Experimental demonstration of high-speed WDM VLC systems employing high-order CAP modulation

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***Abstract*—Inter-symbol interference (ISI) and the light emitting diode (LED) nonlinearity are considered the key problems that seriously deteriorate the system performance in high-speed VLC systems. In this paper, we report three experimental demonstrations of high-speed WDM VLC systems based on RGB LED and carrierless amplitude and phase (CAP) modulation employing advanced pre-equalization and post-equalization technology. In the system based on 3-band CAP64 modulation with weighted pre-equalization and modified cascaded multi-modulus algorithm (M-CMMA) based post-equalization, the total data rate of 1.35 Gb/s over 30-cm transmission is successfully achieved with the BER under 7% FEC limit of 3.8e-3. In the system employing CAP64 and recursive least square (RLS) based adaptive equalization, an aggregate data rate of 4.5Gb/s is successfully achieved over 1.5-m indoor free space transmission with the BER below 3.8e-3. Furthermore, in the system employing Volterra series based nonlinear equalizer, an aggregate data rate of 4.5Gb/s is successfully achieved over 2-m indoor free space transmission with the BER less than 3.8e-3. The results show the benefit and feasibility of CAP modulation in high-speed and short range multi-user VLC systems.**

Keywords—visible light communication; LED; CAP modulation; equalization; M-CMMA; RLS; Volterra series

I. Introduction

Nowadays visible light communication (VLC) using light emitting diodes (LEDs) has become a promising and attracting technology for wireless communication as LEDs are considered to be a major candidate for future illumination [1]. VLC as an emerging wireless optical communications technology, combines lighting and communications, and has many advantages, such as license-free, high-speed, immunity to electromagnetic radiation, good confidentiality and high security. White-light LED, including blue LED in combination with a phosphor, and red-green-blue (RGB) LED, is usually used in VLC system as the light source. Compared with phosphor LEDs, RGB LEDs have higher modulation bandwidth, which makes they are more suitable for high-speed VLC systems. In addition, the three wavelengths of an RGB LED can individually carry different data streams, so it can combine with the wavelength division multiplexing (WDM) technology to greatly increase the transmission data rate.

Due to the limited spectrum bandwidth of LED, it's difficult to realize high-speed transmission in VLC system. In order to achieve high-speed transmission in VLC systems, the advanced high-order modulation techniques are generally used to code and modulate the original data. Carrierless amplitude and phase (CAP) modulation is one of the most promising modulation techniques, which has a lot of advantages, such as, simple structure and low computational complexity [2]. Due to these characteristics, CAP modulation has attracted great interest of researchers, and some outstanding achievements in high-speed VLC systems have been reported. In [3], Wu et al. have presented a VLC system based on CAP32 modulation at the data rate of 1.1Gb/s at the transmission distance of 23cm. By employing RGB-LED and CAP modulation, a 3.22-Gb/s WDM VLC system at the transmission distance of 25cm has been experimentally demonstrated in [4]. However, the transmission distances of these VLC systems are too short so that it is not available for practical applications. In order to improve the system performance and increase the transmission distance, the inter-symbol interference (ISI) and the LED nonlinearity et al. should be taken into consideration. In this respect, researchers propose a series of equalization methods, such as decision feedback equalization (DFE) [4], training symbol [5], and decision-directed least mean square (DD-LMS) [6] to eliminate ISI. However, the LED nonlinearity is not considered in these reports.

In this paper, our research group has proposed some new methods to mitigate ISI and the LED nonlinearity. Firstly, we experimentally demonstrate a high-speed WDM VLC system based on multi-band CAP64 with weighted pre-equalization and modified cascaded multi-modulus algorithm (M-CMMA) based post-equalization, and the total data rate of 1.35 Gb/s over 30-cm transmission is successfully achieved with the bit error rate (BER) less than 3.8e-3 [7]. Secondly, a high-speed WDM CAP64 VLC system employing RLS based adaptive equalization is experimentally demonstrated. We successfully achieved an aggregate data rate of 4.5Gb/s (1.5Gb/s per wavelength) over 1.5-m indoor free space transmission with the BER below 3.8e-3 [8]. Finally, a high speed WDM CAP64 VLC system employing Volterra series based nonlinear equalizer to mitigate the LED nonlinearity is experimentally demonstrated at an aggregate data rate of 4.5Gb/s over 2-m indoor free space transmission [9].

