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Fang-Ming Wu, Chun-Ting Lin, Chia-Chien Wei, Cheng-Wei Chen ...+2 more authors

Institutions: National Chiao Tung University, National Sun Yat-sen University

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1.1-Gb/s White-LED-Based Visible Light Communication Employing Carrier-Less Amplitude and Phase Modulation

Fang-Ming Wu, Chun-Ting Lin, Chia-Chien Wei, Cheng-Wei Chen, Hou-Tzu Huang, and Chun-Hung Ho

***Abstract*— We demonstrate 1.1-Gb/s visible light communication (VLC) employing carrier-less amplitude and phase modulation (CAP) and a commercially available phosphorescent white light emitting diode (LED). Optical blue filtering, pre-compensation, and decision feedback equalization are used to compensate the frequency response of the phosphor-based white LED. Various modulation orders of CAP signals are investigated to maximize the capacity of the VLC system. The record data rate of 1.1 Gb/s with the bit error rate performance below the FEC limit of 10^{-3} is successfully achieved > 23-cm air-transmission via a 220-MBaud 32-CAP signal.**

***Index Terms*— Blue filter, carrier-less amplitude and phase modulation (CAP), decision feedback equalizer, visible light communication, white light emitting diode (LED).**

I. Introduction

White light emitting diodes (LEDs) have attracted lots of attention for next generation illumination due to advantages such as long lifetime, high efficiency, cost effectiveness, small size and low power consumption, compared with incandescent or fluorescent lamp. Hence, LEDs have been widely used in traffic application, flat panel displays, and illumination application. To add the value to LED illumination, visible light communications (VLC) with white LEDs have attracted considerable interests in next generation short range wireless access because of the advantages of worldwide availability, high security, immunity to radio frequency interference, unlicensed spectrum, and spatial reuse of the modulation bandwidth in adjacent communication cells [1]–[3].

White LEDs can be categorized into two main types: red-green-blue (RGB) emitters and phosphor-based emitters. Compared with the RGB LED, the phosphor-based white LED is more attractive for illumination application due to its lower complexity. However, the intrinsic modulation bandwidth of typical phosphor-based white LED is limited to the several MHz range owing to the slow relaxation time of the phosphor [4], [5]. Therefore, a blue filter was adopted to filter out phosphorescent light, and 40-Mbps on-off keying (OOK) signal was implemented [3]. Furthermore, analog equalization was utilized to compensate for the insufficient frequency response and to accomplish 100-Mbps OOK [5].

To realize a higher transmission capacity, spectrally efficient modulation formats with digital signal processing (DSP) technology have been proposed [6], [7]. For instance, quadrature-amplitude-modulation (QAM) with discrete multi-tones (DMT) technology, bit- and power-loading, and symmetrical clipping were used to achieve the data rate of 513 Mbps [6]. However, the highly spectrally efficient single carrier (SC) transmission has not yet been addressed in VLC systems [8].

In this letter, we propose the VLC system employing carrier-less amplitude and phase modulation (CAP) [9], [10] and a commercially-available phosphor-based white LED. The CAP modulation is the vibrational scheme of QAM for single carrier systems. Using CAP modulation, two orthogonal signals do not need overhead and carrier. Moreover, pre-compensation, optical blue filtering, and decision feedback equalization (DFE) are carried out to improve the frequency response of the white LED. Various m-CAP signals with $\log_2 m$bit/symbol are investigated to maximize the capacity of the VLC system. The recode data rate of up to 1.1 Gbps over the 23-cm VLC system is successfully demonstrated via a 220-MBaud 32-CAP signal with the BER of $<10^{-3}$.

