Utilization of multi-band OFDM modulation to increase traffic rate of phosphor-LED wireless VLC

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Abstract: To increase the traffic rate in phosphor-LED visible light communication (VLC), a multi-band orthogonal frequency division multiplexed (OFDM) modulation is first proposed and demonstrated. In the measurement, we do not utilize optical blue filter to increase modulation bandwidth of phosphor-LED in the VLC system. In this proposed scheme, different bands of OFDM signals are applied to different LED chips in a LED lamp, this can avoid the power fading and nonlinearity issue by applying the same OFDM signal to all the LED chips in a LED lamp. Here, the maximum increase percentages of traffic rates are 41.1%, 17.8% and 17.8% under received illuminations of 200, 500 and 1000 Lux, respectively, when the proposed three-band OFDM modulation is used in the VLC system. In addition, the analysis and verification by experiments are also performed.

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References and links

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1. Introduction

Recently, due to the low power consumption, high-efficiency and long lifetime of light emitting diode (LED), the conventional incandescent and fluorescent lamps will be succeeded by the LEDs [1-2]. LED has a much higher modulation bandwidth comparing to these traditional lighting lamps [3]. Therefore, using LED to combine illumination and visible light communication (VLC) has attracted many attentions for the future lighting market and network access [4-6]. Furthermore, compared with the red-green-blue (RGB)-based white-light LED, the white-light phosphor-LED is typically employed for VLC and light applications [7, 8]. However, the long relaxation time of phosphor would reduce the modulation bandwidth. Thus, it could limit the traffic capacity of VLC system [9].

To increase the modulation bandwidth of phosphor-LED, several related technologies have been proposed, such as using a blue filter in front of a photodiode (PD) to remove the slow-response yellow light [10], utilizing spectral-efficient discrete multi-tone (DMT) and orthogonal-frequency-division-multiplexed quadrature-amplitude-modulation (OFDM-QAM) modulations [11, 12], employing multi-input multi-output (MIMO) VLC system [13], and exploiting analogy equalization circuits in Tx and Rx sides [8, 14]. Besides, Haas's group has proposed using special OFDM modulation for high-speed VLC transmission. They discussed the performance of indoor OFDM VLC communication systems in the presence of LED clipping distortions by using asymmetrically clipped optical (ACO) OFDM and DC-biased optical (DCO) OFDM [15, 16]. When they used the RBG-based white-light LED for VLC system, the OFDM-based data rate of 110 Mbit/s was obtained [17].

In this demonstration, we propose and investigate the multi-band OFDM modulation in phosphor-LED VLC system to increase the data rate. In this proposed scheme, different bands of OFDM signals are applied to different LED chips in a LED lamp, this can avoid the power fading and nonlinearity issue by applying the same OFDM signal to all the LED chips in a LED lamp. In the measurement, we do not utilize the blue filter to increase the modulation bandwidth of phosphor-LED. In the experiment, when using one-band OFDM modulation and a LED lamp with six white-light phosphor-LED chips, the VLC can provide 148.4 and 71.3 Mbps data rates, respectively, while the received illuminations are 1000 and 200 Lux in receiver (Rx) side. When we use proposed three-band OFDM technology, the traffic rates can be significantly increased to 174.8 and 100.6 Mbps under the same received illuminations. As a result, using proposed multi-band OFDM modulation could increase the 41.1% and 17.8% traffic rates in phosphor-LED VLC system, when the received illuminations are 200 and 1000 Lux, respectively. In addition, the analysis and verification by experiments are also performed.

2. Experiment and discussions

Figure 1(a) shows the experiment setup of a phosphor-LED VLC system using single band OFDM modulation. Here, we employ a LED lamp with six phosphor-LED chips to act as the signal transmitter (Tx). Lenses are used in front of the LED-Tx and client-Rx sides for enhancing the VLC signal performance. The OFDM modulation signal can be directly applied to the LED lamp by utilizing a bias-tee (BT) for VLC transmission. In the measurement, the proposed new BT without using pre-equalization has also been reported [5]. Besides, due to the influence of power fading, the relative electrical power spectrum would drop rapidly in the higher frequency range, as illustrated in Fig. 1(b). It also results in poor signal to noise ratio (SNR) of each OFDM subcarrier. Thus, the traffic rate would be limited within an effective modulation bandwidth.