II. Principle

In this section, we will briefly introduce the principle of CAP modulation and demodulation, and the schematic diagram of CAP modem is shown in Fig. 1(a). At the transmitter, the

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original data bit stream is generated and inputted to an encoder for high-order coding, such as QAM64. Then, the coded signals are up sampled to achieve the periodic extension of spectrum. After up-sampling, two orthogonal filters called Hilbert filter pair, consisting of square-root raised-cosine pulse and cosine/sine function, are used to generate I/Q signals. Subsequently, the outputs of these two filters are subtracted through a summation meter. The final output CAP signal can be expressed as:

$$s(t) = \sum_{n=-\infty}^{\infty} [a_n P_1(t - nT) - b_n P_2(t - nT)] \quad (1)$$

$$P_1(t) = g(t)\cos(2\pi f_c t) \quad P_2(t) = g(t)\sin(2\pi f_c t) \quad (2)$$

Wherein, $P_1(t)$ and $P_2(t)$ are the Hilbert transform pairs, a_n and b_n are digital signals. $g(t)$ is a baseband pulse signal. Center frequency f_c is set to be greater than the maximum frequency components of $g(t)$.

The direct detection is usually used at the receiver. Firstly, the received signal is split into two paths and imported to two filters that match the Hilbert filters at the transmitter, in order to make the separation of the in-phase and quadrature components. Thereafter, the filter output signal is down-sampled and processed by a post-equalizer to reduce the attenuation and distortion brought in the transmission. Finally, the original transmitted data can be recovered through a decoder.

Compared with traditional QAM modulation and OFDM modulation, CAP modulation uses two orthogonal filters to generate I/Q signals. Therefore, it doesn't require modulation of the electrical or optical complex-to-real-value conversion, making it easier to implement, more convenient, and more flexible. Meanwhile, compared with OFDM modulation, CAP modulation doesn't need to use the discrete Fourier transform (DFT), which greatly reduces the computational complexity and the structure of system [2].

However, the inter-symbol interference (ISI) and the LED nonlinearity seriously deteriorate the system performance in high-speed VLC systems. The ISI is mainly induced by limited modulation bandwidth, while the nonlinearity is caused by the nonlinear relationship between the LED forward current and the bias voltage. The nonlinear characteristic of the red chip of the RGB LED's V-I curve are shown in the red line in Fig.2, while the linearized curve is the green dash line. The LED has a turn on voltage (TOV), which is about 1.85V. The LED is considered as cut-off and can't conduct current when the input voltage is smaller than TOV. So a DC bias is applied to make that the input signal works in operation region. However, when the input voltage becomes larger, the signal may work in the nonlinear region and performs strong nonlinear effects. Besides, the maximum permissible current of LED will limit the maximum magnitude of the input signal.

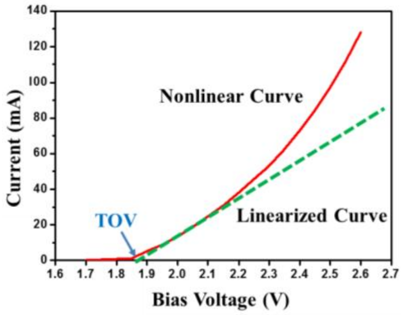

Fig. 2 Nonlinear and linearized LED transfer characteristic curve of the red chip of the RGB LED.