II. Principle of the CAP Transceiver System

Since a directly-modulated LED is an intensity modulator, complex vector signals, such as QAM, must be up-converted to an RF frequency at the transmitter in the traditional scheme [10]. However, it is not ideal for direct-detection systems with very limited bandwidth, such as VLC systems. Alternatively, spectrally-efficient CAP is closely related to the well-known QAM, and they have the same spectral characteristics and theoretical performance [11]. The CAP modulation, however, is carrier-less, and as a consequence, it is more suitable for a band-limited intensity-modulated SC system. The block diagram of the digital CAP transmitter is shown in Fig. 1(a). The bit stream $s[n]$ is passed through an encoder, and mapped into two uncorrelated multi-level digital data, $i[n]$ and $q[n]$, which denote the in-phase and the quadrature signals, respectively.

After the encoder, the signals are fed into the in-phase and quadrature shaping filters, respectively. The subtraction of two

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F.-M. Wu, C.-T. Lin, C.-W. Chen, H.-T. Huang, and C.-H. Ho are with the Institute of Photonic System, National Chiao Tung University, Tainan City 71150, Taiwan (e-mail: ming.eo97g@nctu.ed.tw; jinting@mail.nctu.edu.tw; deslucifers@gmail.com; whang.kurt@gmail.com; cunhonho@gmail.com).

C.-C. Wei is with the Department of Photonics, National Sun Yat-Sen University, Kaohsiung City 80424, Taiwan (e-mail: ccwei@mail.nsysu.edu.tw).

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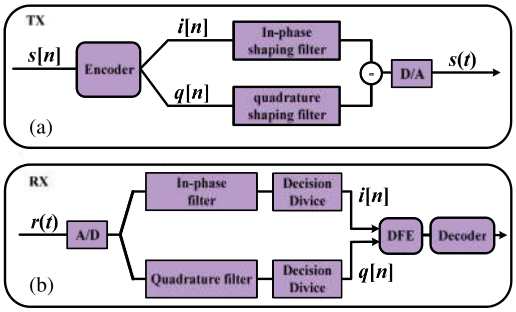

Fig. 1. Block diagrams of the CAP transceiver. (a) CAP modulation and transmitter. (b) CAP receiver and demodulation.

filtered digital signals is then fed into the digital-to-analog converter (DAC). The output CAP signal can be represented as

$$s(t) = \sum_{n=-\infty}^{\infty} i[n] \cdot f(t-nT) - q[n] \cdot \tilde{f}(t-nT) \quad (1)$$

where T indicates the symbol duration, and $f(t)$ and $\tilde{f}(t)$, which are a Hilbert transform pair, are the analog impulse responses of the shaping filters after the DAC. Without considering noise for simplicity, the received signal is

$$r(t) = s(t) \otimes h(t) = \sum_{n=-\infty}^{\infty} i[n] \cdot \rho(t-nT) - q[n] \cdot \tilde{\rho}(t-nT) \quad (2)$$

where $h(t)$ is the channel response, $\otimes$ denotes the convolution, and $\rho(t) = f(t) \otimes h(t)$ and $\tilde{\rho}(t) = \tilde{f}(t) \otimes h(t)$ denote the whole responses in front of the receiver. Notably, $\rho(t)$ and $\tilde{\rho}(t)$ are still a Hilbert transform pair.

As shown in Fig. 1(b), the block diagram of the CAP receiver includes an analog to digital converter (ADC) and a parallel arrangement of Hilbert-pair filters. If the sampling rate of the ADC is sufficient to avoid aliasing, one could reverse the sequence of the ADC and the adaptive filters mathematically, i.e. the parallel analog adaptive filters followed by the ADC, to result in the same outputs. Hence, the receiving filters are assumed to be analog to simplify the explanation. After the Hilbert-pair adaptive filters with the impulse responses of $f^*(t)$ and $\tilde{f}^*(t)$, which are the complex conjugates of $f(t)$ and $\tilde{f}(t)$, the received signals can be written as

$$r_i(t) = \sum_{n=-\infty}^{\infty} i[n] \cdot \gamma(t-nT) - q[n] \cdot \tilde{\gamma}(t-nT)$$
$$r_q(t) = \sum_{n=-\infty}^{\infty} i[n] \cdot \tilde{\gamma}(t-nT) + q[n] \cdot \gamma(t-nT) \quad (3)$$

where $\gamma(t) = \rho(t) \otimes f^*(t) = -\tilde{\rho}(t) \otimes \tilde{f}^*(t)$ and $\tilde{\gamma}(t) = \tilde{\rho}(t) \otimes f^*(t) = \rho(t) \otimes \tilde{f}^*(t)$ are the impulse responses of the CAP transmission system including the transmitter filters, channel response and the receiver adaptive filters.