In this experiment, the six white-light phosphor-LED chips are arranged in series. And the LED lamp is driven at ~18 V and directly modulated by utilizing an arbitrary waveform generator (AWG) to produce OFDM-QAM signal for VLC transmission. In Fig. 1(a), the white-light is emitted from the LED lamp and received by a silicon-based PIN receiver (Rx). The Rx has the detection wavelength range of 350 to 1100 nm with responsivity of 0.63 A/W and active area of 150 mm^2. It also has an operated bandwidth of 50 MHz and the root mean square (rms) noise of 530 μV. Then, the visible-light wireless signal can be directly detected by a PIN-based Rx. Next, the received signal could be then amplified by a wideband RF amplifier, and connected by a real-time oscilloscope for signal demodulation. Finally, according to the measured SNR of each OFDM subcarrier, the corresponding bit error rate (BER) can be calculated and obtained.

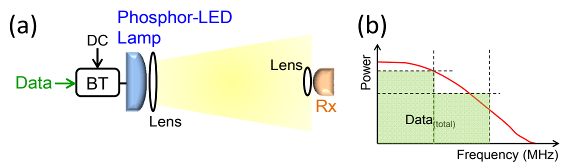

Fig. 1. (a) Experiment setup of proposed phosphor-LED VLC system using single band OFDM modulation. (b) The relative electrical spectrum.

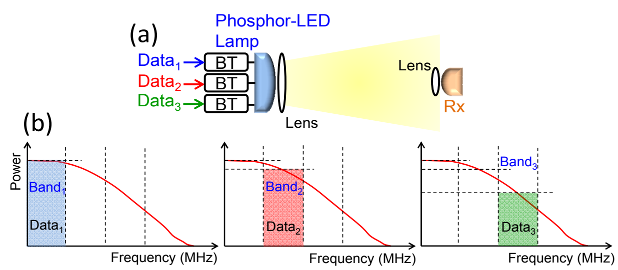

Fig. 2. (a) Experiment setup of proposed phosphor-LED VLC system utilizing three-band OFDM modulation. (b) The relative electrical spectra under three different OFDM bands.

To avoid the power fading and nonlinearity issue of the LED, we first propose the multi-band OFDM modulation technology in LED VLC system to increase the traffic rate. Figure 2(a) presents the experiment setup of three-band OFDM VLC transmission. Here, the total OFDM data is divided in three data rates ($Data_1$, $Data_2$ and $Data_3$) equally under the same modulation bandwidth. Hence, the three OFDM signals are applied to the LED lamp and divided into three sets of phosphor-LED chip by using three BTs for directly modulation. Each set has two phosphor-LED chips and is driven at 6 V. The relative electrical power spectra of three OFDM bands ($Band_1$, $Band_2$ and $Band_3$) could be illustrated conceptually in Fig. 2(b). As the OFDM signal has a high peak-to-average power ratio (PAPR), by dividing

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the OFDM into multiple bands, and different bands are applied to different sets of LED chips, much higher driving power can be applied to each LED set. Thus, the received SNR value can be increased in each OFDM-band. As a result, the total traffic rate could increase in the same LED lamp by proposed multi-band OFDM modulation scheme.

Generally, the phosphor-LED only can provide around 1 MHz modulation bandwidth without using any improvements [6]. In the measurement, the proposed BT circuit only requires to adapt the resistance (R), inductance (L), and capacitance (C) properly for matching the impedance of LED. Then, we can extend the modulation bandwidth. Here, we measure the modulation bandwidth of proposed phosphor-LED VLC system employing proposed BT circuit. Figure 3 shows the frequency response spectrum of phosphor-LED, when the received illumination of Rx side is set at 1000 Lux. As shown in Fig. 3, the effective modulation bandwidth of 25 MHz could be accomplished.

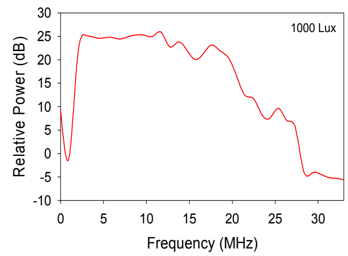

Fig. 3. The frequency response spectrum of phosphor-LED, when the received illumination of Rx-side is set at 1000 Lux.

