Optimized 481 Mb/s visible light communication system using phosphorescent white LED

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We demonstrate a visible light communication system based on DC-biased optical orthogonal frequency-division multiplexing (DCO-OFDM) and achieve a bit rate of 481 Mb/s at a communication distance of 65 cm by employing single 1 W commercial phosphorescent light-emitting diode (LED). The average bit error rate of the received data is 2.3×10^{-3}, which is below the forward error correction limit, 3.8×10^{-3}. The effect of signal clipping in DCO-OFDM system is studied and resource allocation algorithms are utilized. At least 13% capacity improvement can be obtained by suitable signal clipping and resource allocation.

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Light-emitting diodes (LEDs) are considered as one of the most promising candidates for next-generation illumination because of their high efficiency, low cost, and long lifetime. With the popularity of LED illumination, a kind of LED-based wireless communication, visible light communication (VLC), has attracted much attention of research[1–9]. Illumination LED is used as a transmitter in VLC and no extra infrastructure is required. VLC also has advantages of security, no radiation, and no electromagnetic spectrum regulation.

Phosphorescent LED, which is the most common type of white LED device due to its low complexity, consists of a blue LED and a peripheral phosphor layer. In VLC, the slow response of phosphor component leads to a narrow 3 dB bandwidth[1]. Fortunately, the slow phosphor component can be suppressed at the receiver by means of adding a blue filter. As a result, the 3 dB bandwidth can be extended from 2–3 to 15–20 MHz[2].

In order to make full use of the limited bandwidth, orthogonal frequency-division multiplexing (OFDM) or discrete multi-tone (DMT) is adopted to improve spectrum efficiency and implement high-speed communication[3,4]. A data rate of 513 Mb/s transmission utilizing DMT modulation at strong illumination level (about 1000 lx) is reported[5]. In addition, the nonlinearity of LED also brings challenge to researchers[6,7]. A proper DC-bias point and an approximate linear dynamic range should be chosen[8], thus the peak power of the signal is constraint. In Ref. [9], the effect of system's nonlinearity characteristics was considered and a data rate of 1 Gb/s transmission was demonstrated at a communication distance of 10 cm over a commercial phosphorescent LED. Nevertheless, in that report, the data rate was about 600 Mb/s as the communication distance lengthening to 50 cm, and an expensive avalanche photodiode (APD) was used as a receiver.

We present a 481 Mb/s VLC system at a communication distance of 65 cm. The communication distance is longer than the works mentioned above and the experimental scenario is closer to the actual scenario. Single 1 W phosphorescent LED and a low-cost photodiode (PD) is used in our work. Signal clipping effect is discussed and an optimized clipping level is obtained by experimental measurement. An optimal bit and power allocation algorithm is used to utilize the bandwidth of the LED efficiently. The experimental result shows that a 481 Mb/s transmission is achieved with bit error rate (BER) below forward error correction (FEC) limit. At

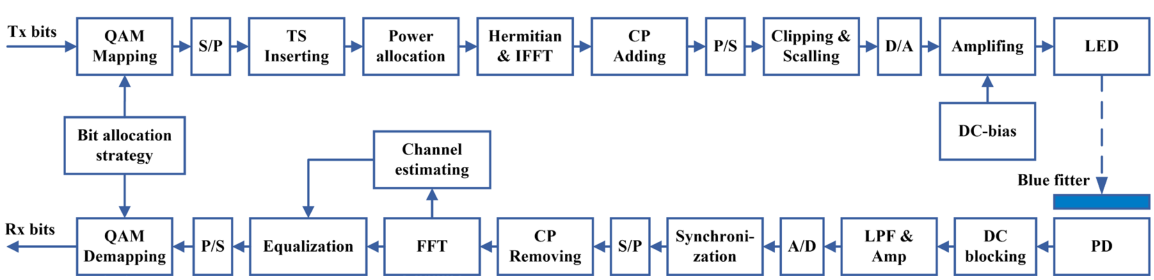


Fig. 1. Block diagram of a complete DCO-OFDM VLC system.

least 13% system capacity can be improved by suitable clipping level with the same experimental setup and in the same conditions.

