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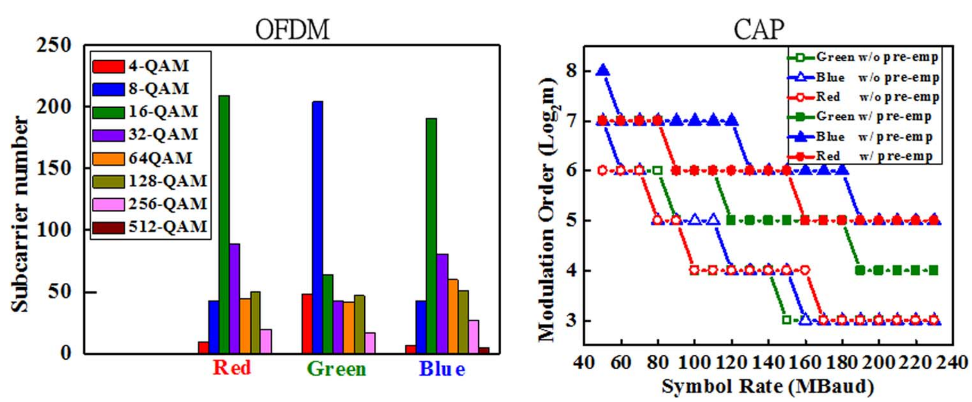

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Performance Comparison of OFDM Signal and CAP Signal Over High Capacity RGB-LED-Based WDM Visible Light Communication

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Abstract: We experimentally demonstrate a visible light communication (VLC) system based on a single commercially available RGB-type LED. High spectrally efficient carrier-less amplitude and phase (CAP) modulation and orthogonal frequency-division multiplexing (OFDM) are adopted in the intensity-modulation and direct-detection VLC system of limited bandwidth. In order to achieve higher capacity of the uneven-frequency-response LED-based VLC system, OFDM signals are combined with the bit- and power-loading techniques, and CAP signals of various modulation are pre-emphasized to modulate one of the RGB chips. To reach the BER of less than 10^{-3}, CAP and OFDM signals demonstrate the maximum data rates of 1.32 and 1.08 Gb/s, respectively, employing the blue chip. In addition to spectrally efficient formats, the wavelength-division-multiplexing (WDM) scheme is applied to further increase the capacity. After individually optimizing RGB chips, the maximum aggregate data rates of CAP and OFDM are 3.22 and 2.93 Gb/s, respectively, in our RGB-LED-based WDM VLC system. Hence, compared with OFDM, the CAP scheme shows competitive performance and provides an alternative spectrally efficient modulation for next generation optical wireless networks.

Index Terms: Visible light communication, carrier-less amplitude and phase modulation, wavelength-division-multiplexing.

1. Introduction

Recently, white light emitting diodes (LEDs) have been emerging as a prominent technology to replace the conventional incandescent and fluorescent lamp for currently illumination installations due to their advantages, such as long lifetime, high efficiency, cost effectiveness, small size and low power consumption. Hence, LEDs have been widely used in traffic application, flat panel displays, illumination application, and ubiquitous indicator light. Meanwhile, LED-based visible light communication (VLC) has attracted considerable interests in recent years. VLC using white LEDs offers many advantages for home area networking and next-generation short-range wireless access, such as worldwide availability, high security, immunity to radio frequency interference, and spatial reuse of the modulation bandwidth in adjacent communication cells [1], [2]. The most important feature of a VLC system is the huge unregulated bandwidth resource available to be the promising complementary for short-range wireless transmission as compared with the limited spectra of the traditional radio frequency and millimeter wave [3]. To realize white-light illumination, phosphor-based LEDs and RGB-type LEDs are two of most popular LEDs. While a phosphor-based LED consists of a blue LED coated with phosphors, the slow relaxation time of phosphors, however, is detrimental to high-speed transmission [4]. In contrast to a phosphor-based LED, an RGB-type LED is a more promising transmitter of future indoor VLC systems [2], [5], [6]. RGB-type LEDs provide the white-light illumination, which is properly composed of three wavelengths of tri-color LED lights. Hence, employing RGB-type LEDs to a VLC system provides not only wider bandwidth without the limitation caused by phosphor, but also the possibility of the wavelength division multiplexing (WDM) technology. In WDM VLC systems, multiple data streams are individually carried by the three wavelengths of an RGB-type, so that the aggregate data rate of the VLC system can be enhanced.

