Optics Communications 292 (2013) 49–52

Contents lists available at SciVerse ScienceDirect

Optics Communications

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

Adaptive scheme for maintaining the performance of the in-home white-LED visible light wireless communications using OFDM

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ARTICLE INFO

Article history:
Received 1 April 2012
Received in revised form
16 November 2012
Accepted 17 November 2012
Available online 20 December 2012

Keywords:
Visible light communication (VLC)
Optical wireless communication (OW)
Orthogonal frequency division
Multiplexing (OFDM)

ABSTRACT

Spectral-efficient orthogonal frequency division multiplexing (OFDM) is a promising modulation format for the light-emitting-diode (LED) optical wireless (OW) visible light communication (VLC). VLC is a directional and line-of-sight communication; hence the offset of the optical receiver (Rx) and the LED light source will result in a large drop of received optical power. In order to keep the same luminance of the LED light source, we propose and demonstrate an adaptive control of the OFDM modulation-order to maintain the VLC transmission performance. Experimental results confirm the feasibility of the proposed scheme.

1. Introduction

It is believed that white light-emitting-diode (LED) will replace the traditional lighting system in the near future, due to the less power consumption and low cost. Besides, the relatively high modulation speed ($\sim$1 MHz) of the high brightness LED (HB-LED) enables optical wireless (OW) visible light communication (VLC) [1–4]. The VLC is electromagnetic interference (EMI) free and license free. Other advantages include providing a secure communication channel (since the light beam is visible and directional), and providing wireless communication in the radio-frequency (RF) communication restricted areas, such as hospital or airplane.

Since the modulation bandwidth of the HB-LED is limited to about 1 MHz, using spectral efficient orthogonal-frequency-division-multiplexing (OFDM) modulation [1,5] to directly modulate the HB-LED is promising. OFDM allows the high data rate signal to be divided into several low data rate parallel sub-channels; hence it is more resistant to frequency selective fading. Channel equalization becomes simpler by using adaptive equalization techniques. Besides, OFDM is spectral efficient by allowing high spectral overlap among its subcarriers. The disadvantage of OFDM is that it has a high peak-to-average power ratio (PAPR) due to the superposition of all subcarriers, therefore the requirement of linearity and dynamic range of the system is high. Besides, the coding and decoding of OFDM signal is more complicated than the traditional on–off -keying (OOK) signal. VLC is a directional and line-of-sight communication; hence in practical deployment, the offset of the optical receiver (Rx) and the LED lamp will result in a large drop of received optical power. In traditional fiber optic systems, we can increase the launching optical power to compensate the power drop [6]. However, this is not practical for a VLC system, since it will also affect the in-home luminance. As the primary purpose of the LED lamp is for lighting, in order to keep the same luminance of the light source, we propose and demonstrate an adaptive control of the OFDM modulation-order to maintain the VLC transmission performance even at high offset angle. Experimental results confirm the feasibility of the proposed scheme.

2. Proposed architecture and experiment

Fig. 1 shows our proposed LED OW VLC architecture with adaptive control of the data rates depending on different channel conditions. The performance evaluation system at the user device evaluates the signal quality and makes the "changing data rate" request via the upstream channel. The upstream adaptive control signal can be sent by using an infra-red (IR) based transmitter (Tx) similar to the one used in the television remote control. As the data rate of the control signal is low, the required received (Rx) optical power can be very low and hence a high upstream

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http://dx.doi.org/10.1016/j.optcom.2012.11.081

transmission angle or even using reflected path communication can be supported.

Fig. 2 shows the proof-of-concept experimental setup of the proposed white-LED VLC system. The randomly generated bit stream was converted to complex vector data, and then it was serial-to-parallel (S/P) converted. Here we used the baseband OFDM of 2N-point fast Fourier transform (FFT), where N equals 64 (total number of subcarriers). The 64 subcarriers occupied frequency from DC to 3 MHz. After transforming to time domain in the inverse FFT (IFFT), cyclic prefix (CP) was added. The signal was digital-to-analog (D/A) converted via an arbitrary waveform generator (AWG) (Agilent 33220A), and applied to the white-light HB-LED with proper DC bias. The white HB-LED was produced by Cree (XLamp XR-E LED). It was cool-white with color temperature from 5000 K to 10,000 K. The measured 3-dB modulation bandwidth of the HB-LED is about 1 MHz [4]. The light was received by a silicon-based photodiode (wavelength range of 350–1100 nm, responsivity 0.65 A/W, bandwidth of 17 MHz with root mean square (rms) noise of 530 μV). A pair of home-made lens was used for collimation. The received electrical signal was amplified (Mini-Circuit ZHL-6A) and captured by using a real-time oscilloscope (RTO) (Tektronix TDS3014C). The white LED is consisted of a blue LED in combination with an yellowish phosphor. The typical modulation bandwidth of this white LED is about 1 MHz. This bandwidth limitation is mainly due to the slow temporal response of the phosphor. The blue light can be readily extracted from the incoming optical beam by using an optical blue filter at the Rx and this increases the bandwidth [7]. However, in the experiment, in order to reduce the optical path loss, no optical blue filtering was used.