The block diagram of a complete DC-biased optical (DCO)-OFDM system is shown in Fig. 1. At the transmitter, a high-speed binary data stream is mapped into quadrature amplitude modulation (QAM) format with various orders according to a bit allocation strategy and decomposed to parallel subcarriers. Some train sequences (TSs) are inserted onto each subcarrier for the use of estimating the sampled channel frequency response and also for the synchronization at the receiver. After the power allocation processing, Hermitian symmetry (mirroring) is performed to ensure that the result of IFFT is real. Clipping and scaling are used to mitigate the peak-to-average power ratio (PAPR) of the signal and make full use of the dynamic range of the LED. After parallel/series (P/S) and digital/analog (D/A) conversion, DC-bias is added to obtain a positive signal. Finally, the real and positive signal is fed to the phosphor-based white LED.

At the receiver, a PD with a blue filter is used to detect the intensity of incident blue light component. Generally, DC component is not used for demodulation, so a DC-block is employed before subsequent processing to remove the DC-bias. After low-pass filtering, amplifying, and A/D conversion, bit synchronization is operated. Then parallelization, cyclic prefix (CP) removing, and FFT should be processed. The sampled channel frequency response can be obtained by the receiver just by comparing the received TS to the original TS, as described in Ref. [10]. A zero-force equalization in frequency domain should be performed. After P/S conversion and demapping, the serial received bit stream is obtained.

It is worth noticing that in such peak power constraint VLC system, the less the PAPR is, the higher the average power can be achieved. Hence, by utilizing signal clipping, we can restrict the PAPR and further improve the average signal power. In addition, the numeric simulation about the DCO-OFDM signal reveals that, although the theoretical PAPR's upper bound is very high, the probability of very high PAPR is rather small, as shown in Fig. 2. So a conservative signal clipping may enhance the average power, and the clipping noise is negligible, thus the received signal-to-noise ratio (SNR) can be increased. Nevertheless, applying an excessive clipping level may introduce severe clipping noise and lower the communication capacity. Therefore, a suitable signal clipping should be performed to reach the maximum capacity. The optimized clipping level in our demonstration is experimentally measured and the result is stated later. After optimizing the clipping level, a bit and power allocation scheme is applied. SNR is measured through error vector magnitude (EVM) method[11]. In this method, an OFDM signal with all subcarriers modulated with binary-phase-shift-keying (BPSK) is fed to LED, after signal receiving, constellation map of each subcarrier can be obtained and used to calculate the SNR of each subcarrier. A bit and power allocation strategy is generated based on a modified Hughes–Hartogs algorithm, a strategy is achieved by adding one bit to the channel requiring the smallest additional power at a time. The strategy's object is maximizing the data rate under condition that average BER is below a present threshold and BER at different subcarriers is not necessary the same.

The experimental setup is shown in Fig. 3. The clipped and scaled OFDM signal is generated by an arbitrary waveform generator (AWG, Rigol, DG5352). Single-side bandwidth of 100 MHz is divided into 64 subcarriers, including 32 effective subcarriers and 32 Hermitian symmetry subcarriers. The discrete signal is 10 times oversampled to smooth the step-like output of the AWG. A self-made coupling circuit is connected to AWG. The circuit supplies DC-bias voltage and can be regarded as a concatenation of attenuator and bias tee. The DC-biased OFDM signal is fed to a commercial phosphor-based white LED (Epistar). A PD module (Thorlabs, PDA10A-EC, 150 MHz, 3 dB bandwidth) is set in front of the LED at a distance of 65 cm. A hemispherical lens with 61 mm diameter and a short pass filter (Asahi, XVS0490, transmissivity of 95% at wavelength of 460 nm, cut-off wavelength of 490 nm) are used in front of the PD. The illuminance at the receiver is about 280 lx. A bias tee (Picosecond, 5575 A) is used as a DC-block and a serial signal analyzer

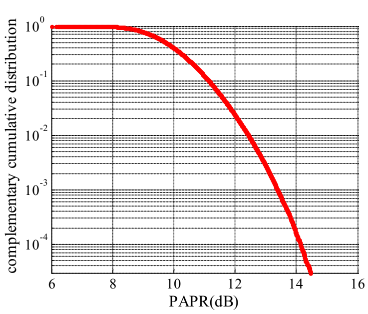


Fig. 2. PAPR distribution of OFDM signal.

