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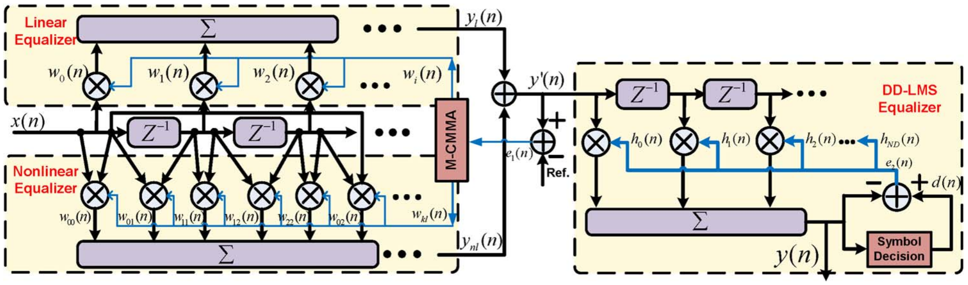

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8-Gb/s RGBY LED-Based WDM VLC System Employing High-Order CAP Modulation and Hybrid Post Equalizer

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Abstract: In this paper, for the first time, we propose the use of a hybrid post equalizer in a high-order carrierless-amplitude-and-phase-modulation-based visible light communication (VLC) system. The hybrid equalizer consists of a linear equalizer, a Volterra-series-based nonlinear equalizer, and a decision-directed least mean squares equalizer to simultaneously mitigate the linear and nonlinear distortions of the VLC system. A commercially available red–blue–green–yellow light-emitting diode (RBGY LED) is utilized for four-wavelength multiplexing. By the hybrid equalizer, an aggregate data rate of 8 Gb/s is experimentally achieved over a 1-m indoor free-space transmission with the bit error rate (BER) below the 7% forward error correction (FEC) limit of 3.8×10^{-3}. To the best of our knowledge, this is the highest data rate ever reported in high-speed VLC systems.

Index Terms: VLC, hybrid equalizer, CAP modulation.

1. Introduction

Recently, visible light communication (VLC) based on light emitting diodes (LEDs) has been considered as a promising technology for future wireless communication, since LEDs can be used for both illumination and data transmission simultaneously [1]. Compared to traditional wireless communication at radio frequency, VLC offers several advantages such as cost-effective, immunity to electromagnetic interference and larger modulation bandwidth. Therefore, a lot of investigations have been attracted for different VLC applications especially indoor high speed wireless access [2]–[4]. So far, the feasibility of multi-color LEDs and phosphor-based LEDs for VLC systems has been both experimentally demonstrated. Compared with phosphor-based LEDs, multi-color LEDs consisting of three or four color chips are more promising solutions to high-speed VLC systems as they allow the wavelength division multiplexing (WDM), which can greatly increase the transmission data rate.

To achieve high spectral efficiency, some advanced modulation formats have been demonstrated and utilized in high-speed VLC systems, such as carrier-less amplitude and phase (CAP)

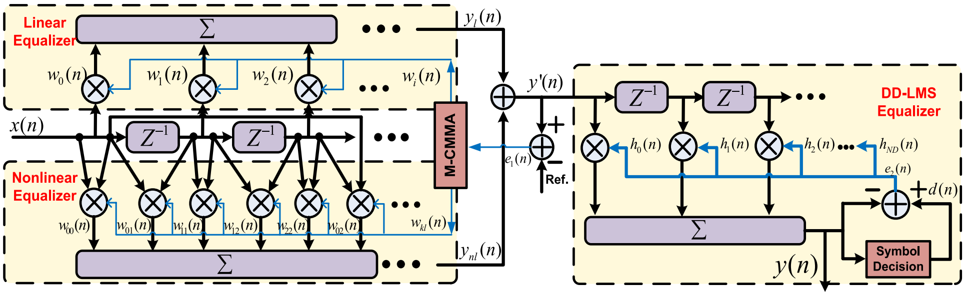

Fig. 1. Schematic diagram of the proposed hybrid equalizer.

modulation [5], discrete multi-tone (DMT) modulation [6], and Nyquist single carrier (N-SC) modulation [7]. Especially in [8], Cossu *et al.* have experimentally demonstrated a 5.6-Gb/s downlink optical wireless transmission employing bit and power loading based DMT modulation and a commercial red-blue-green-yellow LED (RGBY LED). It is the first time that over 5-Gb/s VLC transmission is obtained at 1.5 m.