III. EXPERIMENTAL SETUP

Fig. 1(b) shows the experimental setup of the WDM CAP64 VLC system. At the transmitter, the original bit sequence is firstly mapped into complex symbols for 64QAM. After up-sampling, the QAM signals are sent for CAP modulation. Namely, the in-phase and quadrature components are sent into

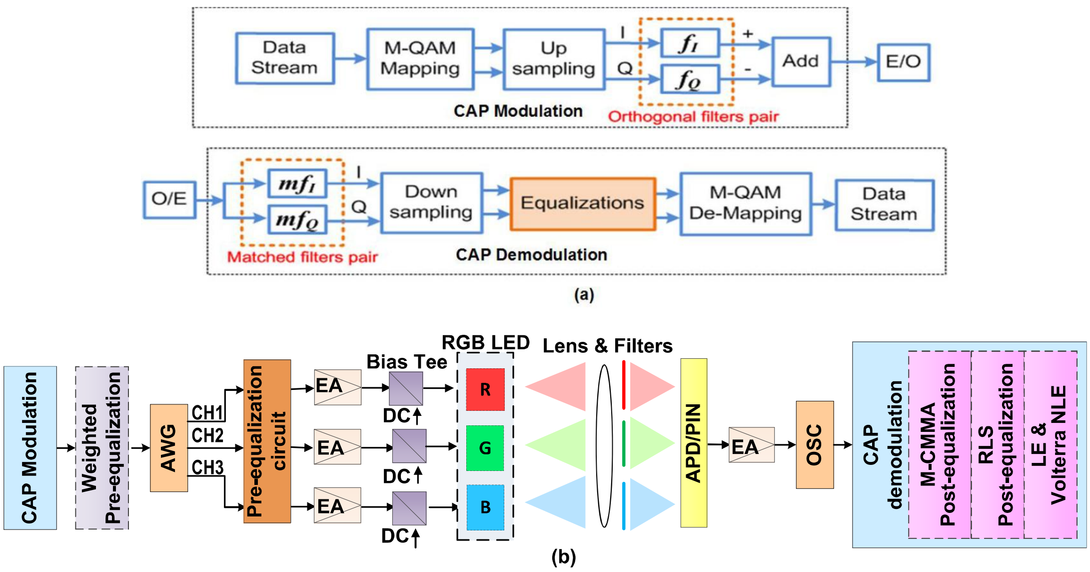

Fig. 1. (a) the schematic diagram of CAP modem, (b) the experimental setup of the WDM VLC system based on CAP64

the shaping filters pair $f_I(t)$ and $f_Q(t)$, respectively. We set 0.02 as the roll-off coefficient of the square-root raised-cosine function for CAP modulation to achieve a high spectral efficiency. In this experiment, a Tektronix AWG 7122C is used to generate the CAP signals applied to the three color chips of the RGB LED. The AWG 7122C have 2 independent outputs, so the output of channel 1 is used for the red chip, while the output of channel 2 and its inverted copy are respectively used for green and blue chip.

In the multi-band CAP experiment, 3 CAP sub-bands are located on the different center frequencies of 15MHz, 45MHz, and 75MHz by using different shaping filter pairs. The bandwidth of each sub-band is 25MHz. While, in the VLC system employing RLS equalization or Volterra equalization, the modulation bandwidth of each color chip is set at 250MHz. After amplified by an electrical amplifier (EA, Mini-circuits, 25-dB gain), the electrical signal and DC-bias voltage are combined by a bias tee, and then applied to the three color chips of the RGB LED respectively. A commercial RGB LED (CREE PLCC Multichip LED, output power: 1W, red: 620nm, green: 520nm, blue: 470nm) is used as the transmitter for WDM. In order to achieve longer transmission distance, a reflection cup with 60° divergence angle is used for the RGB LED to decrease the beam angle of the LED. Lens (100-mm focus length) and R/G/B filters are used in free space transmission to focus light and filter out different colors.

In order to compensate the frequency attenuation at high frequency component, the pre-equalization technologies are used at the transmitter. In our multi-band CAP system, we propose and use weighted pre-equalization scheme to compensate the frequency attenuation and optimize the performances of all the sub-bands. Firstly, the nth sub-band CAP signal is converted to frequency domain and multiplied by the reciprocal of the transfer function of each sub-band $H_n(k)$ to compensate frequency attenuation. Then, the pre-equalized CAP sub-band signal is multiplied by a weighted coefficient A_n to accurately adjust and optimize the performance of each sub-band. The nth sub-band CAP signal after weighted pre-equalization can be expressed as [7]:

$$S_n'(k) = A_n \cdot S_n(k) H_n^{-1}(k) \tag{3}$$

$S_n(k)$ and $S_n'(k)$ are the nth sub-band CAP signal in frequency domain before and after weighted pre-equalization. While, in another two systems, the generated CAP signal is pre-amplified by a self-designed bridged-T based hardware pre-equalizer [10].