Nevertheless, to pursue the high brightness of LEDs for illumination, it is still technically challenged to avoid high diffusion capacitance and resistance, which limit the modulation bandwidth of LEDs to tens or hundreds of megahertz [7]. Therefore, high spectrally efficient modulation format is a straightforward way to increase the capacity under the limited bandwidth, such as orthogonal frequency-division multiplexing (OFDM) [8], [9] and carrier-less amplitude and phase (CAP) modulation [10]. Combined with quadrature amplitude modulation (QAM) and bit- and power-loading techniques [11], OFDM has been used to achieve a gigabit-class WDM VLC system [12] employing avalanche photodiode (APD). In addition, CAP signals composed of the two orthogonal baseband signals allow simpler implementation without the requirement of discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT). With or without the WDM technique, CAP modulation has been also employed to reach gigabit-class VLC systems [10], [13]. In fact, CAP and OFDM have been compared in a short-reach fiber communication system [14] and high-speed transmission [15], and CAP exhibits the potential of lower power consumption, lower cost and lower complexity.

In this paper, we experimentally compare the performance of CAP and OFDM modulation in a high-capacity WDM-VLC system based on a commercially available RGB-type white LED for the first time. Over the VLC channel of limited bandwidth and uneven frequency response, OFDM can maximize its transmission capacity by bit- and power-loading under the constraint of a required bit error rate (BER), but CAP of a fixed modulation order can only optimized its BER performance via power pre-emphasis [9]. Compared with CAP, however, OFDM has higher peak-to-average-power ratio (PAPR), which is crucial for nonlinear E/O systems, such as LED-based VLC systems. Thus, this work applies various m-CAP signals with $\log_2 m$ bit/symbol to investigate the maximum capacity of the VLC system under the FEC limit, i.e., the BER of $<10^{-3}$. For the single-channel case, which provides proper bias to all chips to maintain white-light illumination but modulates only one chip to transmit data, CAP and OFDM signals demonstrate the maximum data rates of 1.32 Gb/s and 1.08 Gb/s, respectively, employing the blue chip. On the other hand, employing the WDM technique the maximum aggregate data rate of 2.93 Gb/s is achieved by OFDM signals in the RGB-LED-based VLC system. Optimizing the formats of power-pre-emphasized CAP signals can demonstrate slightly higher aggregated data rate of 3.22 Gb/s in the same system. As a result, compared with the OFDM scheme, the CAP scheme provides a potentially simpler and lower-cost candidate [16] with competitive performance for next generation optical wireless networks.

2. Experimental Setup

Fig. 1 shows the experimental setup of the WDM-VLC system based on an RGB-type LED, and the photographs of the transmitter and the receiver are shown in insets (a) and (b), respectively. The OFDM and CAP signals are generated by an arbitrary waveform generator (AWG) with an off-line MATLAB program. The sampling rate and the DAC resolution of the AWG are 1 GSample/s and 8 bit, respectively. A commercial RGB-type white LED module (LED ENGIN LZ4-20MC00) is adopted as the WDM-VLC transmitter. The viewing angle is 95° (full opening angle at 50% maximum intensity), and it consists of RGB chips with the center wavelengths of 624 nm (Red),