On the other hand, the linear and nonlinear distortions such as optical multipath, sampling time offset, and LED nonlinearity etc. have been considered as the major obstacles to high-speed VLC transmission. To eliminate the inter-symbol interference (ISI) induced by linear distortions, series of linear equalization schemes have been utilized, such as decision feedback equalization (DFE) [5], training symbol [6], and recursive least square (RLS) [9]. In [7], we have proposed to use decision-directed least mean square (DD-LMS) in N-SC based VLC system. Moreover, some investigations have been reported to compensate the LED nonlinearity including post distortion technique [10] and hybrid time-frequency domain equalization [11]. In [12], we have experimentally demonstrated a 4.5-Gb/s WDM CAP64 VLC system employing Volterra series based nonlinear equalizer to mitigate the LED nonlinearity.

In this paper, in order to eliminate both the linear and nonlinear distortions, and further improve the system performance, for the first time we propose the use of a hybrid post equalizer in a high-order CAP modulation based VLC system. The hybrid equalizer consists of a linear equalizer, a Volterra series based nonlinear equalizer, and a DD-LMS equalizer. Modified cascaded multi-modulus algorithm (M-CMMA) is employed to calculate the error function and update the weights of the linear and the nonlinear equalizer without using training symbols, while DD-LMS will obtain good performance after the pre-convergence. A commercially available RGBY LED is utilized for 4 wavelengths multiplexing. By the hybrid equalizer, an aggregate data rate of 8 Gb/s is experimentally achieved over 1-m indoor free space transmission with the bit error rate (BER) below the 7% forward error correction (FEC) limit of $3.8 \times 10 - 3$ [13]. To our best knowledge, this is the highest data rate ever obtained in single LED based high-speed VLC systems. The results clearly show the benefit and feasibility of the proposed hybrid equalizer for indoor ultra-high-speed VLC systems.

2. Principle

In high-speed VLC systems, there exist severe linear and nonlinear distortions. The linear distortions induced by optical multipath dispersion, sampling time offset etc. will result in the ISI, while the LED nonlinearity will cause the distortion of signal constellations. To simultaneously mitigate the linear and nonlinear distortions and recover the signals, we propose the use of a hybrid post equalizer, as shown in Fig. 1.

It can be found that the hybrid equalizer consists of two-stage filters. The first stage filter includes a linear equalizer and a Volterra series based nonlinear equalizer. M-CMMA is used to

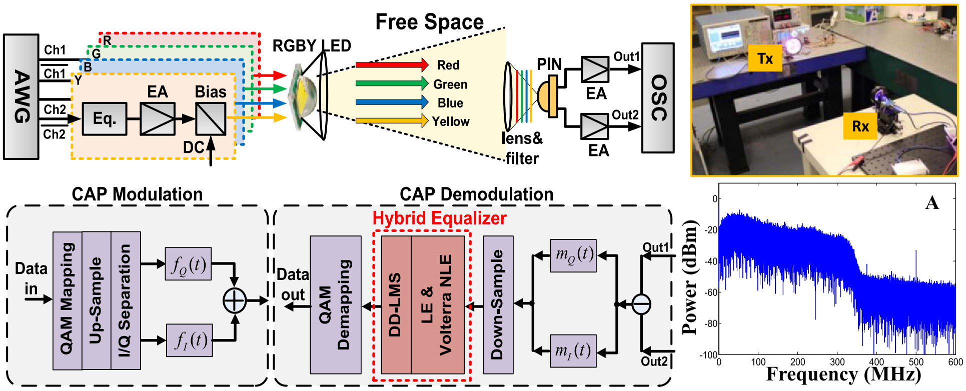

Fig. 2. Experimental setup of the WDM VLC system employing high-order CAP and the hybrid post equalizer.

calculate the error function and update the weights of the linear and nonlinear equalizer [11]. The output of the first stage filter can be expressed as

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

Here, $y_l(n)$ 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. $w_i(n)$ and $w_{kl}(n)$ are the weights of the linear and nonlinear equalizer. In our VLC system, the optimal tap numbers of the linear and the nonlinear equalizer are, respectively, 45 and 25 [12].