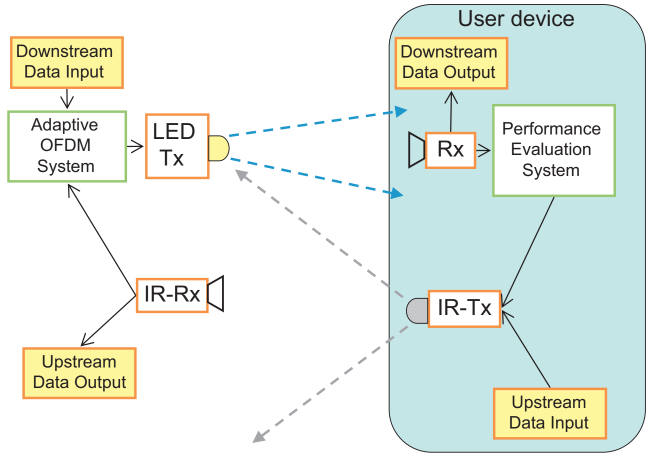

Fig. 1. Architecture of the proposed LED VLC system with adaptive control of OFDM data rates.

The RTO performed the analog-to-digital (A/D) conversion. The received signal then went through the processes of CP removal, synchronization and equalization. Finally, signal-to-noise ratio (SNR) and bit-error-rate (BER) were measured based on the received error vector magnitude (EVM).

3. Results and discussion

In the experiment, the Rx was placed at a distance of 2 m (position “a” in Fig. 2 without offset). The distance of 2 m is the typical transmission distance between the ceiling-lamp to the desk. According to an analysis in Ref. [8], in a standard room of 5 m × 5 m × 3 m, LED lights which are capable of optical transmission are installed at a height of 2.5 m from the floor, and the height of a desk is 0.85 m. Hence, in the experiment the transmission distance of about 2 m was used. The Rx was then offset at a very large angle to position “b”, so that the received electrical signal was highly dropped to about half of its original value. As the transmission distance of 2 m is much higher than the experiments reported in other literatures [2], the SNR of the higher frequency OFDM subcarriers were quite low due to the long transmission distance. Hence at the Rx, we purposely neglected these higher frequency OFDM subcarriers, and 40 lower frequency subcarriers were used. Fig. 3 shows the received average SNR of the 40 OFDM subcarriers obtained from the experiment. The result showed that at position “a”, 16 quadrature amplitude modulation (QAM) OFDM can be operated with SNR > 18 dB, and it was below the forward error correction (FEC) limit (BER < 10^{-3}) for the 16-QAM OFDM signal. However, when the measured received peak-to-peak voltage (V_{PP}) decreased from 247 mV to 140 mV owing to the very large offset angle at position “b”, FEC limit cannot be maintained. Hence in order to maintain the signal quality while keeping the same luminance for in-door, the 16-QAM OFDM was adaptively adjusted to quadrature phase shift keying (QPSK) (also known as 4-QAM) OFDM. We can observe