At the receiver, a commercially available PIN photodiode (Hamamatsu 10784) or avalanche photodiode (Hamamatsu APD, 0.42 A/W sensitivity at 620 nm and gain =1, the maximum gain is 30) is used as the receiver. Then, the output of the receiver is amplified by an EA and recorded by a digital storage oscilloscope (Agilent DSO54855A) for further offline demodulation and signal processing. Firstly, the received signal is fed into a matched filters pair $m_I(t)$ and $m_Q(t)$ for CAP demodulation. Subsequently, the post-equalization is employed to eliminate the ISI or mitigate the LED nonlinear effect. Finally, through the QAM decoder, the original bit sequence is recovered.

In this paper, we propose and use the three post-equalization technologies in the VLC WDM systems for the first time. We introduce the M-CMMA in multi-band CAP system, which calculates both the errors of the real and imaginary components to update the coefficients of the transfer function for the IQ components individually. Furthermore, we employ the post-equalizer based on RLS algorithm at the receiver. The principle of RLS algorithm is that it recursively finds the filter coefficients to minimize a weighted linear least square cost function related to the input signals [11]. Compared to M-CMMA, RLS algorithm has quicker convergence so that the number of training sequence can be greatly reduced, and the computation complexity is much lower. We only use 1000 training symbols and 35 taps to update and converge the filter weights in the system, which can obtain good equalization performance. Moreover, the Volterra series based nonlinear equalizer is used to mitigate the LED nonlinearity. The Volterra series expansion contains of two parts: a linear term utilized for linear equalizer and nonlinear series including multi-order term. Usually, only the second order term is taken into consideration as a tradeoff between computation complexity and equalization performance, and the higher order terms are neglected. So the output of the equalizer is expressed as [9]:

$$\begin{aligned} y(n) &= y_l(n) + y_{nl}(n) \\ &= \sum_{i=0}^{N-1} w_i(n) x(n-i) \\ &\quad + \sum_{K=0}^{NL-1} \sum_{i=k}^{NL-1} w_{kl}(n) x(n-k) x(n-l) \end{aligned} \tag{4}$$

Wherein, $y_l(n)$ is the output of the linear equalizer and $y_{nl}(n)$ is the output of the nonlinear equalizer. N and NL are the tap numbers of the linear and the nonlinear equalizer respectively. $w_i(n)$ and $w_{kl}(n)$ are the weights of the linear and nonlinear equalizer. The optimal tap numbers of the linear and the nonlinear equalizer are respectively 45 and 25 in our system. After the Volterra nonlinear equalizer, we use the M-CMMA algorithm to calculate the error function and update the weights of both the linear and the nonlinear equalizer.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. WDM multi-band CAP64 VLC system employing weighted pre-equalization and M-CMMA based post-equalization

First of all, we investigate the bias voltages and input power of the three LED chips to find the optimal working condition of LED. According to the measurements, the optimal bias voltages of red, green and blue chip are 2.2V, 4.0V and 3.8V, respectively, and the optimal input power of all the three color chips is 11dBm. At this condition, the BER performances versus different distances of the three color chips with weighted pre-equalization and M-CMMA equalization are measured and shown in Fig. 3(a)-(c). The bandwidth of each CAP64 signal is 25MHz, so the data rate of each sub-band and each color chip (3 sub-bands) is 150Mb/s and 450Mb/s, respectively. Finally, the aggregate data rate of the multi-band CAP system can reach to 1.35Gb/s. We can find that all the sub-bands can meet the BER threshold at the distance of 30cm. Therefore the system can achieve the total data rate of 1.35Gb/s with the BER below 3.8e-3.