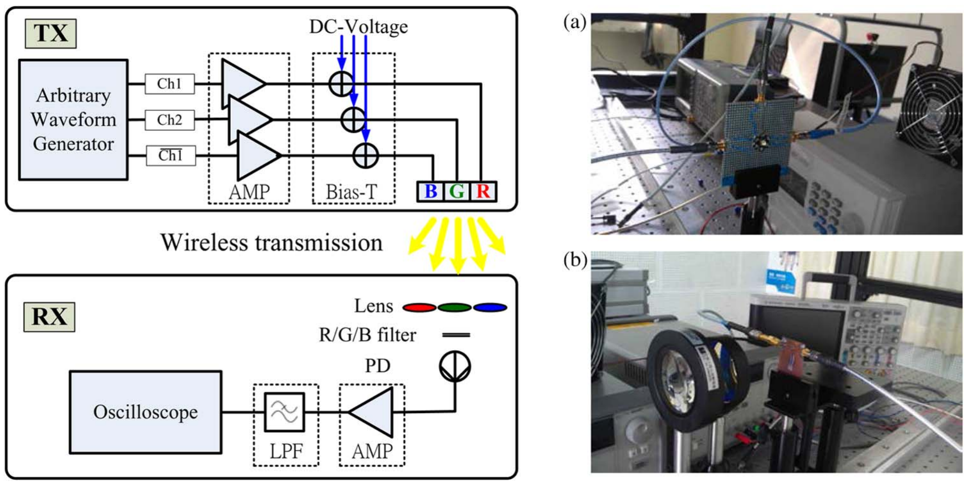

Fig. 1. Experimental setup for the WDM VLC system. (a) The transmitter with an RGB LED and (b) the receiver with a photo-diode.

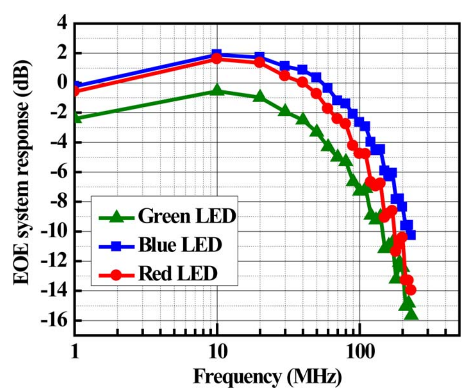

Fig. 2. The measured electrical-optical-electrical (EOE) system response of each chip.

525 nm (Green), and 457 nm (Blue). The bias currents of the red, green and blue chips are set as 350 mA, 340 mA and 380 mA, respectively, to obtain the best E/O linearity, and to maintain white-light illumination condition, the bias currents are provide regardless of which or how many chips are modulated. Fig. 2 shows the measured system response of each chip. The relative response curves are measured with respect to the 0-dB reference level which is defined as the 1-MHz response of the blue chip, and the responses of the blue and red LED chips are slightly better than that of the green one. The responses of over $\sim$200 MHz are seriously degraded by more than 10 dB, and the signals bandwidth is set to $\leq$ 230 MHz throughout this work. With cyclic prefix (CP) of 1/16, fast-Fourier transform size of 2048 and 1- GSample/s DAC sampling rate, the OFDM signals contain 471 subcarriers to occupy fixed 230-MHz bandwidth. To maximize its capacity, the relative power and modulation order of each subcarrier is adjusted by the bit- and power-loading algorithm [10]. Furthermore, the square root raised cosine filter (SRRF) with the roll-off factor of 0 is utilized to generate the CAP signals. The maximum capacity of the CAP signals is investigated via various modulation orders and signal bandwidths, and power pre-emphasis is employed to resolve uneven frequency response. Since different signals would have different PAPR, the amplitudes of modulation signals are adjusted to optimize performance in each case. Moreover, the deployed transmission distance of this single-RGB-LED VLC is about 25 cm owing to the limited radiated power from a single RGB-type LED. Actually, the typical indoor transmission of a few meters could