Considering an ideal flat channel resulting in $\gamma(t) = f(t) \otimes f^*(t)$ and $\tilde{\gamma}(t) = \tilde{f}(t) \otimes f^*(t)$, the design principle of $f(t)$ is such that $r_i[n] = i[n]$ and $r_q[n] = q[n]$, where $r_i[n]$ and $r_q[n]$ are the sampled received signals. Therefore, $\gamma(0) = 1$ and $\gamma(nT) = 0$ as $n \neq 0$ are required to eliminate inter-symbol interference, and $\tilde{\gamma}(nT) = 0$ for all n is needed to separate the in-phase and the quadrature signals. An ideal candidate of the shaping filter is the square root raised cosine filter (SRRF):

$$f(t) = \frac{T}{\pi t}\left\{\sin\left[\frac{\pi t}{T}(1-\alpha)\right] + \frac{4\alpha t}{T}\cos\left[\frac{\pi t}{T}(1-\alpha)\right]\right\} \times \left[1 - \left(\frac{4\alpha t}{T}\right)^2\right]^{-1} \quad (4)$$

where α is the roll-off parameter. However, the ideal shaping filter is non-causal, and the response must be truncated at the price of non-zero interference. Hence, DFE is applied to decrease the interference and the noise enhancement.

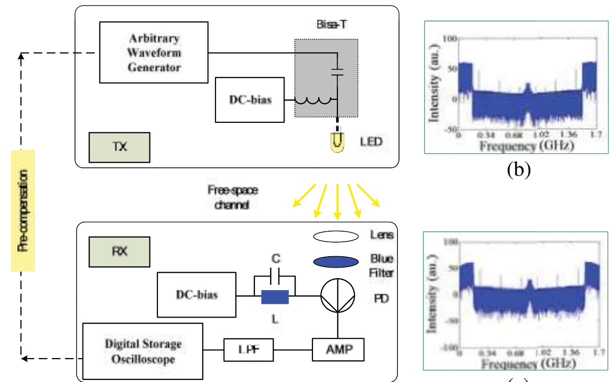

Fig. 2. (a) Experimental setup for the VLC system and the electrical spectra of 170-MBaud CAP signal (b) without the pre-compensation and (c) with pre-compensation.

III. Experimental Setup

Fig. 2(a) shows the experimental setup of the VLC system. The CAP signal is generated by an arbitrary waveform generator (AWG) with an off-line Matlab program [10]. The roll-off parameter is set to zero. The sampling rate and the DAC resolution are 1 GSample/s and 8 bit, respectively. A phosphorescent white LED module (OSTAR LE CWE3B) is adopted as the VLC transmitter. This LED consists of six chips, and the viewing angle is 130° (full opening angle at 50% maximum intensity). The separating distance between the transmitter and receiver is 23 cm.

The optical focusing lens and the blue filter are employed to improve the received power and the frequency response, respectively. A silicon PIN photo- detector (Hamamatsu S10786) is used to detect the optical signal with 3-dB bandwidth 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 CAP signal is captured by the digital storage oscilloscope with the 20-GSample/s sample rate, 8-bits ADC resolution, and 3-dB bandwidth of 16 GHz. The off-line DSP program is applied to demodulate the CAP signal, including synchronization, CAP demodulation, and DFE [10]. The error count is utilized for the bit error rate (BER) measurement.