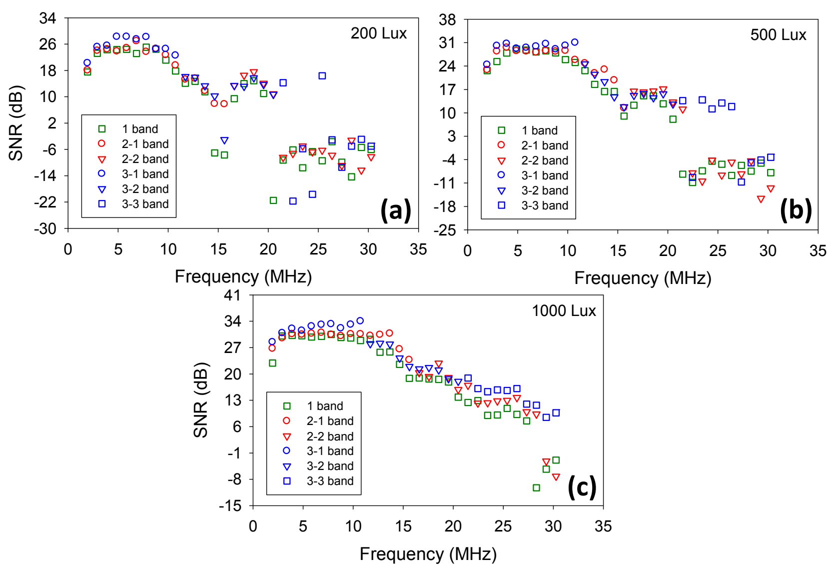

Fig. 4. Corresponding SNR spectra by utilizing single-, dual-, and three-band OFDM modulation, when the different received illuminations of (a) 200, (b) 500 and (c) 1000 Lux in the Rx side, respectively.

First of all, to realize the relationship of illumination and SNR, the 16-QAM OFDM signal with 30 subcarriers under the modulation bandwidth of 1.95 to 30.27 MHz is employed in the VLC system. According to Fig. 3, the 16-QAM OFDM modulation with bit-loading algorithm is used to apply on LED for wireless VLC transmission within ~30 MHz bandwidth. Thus, Figs. 4(a) to 4(c) show the corresponding SNR spectra by utilizing single-, dual-, and three-band OFDM modulation, when the different received illuminations of 200, 500 and 1000 Lux in the Rx side, respectively. As shown in Figs. 4(a) to 4(c), nearly 20, 26 and 30

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MHz modulation bandwidths can be achieved by using multi-band OFDM format, respectively, when the SNR is larger than 10 dB, under the different illuminations. And the obtained SNR performance of three-band OFDM signal is better than that of dual- and single-band. As the received illumination increases gradually in the Rx side, the obtained SNR would also increase no matter in which modulation format. Besides, when we use three-OFDM band modulation, the observed SNR could increase 4 to 21 dB in the third-band comparing with using single-OFDM band, as seen in Figs. 4(a) to 4(c). As a result, when we employ the proposed multi-band OFDM modulation in phosphor-LED VLC system, the entire received SNR increases. That is to say, the proposed multi-band OFDM signal would effectively increase the VLC data traffic according to measured result of Fig. 4. In addition, the corresponding transmission distances of 2.1, 2.0 and 1.4 m are also measured, while the received illuminations are 200, 500 and 1000 Lux in the Rx side, respectively.

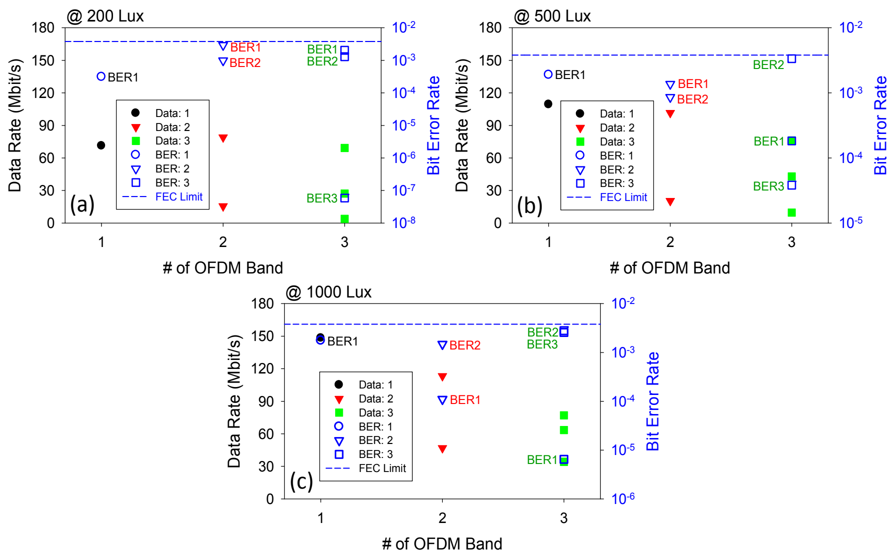

Fig. 5. Measured data rate and corresponding BER under the received illumination of (a) 200, (b) 500 and (c) 1000 Lux in the Rx side, respectively, when the single-, dual- and three-band OFDM modulations are utilized.

