Optics and Laser Technology 104 (2018) 206–209

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Research Note

Using adaptive equalization and polarization-multiplexing technology for gigabit-per-second phosphor-LED wireless visible light communication

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ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 1 January 2018
Accepted 2 February 2018

Keywords:
LED
Visible Light Communication (VLC)
Polarization
Volterra Filtering

ABSTRACT

In the demonstration, we propose and investigate a phosphor white-light LED gigabit-per-second visible light communication (VLC) system by utilizing adaptive filtering and polarization-multiplexing technology. Due to the incoherent light of LED, two orthogonal linear polarizers can be utilized in the LED transmitter (Tx) side and client receiver (Rx) side, respectively, to produce 2×2 polarization-multiplexing multi-input multi-output (MIMO) VLC transmission. Moreover, the Volterra nonlinear equalization (VNLE) filtering is proposed to improve the nonlinearity concern of LED-based VLC system, when the high spectral-efficient orthogonal frequency division multiplexing (OFDM) modulation is employed. Hence, the total VLC data rate of ~1.4 Gbps is reached and the VLC performance is also discussed in the proposed wireless VLC system.

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1. Introduction

In recent years, the indoor wireless communication requires to provide gigabit-per-second connectivity, such as using 4G-LTE and future 5G communication systems [1,2]. Recently, utilizing optical wireless system (OWS) is premeditated as an alternative approach for broadband wireless access, such as the visible laser based point-to-point transmission [3,4] and the laser-phosphor lighting link [5]. However, among the optical wireless methods, using visible light communication (VLC) based on white light emitting diodes (LED) would be the best choice, due to its benefits of long life-time, power-saving, license-free and broadly modulation bandwidth etc. [6–8]. This is because the white LEDs can be employed for indoor illumination and wireless communication, simultaneously [9].

There are two types for white-light LED illumination and VLC transmission. One is using yellow-phosphor and blue LED chip [10]. The alternative white illumination is employing red-greenblue (RGB) LEDs [11]. RGB LEDs could be good choise for VLC transmission due to the higher modulation bandwidth; however the cost is high for lighting. On the other hand, phosphor white light LED is a good choice for lighting due to its low cost. However, due to the slow response of phosphor relaxation in LED, it would limit the modulation bandwidth to a few MHz [12]. To improve the relaxation effect of LED VLC, several technologies have been proposed, such as using the analogy pre- and post-equalization technology [13,14], optical multi-input multi-output (MIMO) [15], and parallel transmission architecture [16]. Moreover, to execute high speed VLC connectivity, the limited frequency bandwidth of the commercial LED requires high spectral-efficient modulation formats, e.g. orthogonal frequency division multiplexing (OFDM), discrete multi-tone (DMT), or pulse-amplitude modulation (PAM) [11,17,18].

In this demonstration, a gigabit-per-second phosphor-LED VLC system is proposed and executed by using advanced adaptive filtering and polarization-multiplexing technology. On account of the incoherent light of LED, two orthogonal linear polarizers are used in the LED Tx side and client Rx side, respectively, to generate 2×2 polarization-multiplexing MIMI VLC transmission. Here, the adaptive filtering of Volterra nonlinear equalization (VNLE) is proposed to reduce the nonlinearity effect of LED-based VLC system. High spectral-efficient OFDM modulation with bit-loading algorithm is employed. As a result, the VLC data rate of nearly 1.4 Gbps can be completed experimentally. In addition, 19.85% improvement of traffic rate is also observed in the proposed VLC system.

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https://doi.org/10.1016/j.optlastec.2018.02.004
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2. Experiments

Fig. 1 shows the proposed phosphor-LED VLC architecture by employing two pairs of orthogonal linear polarizers achieving 2 × 2 polarization-multiplexing MIMO VLC for data rate enhancement. In Fig. 1, the experimental setup is consisted of two phosphor-LEDs, two pairs of lenses with 18° emitting angle, two pairs of orthogonal linear polarizers, a pair of blue filter, and a pair of PIN-based receiver (Rx). In the experiment, the polarization status of p-polarizer and an s-polarizer are orthogonal. And the operation ranges of two polarizers are in the wavelength range of 400 to 700 nm. The commercially polarizers also could result in 3 dB optical loss. As depicted in Fig. 1, the OFDM-QAM signal is applied on LED, which is driven at ~3 V, for directly modulation via a bias-tee (BT) with pre-equalization design in the transmitter (Tx) side. 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. Moreover, the related detail specifications of pre-equalization and OFDM-QAM were also analyzed and discussed in past studies [19–22]. Hence, the available bandwidth can be extended by utilizing the proposed pre-equalization BT.

Two pairs of lenses are utilized to focus the light beam and improve the signal to noise ratio (SNR) in the proposed VLC system. As depicted in Fig. 1, due to the incoherent light of LED, two pairs of orthogonal linear polarizers in front of the Tx and Rx sides can result in 2 × 2 polarization-multiplexing MIMO transmission for VLC enhancement. If the two polarizers have same polarization states, the two downstream signals from LEDs would interfere with each other. Then, the two downstream traffics could be not decoded. Hence, because of the orthogonality of two polarizers utilized in the setup of Fig. 1, the emitted lights from two phosphor-LEDs can be separated to prevent the interference of VLC signal in the Rx side [23].