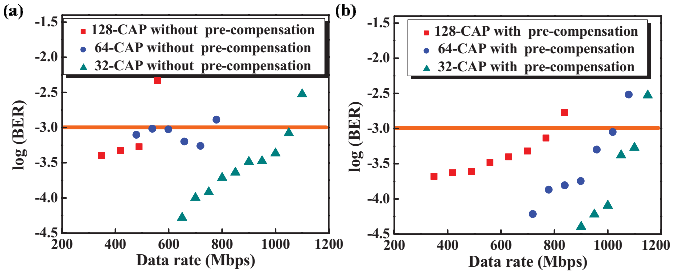

Fig. 3. BERs with various data rates (a) without and (b) with precompensation.

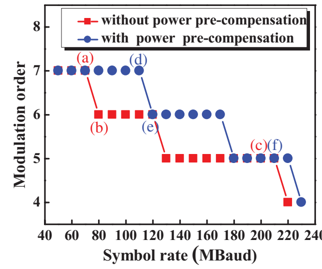

Fig. 4. Maximum modulation order as a function of symbol rate and the constellation diagrams under the individual maximum symbol rates.

In this letter, the symbol rates of the CAP signals are investigated from 50-MBaud to 230-MBaud, and different modulation orders of 5, 6, and 7 bit/Symbol (i.e. 32-CAP, 64-CAP and 128-CAP, respectively) are examined. To compensate for the frequency response, the pre-compensation via a finite impulse response (FIR) filter is applied based on the criterion that the whole frequency response of the system is roughly even such that the system performance is optimized. Figures 2(b) and 2(c) show the electrical spectra of 170-MBaud CAP signals with and without pre-compensation before transmission, respectively.

IV. Experimental Result and Discussion

Figure 3(a) and (b) show the BERs of the 128-CAP, 64-CAP and 32-CAP signals without and with pre-compensation at the symbol rate within 50 MBaud and 230 MBaud. Without pre-compensation, the maximum date rates with the BER performance below the FEC limit of 10^{-3} of 128-CAP, 64-CAP and 32-CAP are 490 Mbps, 720 Mbps, and 1050 Mbps, respectively. Notably, the fluctuation of 64-CAP BERs around 500 Mbps is mainly caused by the uneven frequency response of our electrical transmitter at 80∼90 MHz. Furthermore, in order to increase the data rate, pre compensation is used to improve the frequency response of the white LED. To achieve the BER of $< 10^{-3}$, the highest data rates of this work are 770 Mbps, 1.02 Gbps and 1.1 Gbps for 128-CAP, 64-CAP and 32-CAP signals, respectively.

In accordance with Fig. 3, Fig. 4 exhibits the maximum modulation orders of the CAP signal to achieve the BER below the FEC limit of 10^{-3} at different symbol rates. Without pre-compensation, the maximum symbol rates of 128-CAP, 64-CAP, and 32-CAP signals are 70 MBaud, 120 MBaud, and 210 MBaud, respectively. After applying the pre-compensation, the maximum symbol rates of the 128-CAP, 64-CAP and 32-CAP signals can be increased to 110 MBaud, 170 MBaud and 220 MBaud, respectively. While the CAP signals with higher modulation orders require higher signal-to-noise ratio to achieve the FEC limit and are operated at lower symbol rates, their maximum symbol rates can be improved more by pre-compensation. Hence, the 128-CAP and 64-CAP signals shows 57% and 42% improvement of the maximum symbol rates by applying pre-compensation, respectively, but only 4.8% improvement can be obtained for the 32-CAP signal.

V. Conclusion

In this letter, we experimentally demonstrate a VLC system based on the CAP modulation with a commercially-available phosphorescent white LED. Optical blue filter, pre-compensation, and DFE are utilized to improve the frequency response of the VLC system. The maximum symbol rates to achieve the BER of $< 10^{-3}$ are measured under different modulation orders, and they are 110-MBaud, 170-MBaud and 220-MBaud for 128-CAP, 64-CAP and 32-CAP signals, respectively. In addition, the record data rate of 1.1 Gbps is successfully demonstrated.

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