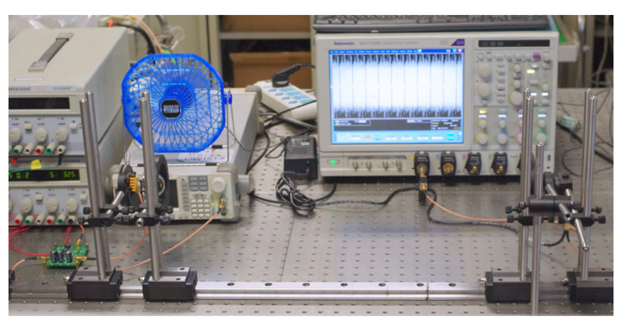


Fig. 3. Experimental setup.

(Tektronix, DSA71254C, max sample rate of 100 Gs/s) is used to sample and save the received data for off-line signal processing.

Before a data transmission experiment, some parameters are to be determined. We measure the relationship between the LED input voltage and the illuminance at the receiver to obtain the LED's nonlinear characteristic, as shown in Fig. 4. Proper DC-bias point and dynamic range is obtained according to the measurement. A DC-bias of 3.6 V is used. Considering the attenuation introduced by the self-made bias circuit, the corresponding dynamic range of AWG output is about −5 – 5 V, so the peak envelope of the generated OFDM signal is 5 V.

Effect of signal clipping and scaling is studied through experimental measurement. In this measurement, we change the clipping level, and fix the peak envelope of the post-clipping signal to 5 V by scaling, which is the upper bound of the dynamic range. For different clipping levels, EVM method is performed to estimate the received SNR. Then the bit and power allocation algorithm is applied based on the estimated SNR to calculate a bit and power allocation strategy. Thus the system capacity of different clipping levels is derived, as shown in Fig. 5. The PAPR of the post-clipping signal is used to represent the clipping level. From Fig. 5, we can see that when a conservative clipping level of 14 dB is processed, the system capacity is about 425 Mb/s. As the clipping level reduces, the system capacity tends to increase obviously. At an optimal clipping level of 12 dB, the system is at maximum capacity of about 481.25 Mb/s.

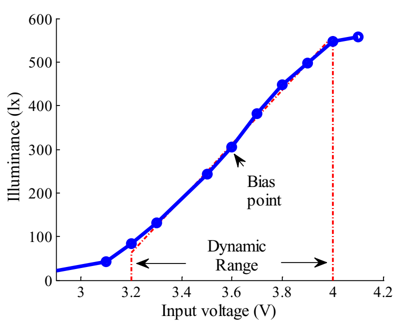


Fig. 4. Nonlinear characteristic of LED.

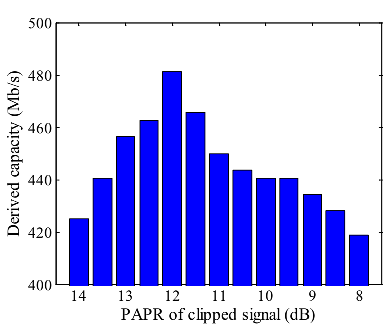


Fig. 5. Derived capacity of different clipping levels.

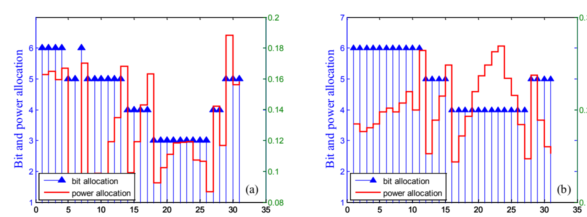
However, the system capacity tends to decrease as the clipping level continues to decrease.

Then we demonstrate the data transmission system at the clipping levels of 14 and 12 dB, respectively. The bit and power allocation strategies in the two experiments are shown in Fig. 6. Both data rates of 425 and 481.25 Mb/s are successfully transmitted through our experimental setup.

The BER values of the two experiments are about 2.1×10^{-3} and 2.3×10^{-3} respectively. The BER values are almost similar to the parameters in the bit and power allocation algorithm, 2×10^{-3}, and are below the FEC limit of 3.8×10^{-3}. The BER of each subcarrier is shown in Fig. 7, the red line represents the average BER of the transmission. There is variation in BER achieved at different subcarriers. On one hand, the target BER in bit and power allocation strategy is not exactly the same, and on the other hand, there are errors between the SNR estimated by the EVM method and the actual SNR in experiment, these errors may also lead to BER variation.