Here, when the transmitted light is emitted from LED, then the VLC wireless signal is detected by the PIN-Rx. In the measurement, the photosensitive area size, response bandwidth, responsivity, and spectral response range of PIN-Rx are 7 mm^2, 250 MHz, 0.45 A/W, and 340–1040 nm, respectively. Besides, a pair of blue filter is utilized in the Rx side, as illustrated in Fig. 1, to mitigate the optical signal to evade the saturation of Rx and to enhance the modulation bandwidth.

To reduce the nonlinearity concern of phosphor-LED in OFDM-QAM VLC transmission, the Volterra nonlinear equalization (VNLE) method is utilized. In the experiment, the transmission curve of the phosphor-LED optical output power and the driving signal would essentially result in the nonlinearity problem. The Volterra series extensions are the linear combination of input signal functions. Hence, the VNLE filtering is desirable for LED VLC system. Here, a training sequence is delivered from LED and then launches into PIN-Rx under the adaptive equalization procedure. Thus, the equalizer of Rx could alter to a properly setting for minimizing the error rate. The filtering function can be adapted by observing the filter coefficients properly, while the equalizer is trained suitably. As a result, when the VNLE is used for the proposed VLC system, the LED nonlinearity improvement can be completed significantly.

As illustrated in Fig. 1, the OFDM-QAM signal with VNLE operation is produced by an arbitrary waveform generator (AWG) by employing off-line Matlab program. Here, a sampling rate of 625 MSample/s and digital-to-analog conversion (DAC) resolution of 8-bit from the AWG is applied the OFDM signal on the BT circuit. Here, the serial binary stream can be converted into several parallel streams. The inverse fast Fourier transform (IFFT) process is executed on the QAM symbols to create the digital OFDM symbols. The fast-Fourier transform (FFT) size and cyclic prefix (CP) are 25 and 0.3% and added in each OFDM symbol to reduce the dispersion-induced characteristic deprivation. The number of OFDM subcarriers is 55. Then, the VLC signal can be directly detected via a PIN-PD, which is linked by a real-time oscilloscope with sampling rate of 625 Msample/s for VLC signal decode. Finally, the VLC OFDM signal can be demodulation offline by retreat process of the encoder.

3. Results and discussion

In the measurement, to understand the obtainable frequency bandwidth of phosphor-LED is important issue for VLC transmission. In general, the available bandwidth of phosphor-LED without using analogy equalization is nearly a few MHz [12]. Here, Fig. 2 presents the observed electrical power spectrum of LED, while the analogy pre-equalization is employed in the Tx side. The available modulation bandwidth has been extended to around 109 MHz, as shown in Fig. 2. Then, we can compare the corresponding SNR of each subcarrier with and without the adaptive VNLE technology. Fig. 3 shows the obtained SNR spectra in the frequency range of 4 to 132 MHz. As the VNLE is not applied on BT circuit, the observed SNR value is between 11.0 and 23.7 dB in the frequency range. The started frequency of 4 MHz can avoid the lower frequency (within 2 MHz) noises of AC power and optical background power [24]. As shown in Fig. 3, with the increase of frequency gradually, the observed SNRs would also drop, due to the RF fading effect. When the proposed third order VNLE is applied, the retrieved SNR range is from 12.5 to 25.3 dB as seen in Fig. 3. Moreover, as the SNR is larger than 20 dB, the available bandwidths are 30 and 75 MHz, respectively, when the BT circuit is without and with the third order VNLE. Hence, the effective bandwidth can increase 2.5 times after using VNLE, as illustrated in Fig. 3. In addition, higher SNR subcarrier can be applied for the higher number of bit-loading.

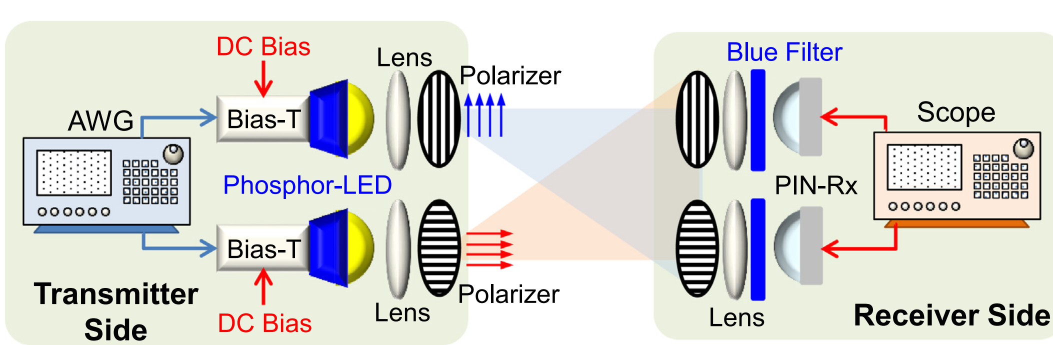

Fig. 1. Proposed phosphor-LED VLC architecture.

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