In addition, the insets in Fig. 3(a)-(c) show the electrical spectra of the three color chips before and after weighted pre-equalization. It can be observed that all the three colors of RGB LED suffer from the large attenuation at the high frequency component. While, after using weighted pre-equalization to compensate the frequency attenuation, the electrical spectra of the three color chips becomes more flat. That is, the frequency attenuations of all the sub-bands have been compensated, and each sub-band obtains its own optimal performances.

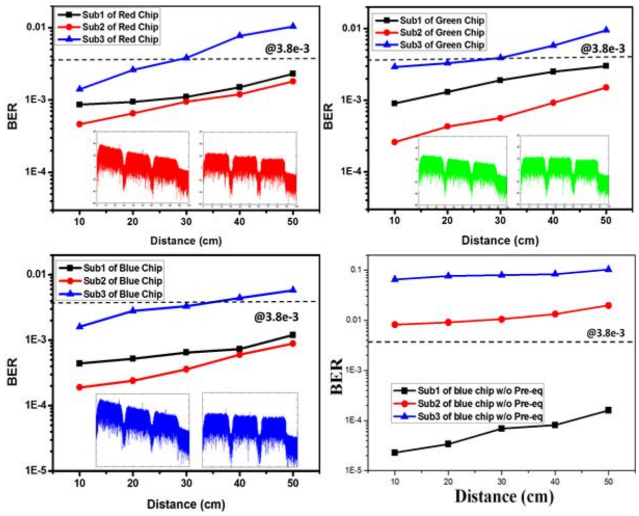

Fig. 3. The measured BER versus different distances with weighted pre-equalization of (a) red chip, (b) green chip, (c) blue chip; (d) the BER performance of blue chip without weighted pre-equalization

We also measure the BER performance versus different distances of blue chip without weighted pre-equalization, as shown in Fig. 3(d), to further compare the performance of system with/without pre-equalizations. As we can see, the BER performances without employing weighted pre-equalization become much worse in the second and the third sub-band, and they cannot meet the BER requirement in this system.

B. WDM CAP64 VLC system employing RLS based adaptive equalization

Firstly, the bias voltages and input signal peak-to-peak value (Vpp) of the RGB LED are measured to find the optimal working condition of LED. The contour map for measured BER performance of the three color chips versus bias voltages and input signal Vpp is shown in Fig. 4(a)-(c). It can be found that the optimal working point of the red, green and blue chip is at (2.4V bias voltage, 0.9V input signal Vpp), (4.1V, 0.55V) and (4.1V, 0.5V), respectively. We also draw the constellations of CAP64 signal applied to the three color chips at the optimum operating point, as shown in Fig. 4(d).

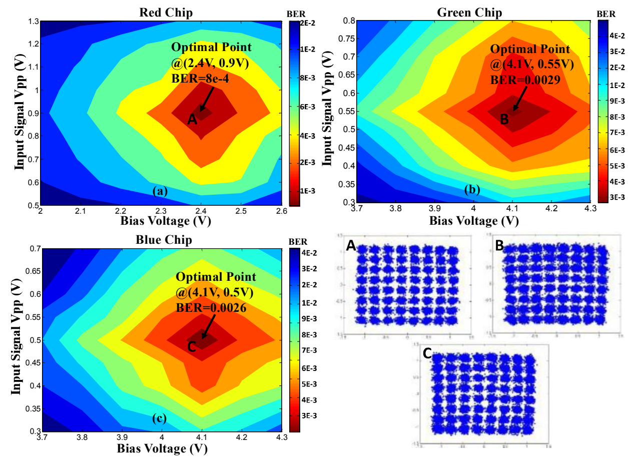

Fig. 4. The contour map for measured BER versus different bias voltages and input signal Vpp of (a) the red chip, (b) the green chip, (c) the blue chip; (d) constellation at the optimal working point

The BER performance versus different transmission distances employing RLS based equalization and M-CMMA based equalization are presented in Fig. 5(a) and 5(b), respectively. It can be found that the BER of the three color chips with RLS based equalization can below the 7% FEC limit of 3.8e-3 when the distance less than 1.5-m. In this system, 250-MHz 64QAM CAP signals are respectively applied to the three color chips, so the aggregate data rate of the WDM VLC system can reach to 4.5Gb/s (1.5Gb/s per wavelength) and it has been successfully achieved. We also measure the BER performance employing M-CMMA based equalization for comparison. As we can observe, the BER performances worsen in all the three color chips, and the BER of green and blue chip even cannot reach the 7% FEC threshold at 1.5-m distance. That shows RLS has better equalization performance than M-CMMA under the same conditions.