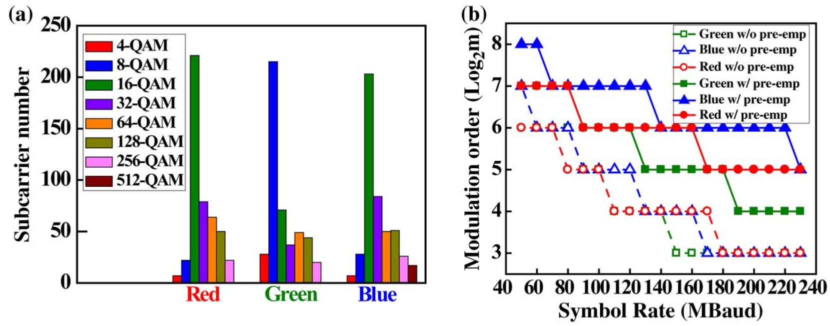

Fig. 3. The modulation orders of each chip for the single-channel case. (a) The subcarrier histogram of modulation orders for the OFDM signals and (b) the highest modulation order as a function of symbol rate without and with pre-emphasis for CAP signals.

be achieved by employing LED arrays and/or high sensitivity receiver [17]. At the receiver, the optical focusing lens (Thorlabs UA1979R) and the dichroic filters are employed to improve the received optical power and separate the WDM signals, respectively. A commercial silicon PIN photo-detector (Hamamatsu S10784) is used to detect the optical signals with relative 3-dB bandwidths of 300 MHz at 660 nm and 250 MHz at 780 nm. After air-transmission and photo-detection, background noise is suppressed by a low-pass filter (DC∼280 MHz) and a simple LC circuit. Then, the received electrical signals are captured by a digital storage oscilloscope with 20-GSample/s sample rate, 8-bit ADC resolution, and 3-dB bandwidth of 16 GHz. The off-line DSP programs are applied to demodulate the OFDM and CAP signals. For the OFDM signals, synchronization and one-tap equalization are included. For the CAP signals, the same SRRF with the roll-off factor of 0 is adopted in demodulation, which also includes synchronization and decision feedback equalization (DFE). Finally, the BER performances of OFDM and CAP signals are evaluated by error counting in this work.

3. Results and Discussion

First, the experimental results of single-channel cases are shown in Fig. 3, and there is no AC interference from adjacent channels. Fig. 3(a) shows the histogram of modulation orders of OFDM subcarriers after bit- and power-loading. Employing the blue chip, the OFDM signal, which consists of the modulation orders from 4 QAM to 512 QAM, can achieve the maximum data rate of 1.08 Gb/s, excluding CP. Compared with the blue chip, the OFDM signal of the red chip has the similar distribution of modulation orders, of which about half are 16-QAM, but it shows the slightly lower data rate of 1.04 Gb/s. In addition, due to the worse system response of the green chip, as shown in Fig. 2, the OFDM subcarriers of the green chip are mostly encoded as 8-QAM, and the resulted data rate is only 0.89 Gb/s. Furthermore, the CAP signals are measured in the same system for comparison. Because CAP is a single-carrier modulation scheme, its maximum capacity is investigated via measuring the highest modulation orders over different symbol rates. Fig. 3(b) exhibits the highest modulation orders of the CAP signals of the single-channel case to achieve the FEC limit at symbol rates of 50 MBaud ∼ 230 MBaud. For the CAP signals, although DFE is applied at the receiver to overcome insufficient frequency response and detrimental inter-symbol interference (ISI), noise at high frequency would be intensified due to the limited and uneven channel responses. Therefore, based on a finite impulse response (FIR) filter, the pre-emphasis is employed at the transmitter to compensate the system response and to reduce ISI without noise intensification. Moreover, the DFE is still applied to decrease the remaining ISI of the VLC system. Applying pre-emphasis, the highest modulation order of each symbol rate is increased by at least one order, and therefore, the corresponding maximum data rate can be effectively enhanced. For the blue chip, employing pre-emphasis will increase the maximum data rate from 0.69 Gb/s of 230-MBaud 8-CAP to 1.32 Gb/s of 220-MBaud 64-CAP. For different LED chips, however, the highest modulation orders of the same symbol rate are not identical due to the various system responses. The maximum data rate