Then the output of the first stage filter is sent into the second stage filter. The second stage filter is a DD-LMS equalizer to obtain good performance after the pre-convergence. DD-LMS is a stochastic gradient descent algorithm, and does not depend on the statistics of symbols but rely on the symbol decisions. The detailed principle of DD-LMS has been well described in [6]. Therefore, the output of the DD-LMS equalizer can be written as

$$y(n) = \sum_{i=0}^{ND-1} h_i(n)y\prime(n-i). \tag{2}$$

Here, $h_i(n)$ and ND are, respectively, the weights and the tap number of the DD-LMS equalizer. The optimal tap number of the DD-LMS equalizer is 33 in the VLC system [14].

3. Experimental Setup

Fig. 2 shows the experimental setup of the RGBY LED based WDM VLC system employing high-order CAP modulation and the proposed hybrid post equalizer. At the transmitter, the original bit sequence is firstly mapped into complex symbols. Then the high-order QAM signal is sent for CAP modulation. The detail of the CAP modulation and demodulation has been well described in [15]. Here $f_I(t)$ and $f_Q(t)$ are the orthogonal shaping filter pair. The roll-off coefficient of the square-root raised-cosine function for CAP modulation is set to 0.01 for a high spectral efficiency.

In this experiment, we use Tektronix AWG 7122C to generate the CAP signals for the four color chips of the RGBY LED. The AWG 7122C have independent outputs; therefore, we use the output of channel 1 and its inverted output for the red and green chip, while the output of channel 2 and its inverted output are used for the blue and yellow chip, respectively. The modulation

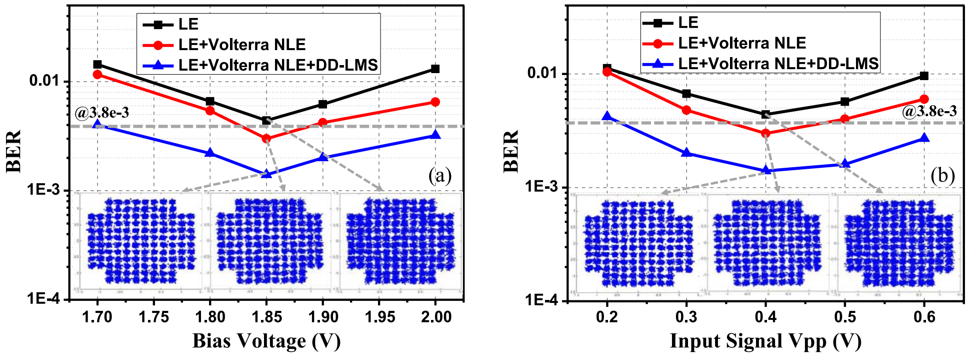

Fig. 3. Measured BER of the red chip versus (a) different bias voltages and (b) different input signal Vpp.

bandwidth of each color chip is fixed at 320 MHz. The generated CAP signals are then pre-amplified by a self-designed bridged-T based pre-equalizer to compensate the LED frequency attenuation at high frequency component [16]. The received electrical spectrum after the pre-equalizer is shown in the inset A of Fig. 2. Through an electrical amplifier (EA, Mini-circuits, 25-dB gain), the electrical signal and DC-bias voltage are combined by a bias tee and, respectively, used to drive the four color chips of the RGBY LED. Here, a commercially available RGBY LED (LED Engine, output power: 1 W) is utilized as the transmitter. A reflection cup with 60° divergence angle is applied to the RGB LED to decrease the beam angle of the LED for longer transmission distance.

At the receiver, a commercial PIN photodiode (Hamamatsu 10784) are used to detect the optical signals. Before the PIN, lens (50-mm diameter and 50-mm focus length) are used to focus light, and optical R/G/B/Y filters are also employed to filter out different colors. Here, we design a differential receiving circuit for the PIN, so that two received differential signals (Out1 and Out2) are obtained. The differential outputs of the receiver are amplified by EAs and then recorded by two different channels of a digital storage oscilloscope (Agilent DSO54855A) for further offline demodulation and signal processing.

In offline signal processing, the subtraction is firstly operated between the received differential signals to increase the SNR. Then the subtracted signal is sent for CAP demodulation. Accordingly, $m_I(t)$ and $m_Q(t)$ are the matching filter pair for demodulation. After demodulation, the proposed hybrid post equalizer is employed, and QAM decoder is followed to further recover the original bit sequence.

