC system.

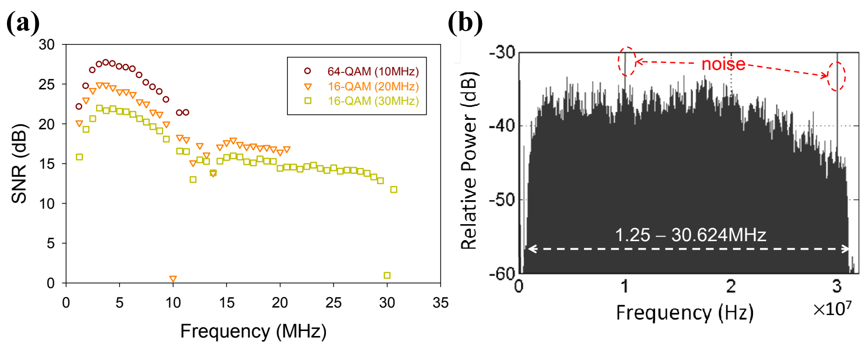

Fig. 4. (a) Using a 64-QAM and 16-QAM OFDM signals for applying on LED to test its effective bandwidth under the frequency ranges of 10, 20 and 30 MHz, respectively. (b) Electrical power spectrum of 1.25 to 30.625 MHz bandwidth at a free space transmission length of 1.5 m.

In this measurement, Fig. 3 shows the received illumination versus transmission distance in the field of view (FOV) of proposed LED VLC system. The received illuminations are 180 and 1700 Lux, respectively, when the corresponding transmission distances are 0.75 and 2 m. Here, we first utilized different OFDM-QAM signals applying on LED to test its effective bandwidth under the different modulation bandwidths in 1.5 m free space transmission length, respectively. Figure 4(a) shows the SNR of each subcarrier in the different bandwidths of 10, 20 and 30 MHz, respectively, when the 64-QAM, 16-QAM and 16-QAM OFDM signals are utilized. Here, the proposed pre-equalization circuit could extend the bandwidth from 1 MHz to 30 MHz, when the 16-QAM OFDM signal is applied on LED, as shown in Fig. 4(a). In addition, Fig. 4(b) shows the electrical power spectrum of 1.25 to 30.625 MHz bandwidth at a free space transmission length of 1.5 m. There are two peak noises observing at the frequency of 10 and 30 MHz, as shown in Fig. 4(b), due to the received noise of PIN Rx. And, the RF power would drop gradually from 20 MHz due to power fading. Hence, to avoid the two noise interferences, we could ignore these two frequencies in the OFDM demodulation.

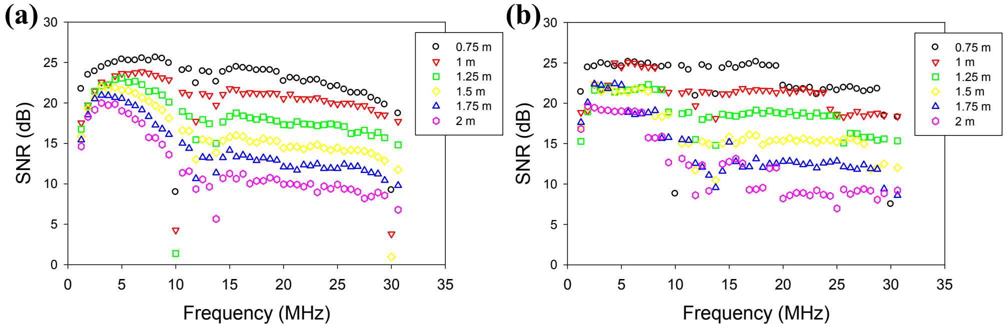

Fig. 5. Obtained SNR of each subcarrier in the bandwidth of 1.250 to 30.625 MHz when the 16-QAM OFDM modulation signal is applied on LED (a) without and (b) with bit-loading under the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively.

To realize the relationship of transmission distance and SNR, the 16-QAM OFMD signal with 48 subcarriers was employed in the proposed VLC transmission. Figure 5(a) shows the obtained SNR of each subcarrier in the bandwidth of 1.250 to 30.625 MHz when the 16-QAM OFDM modulation signal is applied on phosphor-LED under the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively. We also observed that the two SNRs at the frequencies of 10 and 30 MHz could be dropped at different transmission distances simultaneously. As seen in Fig. 5(a), with the increase of transmission distance gradually, the corresponding SNR is also drop. As seen in Fig. 5(a), while the transmission length is 1.25 m, the entire SNRs could be larger than 14.8 dB. When the transmission length was increased gradually, the corresponding measured SNR would also drop. As a result, the effectively modulation bandwidth of phosphor-LED with pre-equalization could achieve ~30 MHz under practical free space transmission length. The SNR can be maintained even if the transmission distance increases. This can be done by using optical lens to focus the light to the Rx, or increase the active area of the Rx.