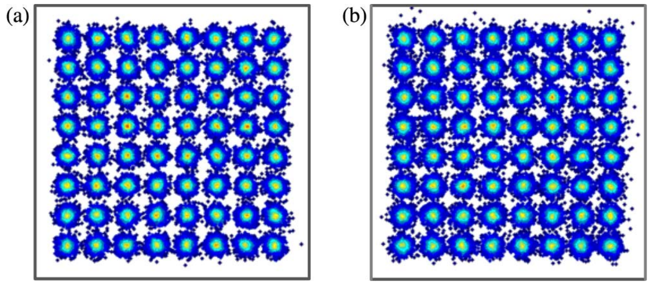

Fig. 4. The constellation diagrams of the 64-CAP signals with pre-emphasis at symbol rate of (a) 220 MBaud and (b) 230 MBaud.

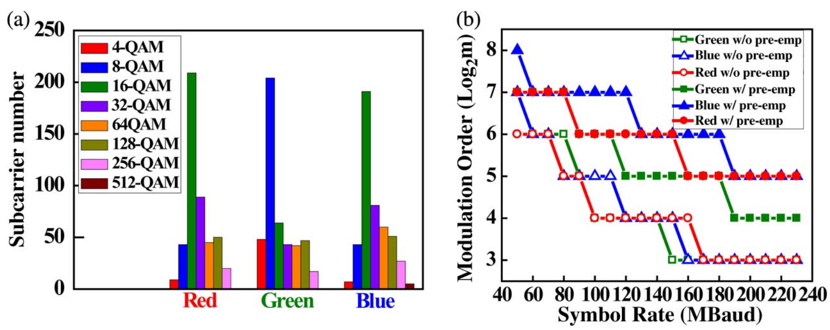

Fig. 5. The modulation orders of each chip for the WDM case. (a) The subcarrier histogram of modulation orders for the OFDM signals and (b) the highest modulation order as a function of symbol rate without and with pre-emphasis for CAP signals.

with pre-emphasis for the red chip and green chip are 1.15 Gb/s of 230-MBaud 32-CAP and 0.92 Gb/s of 230-MBaud 4-CAP, respectively. Notably, the maximum data rate of the blue chip is reached at the symbol rate of 220 MBaud, instead of 230 MBaud, because 230-MBaud 64-CAP signals cannot reach the BER of 10^{-3}. Fig. 4(a) and (b) shows the constellation diagrams of the 220-MBaud and 230-MBaud 64-CAP signals employing blue chip, and the BERs for the two different symbol rate are 9.11×10^{-4} and 1.7×10^{-3}, respectively.

As the WDM technique is applied to further increase the capacity, the AC driving signal of each chip is turned on simultaneously without changing the bias currents. Similar to Fig. 3(a), Fig. 5(a) shows the histogram of modulation orders of OFDM subcarriers after applying the WDM technique, and it is similar to that of the single-channel case. Due to the AC interference from adjacent channels, the maximum data rates of 1.01 Gb/s, 0.87 Gb/s, and 1.05 Gb/s for the red, green and blue chips, respectively, are slightly lower than those in the single-channel case. In addition, the highest modulation orders of the CAP signals with the WDM technique are also exhibited in Fig. 5(b). In this case, the highest achievable modulation orders are also improved by more than one order by pre-emphasis. The maximum data rates with pre-emphasis for the red, green and blue chips are 1.15 Gb/s, 0.92 Gb/s, and 1.15 Gb/s, respectively, and all of them are accomplished at the symbol rate of 230 MBaud. As a consequence, the aggregate data rates of the OFDM signals and CAP signals are 2.93 Gb/s and 3.22 Gb/s, respectively. Compared with the OFDM signals with bit- and power-loading, the CAP signals with pre-emphasis provide slightly more capacity of 0.29 Gb/s.