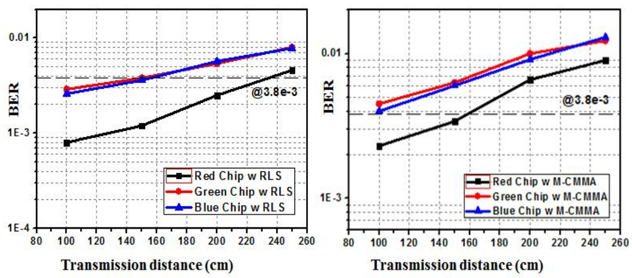

Fig. 5. The measured BER versus different transmission distance employing (a) RLS equalization, (b) M-CMMA equalization

C. WDM CAP64 VLC system employing Volterra series based nonlinear equalizer

The optimal working point of the RGB LED is the same as the above RLS based VLC system, and the aggregate data rate of the WDM VLC system is 4.5Gb/s. At the optimal working point, the aggregate data rate of 4.5Gb/s can be successfully achieved at the free space transmission distance of 2-m with the BERs of the three color chips all below 3.8e-3. Furthermore, in order to compare the contribution of different equalization technologies, we measure the Q factor versus transmission distance with Volterra combined with M-CMMA, M-CMMA and CMMA equalization respectively, as shown in Fig. 6. The measurements show that Volterra combined with M-CMMA can improve the Q factor of 1.5dB at the distance of 2-m, compared to M-CMMA. Moreover, it can greatly outperform CMMA by Q factor of 2.6dB.

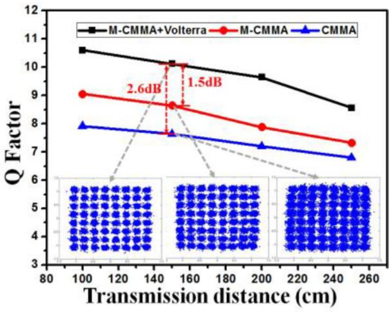

Fig. 6. The Q factor versus different transmission distance with M-CMMA + Volterra, M-CMMA and CMMA equalization

In the WDM systems, the multiple data streams are individually carried by the three wavelengths of an RGB LED, and each wavelength can provide several sub-bands. Therefore, with the combination of different wavelengths and sub-bands, the system can be assigned to multiple users in order to realize the multi-user access. For example, in the WDM multi-band CAP64 VLC system, it has three wavelengths, and each wavelength can provide 3 sub-bands. So this system can achieve a dynamic capacity for up to 9 users' access. Furthermore, with the increasing number of sub-bands, the number of system user access can also be greatly increased. Therefore, it can provide flexible user access and simpler system structure.

V. CONCLUSION

In this paper, we report three experimental demonstrations of high-speed WDM VLC systems employing RGB LED and high-order CAP modulation. In the system based on 3-band CAP64 modulation, we propose a weighted pre-equalization method to compensate frequency attenuation of the RGB LED at the transmitter, and employ M-CMMA based post-equalization at the receiver. The total data rate of 1.35 Gb/s over 30-cm transmission is successfully achieved with the BER under 7% FEC limit of 3.8e-3, and this system can achieve a dynamic capacity for up to 9 users access. In the system employing RLS based adaptive equalization, an aggregate data rate of 4.5Gb/s is successfully achieved over 1.5-m indoor free space transmission with the BER below 3.8e-3. Furthermore, in the system employing Volterra series based nonlinear equalizer, an aggregate data rate of 4.5Gb/s is successfully achieved over 2-m indoor free space transmission with the BER less than 3.8e-3. The results clearly demonstrate the benefit and feasibility of the CAP modulation with advanced pre-equalization and post-equalization technology for the high-speed and short range multi-user VLC systems.

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