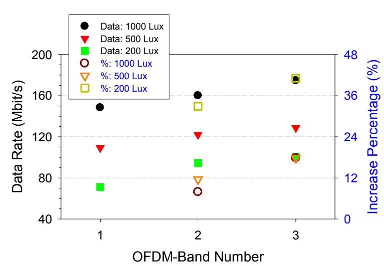

Fig. 6. Bit-loading strategy of different DMT subcarriers used in the experiment.

Figures 5(a) to 5(c) present the measured data rate and corresponding BER under the received illuminations of 200, 500 and 1000 Lux in the Rx side, respectively. Single-, dual- and three-band OFDM modulations are utilized under the modulation bandwidth of 1.95 to 30.27 MHz. When we only utilize the single-band OFDM format, the data rates of 71.3, 109.4 and 148.8 Mbit/s and the BERs of 3.13×10^{-4}, 1.89×10^{-3} and 1.76×10^{-3} are obtained at the illuminations of 200, 500 and 1000 Lux, respectively. Figures 5(a) to 5(c) also show the data rate and BER of each sub band when the proposed multi-band OFDM modulations are used.

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When the dual-band OFDM format is used, we can observe the data rates are 79.1 and 15.6 Mbit/s (total = 94.7 Mbit/s), 101.6 and 20.5 Mbit/s (total = 122.1 Mbit/s), and 113.3 and 46.9 Mbit/s (total = 160.2 Mbit/s), respectively at different illuminations. The measured BER of each sub band is below the forward error correction (FEC) threshold (BER = 3.8×10^{-3}), and the average BERs are 2.60×10^{-3}, 1.30×10^{-3} and 5.11×10^{-4} respectively at different illuminations. When the three-band OFDM modulation is employed in the proposed VLC system, the traffic rates of 69.4, 27.3 and 3.9 Mbit/s (total = 100.6 Mbit/s), 76.2, 43.0 and 9.7 Mbit/s (total = 128.9 Mbit/s), and 77.1, 63.5 and 34.2 Mbit/s (total = 174.8 Mbit/s), and the average BERs of 1.71×10^{-3}, 1.20×10^{-3} and 1.50×10^{-3} are achieved respectively.

Figure 6 shows the received total data rate and traffic increase percentage under the single-, dual-, and three-band OFDM modulation at the received illuminations of 200, 500, and 1000 Lux, respectively. In the measurement, the data rates achieve to 94.7, 122.1 and 160.2, and 100.6, 128.9 and 174.8 Mbit/s respectively, by using dual-band and three-band OFDM modulations, as shown in Fig. 6. Therefore, the maximum increase percentages of traffic rates are 32.9, 11.6 and 7.9%, and 41.1, 17.8 and 17.8% at the illuminations of 200, 500 and 1000 Lux, respectively, when the proposed dual-band and three-band OFDM signals are used in VLC system. According to Fig. 6, with the increase number of OFDM-band gradually, the obtained VLC data rate is also increase. As a result, utilizing multi-band OFDM modulation could increase the total data rate in phosphor-LED VLC wireless system.

4. Conclusion

In summary, to increase the data rate in phosphor-LED wireless VLC system, a multi-band OFDM modulation was first proposed and demonstrated. In the measurement, we did not employ optical blue filter to increase modulation bandwidth of phosphor-LED in the VLC system. As the OFDM signal had a high PAPR, by dividing the OFDM into multiple bands, and different bands were applied to different sets of LED chips, much higher driving power can be applied to each LED set. Thus, the received SNR value can be increased in each OFDM-band. Here, the data rates achieved to 94.7, 122.1 and 160.2, and 100.6, 128.9 and 174.8 Mbit/s by utilizing dual-band and three-band OFDM modulations, respectively. Hence, using proposed multi-band OFDM modulation could increase the 41.1% and 17.8% traffic rates in phosphor-LED VLC system, when the received illuminations are 200 and 1000 Lux, respectively. In addition, the analysis and verification by experiments are also executed. The maximum increase percentages of traffic rates were 41.1, 17.8 and 17.8% at the illuminations of 200, 500 and 1000 Lux, respectively, when the three-band OFDM signals was used in VLC system. Therefore, utilizing the proposed multi-band OFDM modulation not only could avoid power fading and nonlinearity, but also increase the data rate in phosphor-LED VLC wireless system.

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