Table 1 summarizes the maximum data rates of the CAP and the OFDM signals in the single-channel and the WDM cases, and the overhead of CP has been deducted from the data rates of the OFDM signals. The measured BERs at the corresponding data rates are also summarized in Table 1. Since the bit- and power-loading algorithm is applied to maximize the capacities of the OFDM signals, the measured BERs are close to the set BER limit of 10^{-3}. Hence, for all the chips, the OFDM signals have $2 \sim 3\%$ capacity reduction caused by the AC interference from adjacent channels. Furthermore, the CAP signals with fixed modulation orders may even have the BERs of

TABLE 1

The maximum data rate of each chip

	Single-channel case				WDM case			
	CAP		OFDM		CAP		OFDM	
	Data rate	BER	Data rate	BER	Data rate	BER	Data rate	BER
Red w/o pre-emphasis	0.69 Gbps (8-CAP)	2.84×10^{-4}	-	-	0.69 Gbps (8-CAP)	3.27×10^{-4}	-	-
Green w/o pre-emphasis	0.69 Gbps (8-CAP)	3.12×10^{-4}	-	-	0.69 Gbps (8-CAP)	3.19×10^{-4}	-	-
Blue w/o pre-emphasis	0.69 Gbps (8-CAP)	3.12×10^{-4}	-	-	0.69 Gbps (8-CAP)	8.75×10^{-4}	-	-
Red w/ pre-emphasis or bit- and power-loading	1.15 Gbps (32-CAP)	2.25×10^{-4}	1.04 Gbps	9.96×10^{-4}	1.15 Gbps (32-CAP)	3.29×10^{-4}	1.01 Gbps	9.33×10^{-4}
Green w/ pre-emphasis or bit- and power-loading	0.92 Gbps (16-CAP)	9.89×10^{-5}	0.89 Gbps	9.11×10^{-4}	0.92 Gbps (16-CAP)	3.17×10^{-4}	0.87 Gbps	9.13×10^{-4}
Blue w/ pre-emphasis or bit- and power-loading	1.32 Gbps (64-CAP)	8.68×10^{-4}	1.08 Gbps	9.04×10^{-4}	1.15 Gbps (32-CAP)	2.54×10^{-4}	1.05 Gbps	9.98×10^{-4}
Maximum aggregate data rate	-	-	-	-	3.22 Gbps	-	2.93 Gbps	-

as low as 10^{-4}. The AC interference from adjacent channels does not increase the BERs to $>10^{-3}$ for the red and green chips, and therefore, their capacities in the single-channel and the WDM cases are identical. Nonetheless, for the blue chip, the CAP signal of the maximum capacity in the single-channel case cannot reach the FEC limit with the additional AC interference, which results in 12.9% capacity reduction in the WDM case. Accordingly, the total capacity difference is about 5% between two cases for the CAP signals. Notably, the similarity between the single-channel case and WDM case indicates that the AC interference from the adjacent channels is limited, and this is because of the wide LED spectral bandwidth compared with the modulation bandwidth.

4. Conclusion

In this paper, the performances of the OFDM and CAP signals are compared in the VLC system based on a single commercially available RGB-type LED. For the OFDM signals, the bit- and power-loading techniques are used to achieve higher capacity of the uneven-frequency-response LED-based VLC system. To reach the BER of less than 10^{-3}, OFDM signals demonstrate the maximum single-channel data rates of 1.08 Gb/s employing the blue chip. For the CAP signals, the pre-emphasis and DFE are used to reduce the serious ISI due to the uneven system response, and the single-channel data rate of 1.32 Gb/s is achieved via the blue chip. Moreover, in order to enhance the data rates of the limited-bandwidth LED, the WDM scheme is also applied to further increase the capacity. After individually optimizing the driving signals of the RGB chips, the maximum aggregate data rates of the OFDM and the CAP signals are 2.93 Gb/s and 3.22 Gb/s, respectively, in our WDM VLC system. Hence, compared with OFDM, the CAP scheme is an alternative candidate with competitive performance for next generation optical wireless networks.

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