4. Experimental Results and Discussions

To render the RGBY LED working at the optimal condition, we firstly study the influence of different bias voltages and input signal peak-to-peak values (Vpp). The measured BER performance of the red chip versus different bias voltages is shown in Fig. 3(a). At this time, the input signal Vpp is fixed at 0.4 V. Then, the BER performance versus different input signal Vpps is measured at the fixed bias voltage of 1.85 V, as shown in Fig. 3(b). It can be found that compared to using only the linear and nonlinear equalizer, the best BER performance can be obtained by the hybrid equalizer. Moreover, the performance improvement is much better at higher bias voltage and larger signal Vpp. It can be explained by noting that the utilized Volterra nonlinear equalizer can bring better performance at higher bias voltage and larger signal Vpp, because of the mitigation of the LED nonlinearity. We also measure the BER performances versus bias voltages and input signal Vpps of the other three color chips. According to the measurements, the optimal working point of the RGBY chip is, respectively, at (1.85 V bias voltage, 0.4 V input signal Vpp), (3.0 V, 0.45 V), (2.9 V, 0.35 V), and (2.1 V, 0.8 V).

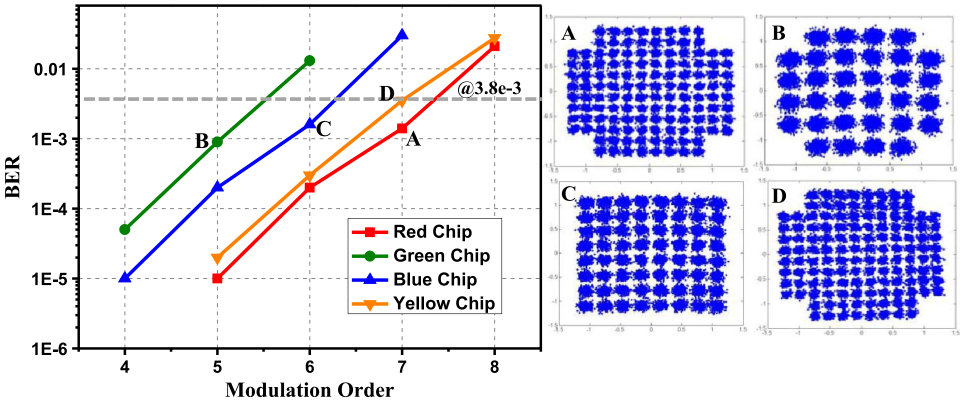

Fig. 4. BER performance versus different modulation orders of the four color chips.

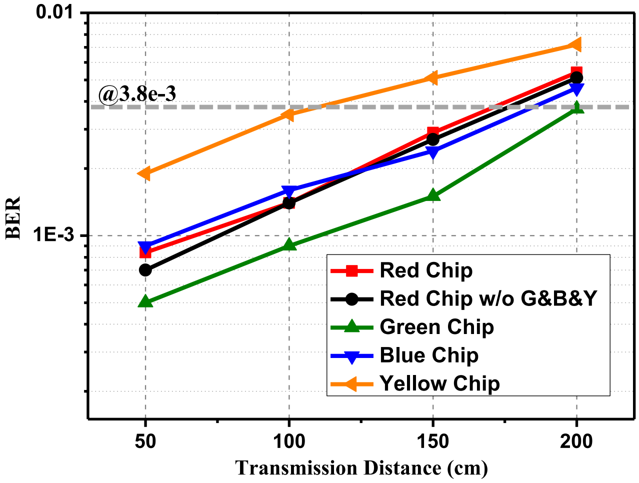

Fig. 5. BER performance versus different transmission distances.

At the optimal working point, we measure the BER performances of the four color chips versus different modulation orders, as shown in Fig. 4. The measurement is operated at 1-m transmission distance. It is observed that the highest modulation orders meeting the 7% FEC threshold of 3.8×10^{-3} for the four color chips (RGBY) are 128 QAM, 32 QAM, 64 QAM, and 128 QAM, respectively. Therefore, the aggregate data rate of $320 \times (7+5+6+7) = 8$ Gb/s is successfully achieved at a distance of 1 m. It is worth noting that the red chip has better performance because the best responsivity of the utilized PD is at 620 nm, which is close to the red light wavelength. It means that when the four color channels are modulated by the same order CAP signals, the red chip will have the best BER performance. In other words, the red chip can support the transmission of higher order CAP signal (128 QAM). Therefore, to maximum the VLC system capacity, we choose 128 QAM CAP signal for the red chip, while 128 QAM for yellow, 64 QAM for blue and 32 QAM for green. In this case, the performance of 128 QAM red chip is not the best (little worse than 32 QAM green chip).