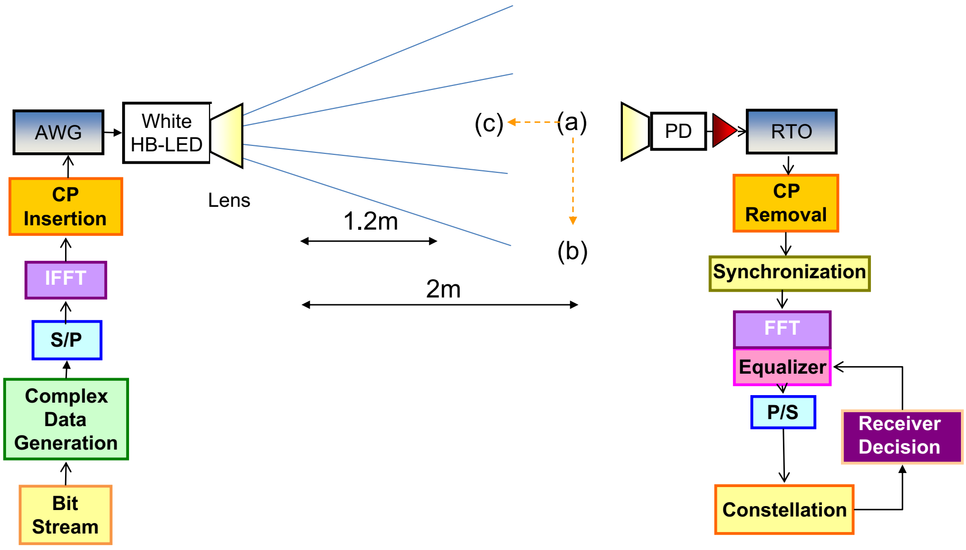

Fig. 2. Experimental setup of the white-LED VLC system with the adaptive control of transmission performance.

that the SNR of 18 dB can be restored. The performance of the QPSK OFDM signal at position “a” was included in Fig. 3 for reference.

Besides, we also experimentally evaluated the proposed system if the Rx is positioned closer to the LED lamp. The free space transmission distance was changed from 2 m to 1.2 m (typical communication distance between desk-lamp to desk). Higher data rate VLC link can be operated due to higher received SNR. By decreasing the distance, the number of effective OFDM subcarriers and hence the total data rate can be increased. In the experiment, the average SNRs were kept at ~20 dB and ~18 dB for the QPSK OFDM and 16-QAM OFDM signals respectively while the OFDM subcarriers were increased from 40 to 48. The average SNRs of 20 dB and 18 dB corresponded to the BER of $< 10^{-10}$ for QPSK and BER of $< 10^{-3}$ for 16-QAM OFDM signals. As a result, the data rate can be increased from 5.12 Mb/s to 6.14 Mb/s in 16-QAM OFDM and from 2.56 Mb/s to 3.07 Mb/s in QPSK OFDM signals, as shown in Fig. 4. The direct modulation bandwidth of

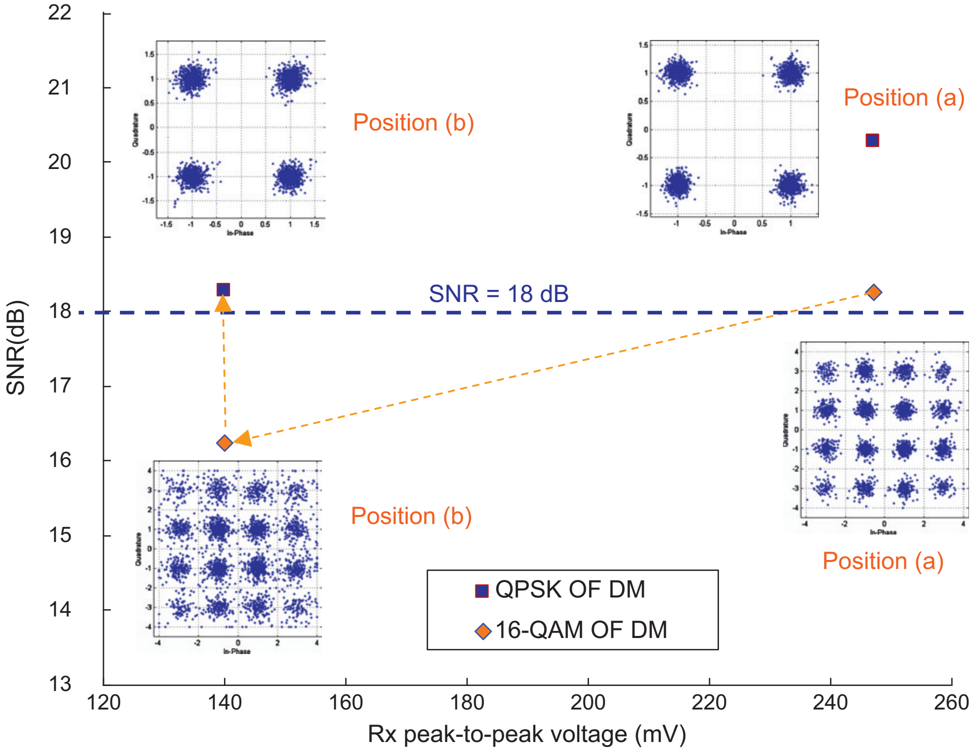

Fig. 3. SNR of the received OFDM signals (16-QAM and QPSK) at line-of-sight and with a high offset angle.