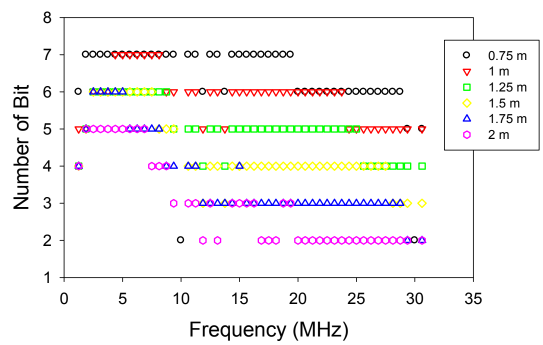

Fig. 6. The corresponding bit number of each subcarrier in the same modulation bandwidth under the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively.

In this measurement, to obtain the better SNR of each OFDM subcarrier, a bit-loading algorithm was also used in 16-QAM OFDM modulation. Hence, we employed the bit-loading OFDM modulation to obtain the optimal SNR of each subcarrier utilizing the same modulation conditions. Therefore, Fig. 5(b) presents the measured SNR of each subcarrier in the bandwidth of 1.25 to 30.625 MHz by using 16-QAM OFDM format with bit-loading algorithm at the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively. Here, the minimum SNRs of 18.4, 18.4, 15.3, 10.5, 8.6 and 8.2 dB were retrieved within the modulation bandwidth at the transmission distances of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively, when the two frequencies of 10 and 30 MHz were ignored, as also shown in Fig. 5(b).

According to the OFDM bit-loading method, we could also obtain the corresponding bit number of each subcarrier in the same modulation bandwidth at the transmission distances of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively, as shown in Fig. 6. Here, Fig. 6 shows that the measured bit numbers are between 5 and 7, 5 and 7, 4 and 6, 3 and 6, 2 and 6, and 2 and 5 at the transmission distances of 0.75, 1, 1.25, 1.5, 1.75 and 2 m, respectively, while the two frequencies of 10 and 30 MHz are ignored. Therefore, utilizing the various observed bit numbers under different transmission links, we could retrieve the optimal signal performances of proposed VLC system.

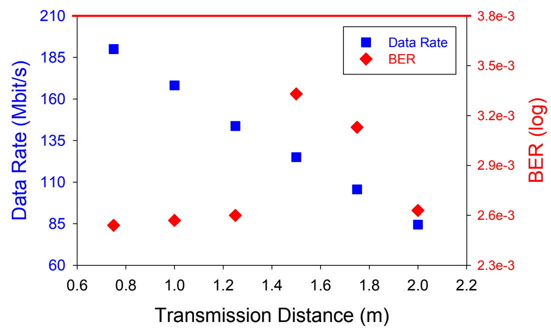

Fig. 7. Measured traffic rate and its corresponding BER of proposed phosphor-LED VLC system using 16-QAM OFDM format with bit-loading algorithm at the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75, and 2 m, respectively.

Finally, Fig. 7 shows the measured traffic rate and its corresponding BER of proposed phosphor-LED VLC system using 16-QAM OFDM format with bit-loading algorithm at the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75, and 2 m, respectively. The traffic rates were observed at 190, 168.13, 143.75, 125, 105.63, and 84.44 Mbit/s, respectively, in the different transmission distances. In addition, the corresponding BERs of 2.54×10^{-3}, 2.57×10^{-3}, 2.6×10^{-3}, 3.3×10^{-3}, 3.1×10^{-3}, 2.6×10^{-3} were also obtained, as illustrated in Fig. 5. The entire measured BER values were below the forward error correction (FEC) threshold (BER = 3.8×10^{-3}) [16], as seen in Fig. 7. As a result, the maximum and minimum traffic rates of 190 and 84.44 Mbit/s could be obtained at the free space transmission lengths of 0.75 and 2 m, respectively.

4. Conclusion

In summary, we have proposed and investigated a white-light phosphor-LED VLC system with the adaptive traffic rate of 84.44 to 190 Mbit/s by using 16-QAM OFDM modulation format with bit-loading method under the free space transmission lengths of 0.75 to 2 m. Here, we also designed an optimal analogy pre-equalization circuit design at LED-Tx side and employed no blue filter at Rx side to increase the modulation bandwidth of phosphor-LED from 1 MHz to 30 MHz. In addition, the whole obtained BERs could be less than the FEC threshold at the different transmission lengths of 0.75, 1, 1.25, 1.5, 1.75, and 2 m, respectively. In addition, we could adjust the traffic data rate of proposed VLC system adaptively, according to the different transmission lengths and received sensitivities at the Rx side.

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