The BER performance versus different distances employing the proposed hybrid equalizer is presented in Fig. 5. We, respectively, measure the BER performances at 0.5 m, 1 m, 1.5 m, and 2 m. It can be observed that at the distance of 0.5 m and 1 m, BER of all the four color chips are below the 7% FEC limit of 3.8×10^{-3}, while at the distance of 1.5 m, only the yellow chip cannot meet the 7% FEC requirement.

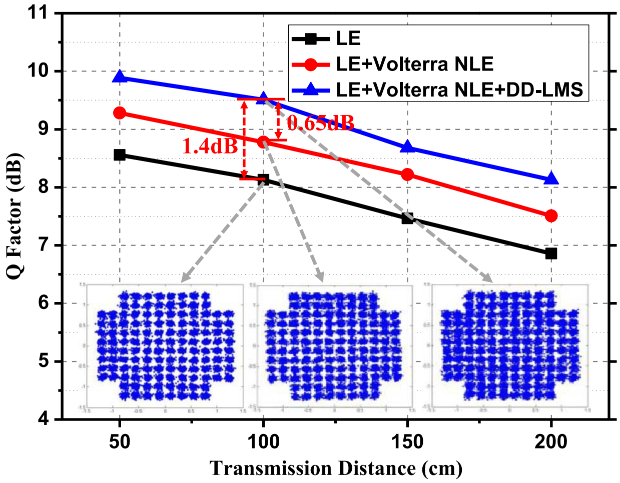

Fig. 6. Q-factor comparison between different equalizers of the red chip.

In our experiment, the CAP signals are independently modulated onto the four color channels. Then the four color chips of the RGBY LED are lighted to simultaneously transmit signals. In order to investigate the crosstalk for each channel, we measure the BER performances of the red chip without the other three color chips, as shown in Fig. 5 (the black line). Compared to the performance of the red chip with the other three channels (the red line), it can be clearly seen that there is almost no crosstalk induced by other three channels. It is because the wavelengths of the four color channels are different, and we use the R/G/B/Y filters in front of the PIN. Therefore the crosstalk from other channels has been filtered out before detection.

In order to make a clear comparison, we measure the Q factor of the red chip versus different transmission distances with the linear equalizer, the linear equalizer + the Volterra nonlinear equalizer, and the proposed hybrid equalizer respectively, as shown in Fig. 6. The results show that the hybrid equalizer can outperform the linear equalizer + the Volterra nonlinear equalizer by Q factor of 0.65 dB and outperform the linear equalizer by 1.4 dB at the distance of 1 m.

It should be noted that in VLC system the luminance of the LED is the key factor that can limit the transmission distance. In our experiment, the measured luminance of the RGBY LED at 1 m is about 450lx. The illumination level is below the standard value for brightness (500lx). So it is believed that transmission distance and system performance can be further improved by increasing the optical power of LEDs or deploying LED array. On the other hand, it is very important for a VLC system to be suitable for practice. Now, we are trying to design an auto-focus system in smaller size to improve its practicality, which integrates the lens and the optical filters to realize focusing and filtering simultaneously.

5. Conclusion

In this paper, for the first time, we experimentally demonstrate the feasibility of a hybrid post equalizer in a high-order CAP modulation based VLC system. The hybrid equalizer consists of a linear equalizer, a Volterra series based nonlinear equalizer, and a DD-LMS equalizer, so that both the linear and nonlinear distortions of the VLC system can be eliminated. A commercially available RGBY LED is utilized for 4 wavelengths multiplexing. The influence of the bias voltages and input signal Vpp is also studied to find the optimal working condition. By the hybrid equalizer, an aggregate data rate of 8 Gb/s is successfully achieved over 1-m indoor free space transmission with the BER below the 7% FEC limit of 3.8×10^{-3}. To our best knowledge, this is the highest data rate ever obtained in high-speed VLC systems.

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