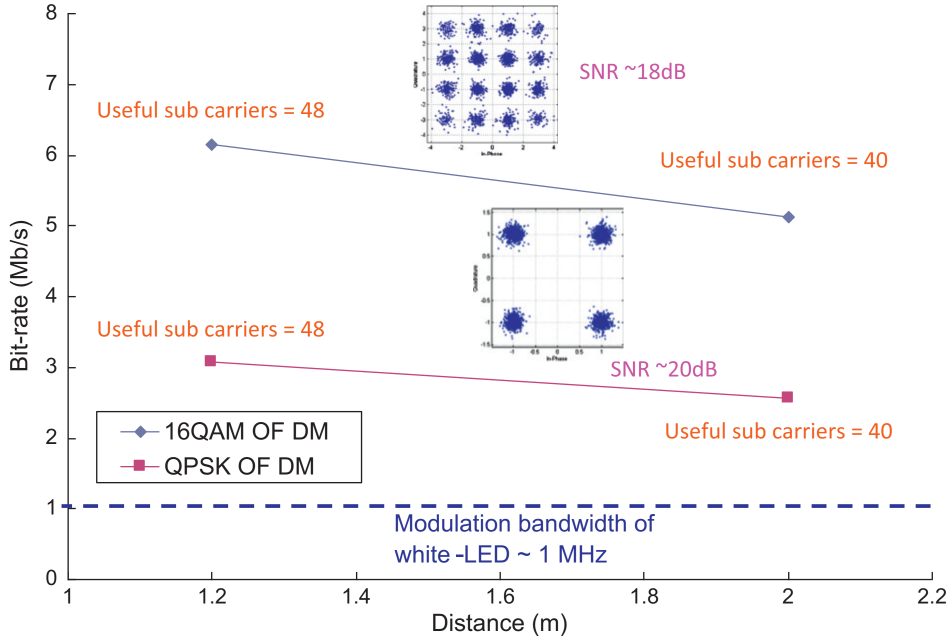

Fig. 4. Bit-rate improvement by decreasing the distance, hence the number of effective OFDM subcarriers can be increased.

1 MHz of the white-LED was also included in Fig. 4 for reference. In our experiment, the maximum achievable data rate is 6.14 Mb/s (using 16-QAM OFDM), achieving a data rate enhancement of about 6 times without using blue filtering (the bandwidth of the LED is ~1 MHz). Studies have shown that by using blue filtering to remove the slow phosphor response, the direct modulation bandwidth of the LED can be increased to 14 MHz and a 100 Mb/s VLC transmission link can be setup by using these 14 MHz LEDs [6] (data rate enhancement of about 7 times). The data rate enhancement in this demonstration is similar to other reported scheme without having the function of adaptive control.

4. Conclusion

As the modulation bandwidth of the white HB-LED is limited to about 1 MHz, using spectral-efficient OFDM for the LED VLC is promising. VLC is a directional and line-of-sight communication; hence in practical deployment, the offset of the optical Rx and the LED lamp will result in a large drop of received optical power. In order to keep the same luminance of the LED lamp, we proposed and demonstrated an adaptive control of the OFDM modulation-order to maintain the VLC transmission performance. At a very high offset angle, by switching the OFDM order from 16-QAM to QPSK, SNR of 18 dB can be restored. Besides, by decreasing the free space transmission distance from 2 m to 1.2 m, the number of effective OFDM subcarriers and hence the total data rate can be increased. In our experiment, the maximum achievable data rate is 6.14 Mb/s, achieving a data rate enhancement of about 6 times without using blue filtering.

Acknowledgment

This work was supported in part by the National Science Council, Taiwan under Contract nos. NSC-100–2221-E-009–088-MY3and NSC-98–2221-E-009–017-MY3.

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