Constellation map of some subcarriers is shown in Fig. 8, a bit distortion mostly caused by time jitter and phase noise of equipment and device is seen. The experimental results verify that in peak power constraint DCO-OFDM VLC systems, suitable signal clipping and optimal bit and power allocation can effectively increase the system capacity by at least 13%.

In this experimental setup, a PD module is used, which consists of a low-cost PD (FDS010) and an amplifier. There are two kinds of common photo detector in VLC systems, PD and APD. Compared with APD, PD has lower sensitivity and lower response, which means the receiver SNR is lower. But the cost of a PD is much lower, and the peripheral circuit of a PD-based receiver is much simpler. Taking into consideration performance,



(a) (b)

Fig. 6. Bit and power allocation strategy: (a) 14 and (b) 12 dB signal clippings.

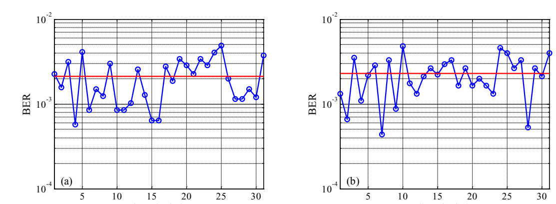


Fig. 7. BER of each subcarrier: (a) 14 and (b) 12 dB signal clippings.

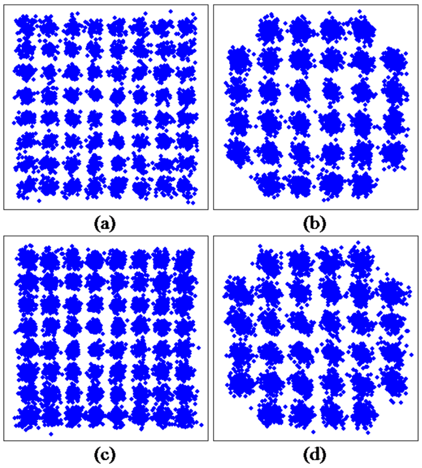


Fig. 8. Constellation map: (a) 64 QAM and (b) 32 QAM in 14 dB clipping; (c) 64 QAM and (d) 32 QAM in 12 dB clipping.

price, and complexity, we find that a PD-based VLC receiver is more suitable for practical application.

A lens is used at the transmitter to adjust the luminous intensity distribution since the half-intensity beam angle (HIBA) of LED is much wider. By adding the lens, the HIBA turns from 70° to 30°, as shown in Fig. 9, improving VLC performance while meeting requirements of the lighting standard[12]. It is noted that the illuminance at the receiver is 280 lx, only about half of the standard indoor illumination for office work[13]. A higher SNR can be achieved in a higher illuminance situation. Therefore, it can be predicted that the communication capacity can reach a higher level in actual scenario.

In conclusion, we report a high-speed VLC experiment based on single commercial phosphorescent white LED

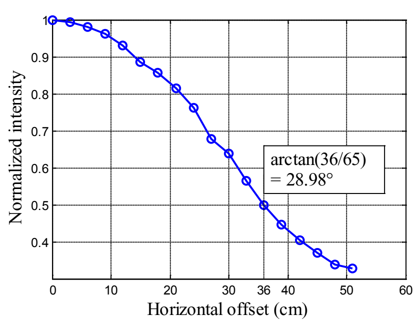


Fig. 9. Luminous intensity distribution after adding lens.

and low-cost PD. The effect of signal clipping in such peak power constraint system is studied. Optimum signal clipping, DCO-OFDM, and a greedy bit and power allocation algorithm are implemented to make full use of the limited bandwidth and power resource. High-speed transmission is demonstrated at a communication distance of 65 cm. A gross data rate of 481.25 Mb/s is achieved with a BER of 2.3×10^{-3}, below the FEC limit. At least 13% system capacity improvement is obtained by applying suitable clipping level and resource allocation. We predict that the data rate can be further increased in actual scenario because the illuminance in our demonstration is less than the national standard value.

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