4.5-Gb/s RGB-LED based WDM visible light communication system employing CAP modulation and RLS based adaptive equalization

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Abstract: Inter-symbol interference (ISI) is one of the key problems that seriously limit transmission data rate in high-speed VLC systems. To eliminate ISI and further improve the system performance, series of equalization schemes have been widely investigated. As an adaptive algorithm commonly used in wireless communication, RLS is also suitable for visible light communication due to its quick convergence and better performance. In this paper, for the first time we experimentally demonstrate a high-speed RGB-LED based WDM VLC system employing carrier-less amplitude and phase (CAP) modulation 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 bit error rate (BER) below the 7% forward error correction (FEC) limit of $3.8x10^{-3}$. To the best of our knowledge, this is the highest data rate ever achieved in RGB-LED based VLC systems.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2605) Free-space optical communication; (230.3670) Light-emitting diodes.

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1. Introduction

Nowadays visible light communication (VLC) using light emitting diodes (LEDs) has become a promising technology for wireless communication as LEDs are considered to be a major candidate for future illumination [1]. Due to the combination of illumination and communication, a lot of investigations have been attracted in VLC applications such as indoor high speed wireless access and positioning [2,3]. The feasibility of VLC has been both demonstrated by employing red-green-blue (RGB) LED and phosphor-based LED. RGB LEDs, compared with phosphor-based LEDs, are more promising solutions to high speed VLC systems as they offer the possibility of the wavelength division multiplexing (WDM) which can greatly increase the transmission data rate. Employing RGB-LED and spectrally efficient modulations, some outstanding achievements on high speed VLC transmission have been reported. In [4], Wu et al have presented a 3.22-Gb/s RGB-LED based VLC system utilizing carrier-less amplitude and phase (CAP) modulation. A 3.4-Gb/s WDM VLC system based on discrete multi-tone (DMT) has been experimentally demonstrated in [5]. And we also have reported a 4.22-Gb/s Nyquist single carrier VLC system employing an RGB LED [6]. However, the transmission distances of these VLC systems are only few centimeters (ranging from 1cm to 25cm), which is obviously not suitable for practical use. In [7], a 5.6-Gb/s downlink optical wireless transmission has been demonstrated with bit and power loading based DMT modulation. It is the first time that over 5Gb/s VLC transmission is obtained at 1.5m. However, the authors utilize not a common RGB LED emitting white light, but a special red-blue-green-yellow LED (RGBY LED) with 4 wavelengths, and the data rate per wavelength is less than 1.5Gb/s. If transmission distance is shorter, the data rate per channel may be increased to 1.5Gb/s.

On the other hand, the inter-symbol interference (ISI) induced by optical multipath, sampling time offset et al has been recognized as the major obstacle to high-speed VLC transmission. To eliminate ISI and further improve the system performance, series of equalization schemes, such as decision feedback equalization (DFE) [4], training symbol [5], decision-directed least mean square (DD-LMS) [6] and modified cascaded multi-modulus algorithm (M-CMMA) [8], have been widely investigated and utilized. As an adaptive algorithm commonly used in wireless communication, recursive least square (RLS) is also suitable for visible light communication due to its quick convergence and better performance. In [9] and [10], Bandara et al have investigated RLS based VLC system and presented the reduction of training sequence for VLC system by employing RLS adaptive equalization. However, the studies are only based on theoretical analysis and numerical simulations, and lack of experimental demonstration.

In this paper, for the first time we experimentally demonstrate a high-speed WDM VLC system employing CAP modulation and RLS based adaptive equalization. A commercially available RGB LED is used to carry different data on the three wavelength channels. On the basis of RLS equalization, an aggregate data rate of 4.5Gb/s (1.5Gb/s per wavelength) is successfully achieved over 1.5-m indoor free space transmission with the bit error rate (BER) below the 7% forward error correction (FEC) limit of $3.8\text{x}10^{-3}$ [11]. To the best of our knowledge, this is the highest data rate ever achieved in RGB-LED based VLC systems at common indoor distance. The results clearly show the benefit and feasibility of RLS based adaptive equalization scheme for indoor high-speed VLC systems.

2. Principle

In high-speed VLC systems, the ISI induced by optical multipath dispersion, sampling time offset et al will seriously degrade the system performance and reduce the transmission distance. Considering that the distortion induced by ISI is linear, an equalizer is needed to mitigate the interference and recover the signals. Since the VLC channel is unknown to the receiver, the adaptive algorithm should be used to adapt the filter weights of the equalizer. Owing to its quick convergence and better performance, RLS adaptive algorithm is suitable for VLC systems. The schematic diagram of the RLS based equalizer is shown in Fig. 1.

The detailed principle of RLS algorithm has been well described in [9] and [10]. The RLS algorithm recursively finds the filter coefficients that minimize a weighted linear least square cost function related to the input signals. The advantage of the RLS algorithm is that it has quicker convergence than other methods so that the number of training sequence can be greatly reduced. And due to the lower error value, the performance of RLS is better.

In RLS algorithm, $d(n)$ is the desired output of the equalizer. So training sequence is needed to calculate the error value and update the weight vectors. To evaluate the convergence and performance of RLS algorithm, the error value of RLS with iteration number is displayed in Fig. 2(a). In [8], we have reported a multi-band CAP based VLC system using M-CMMA equalization. The error value of M-CMMA is also shown in Fig. 2(b).

In order to make a computation comparison between RLS and M-CMMA, we calculate the required computation in one interation as shown in Table 1. Here, N is the tap number of the equalizer. It can be found that the required multiplier and adder of M-CMMA are obviously less than RLS in one interation. However, the convergence speed of RLS is much faster than M-CMMA as shown in Fig. 2. The required interation number of RLS until desired convergence is about 200, while the interation number of M-CMMA is more than 2000. RLS has better equalization performance and faster convergence speed than M-CMMA at the cost of required computation in one interation.

Moreover, M-CMMA is a blind equalization algorithm, so the interation has to be conducted over all the symbols. For RLS, a short training sequence is needed to update and converge the weight vectors until the desired convergence. After that, the interation is not needed and the symbols are equalized by multiplying the calculated weight vector. Therefore, the whole computation complexity of RLS is much lower than M-CMMA.

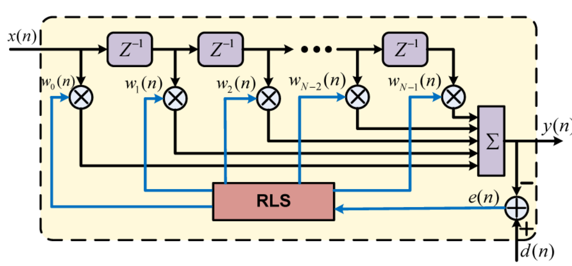

Fig. 1. The schematic diagram of RLS based equalizer

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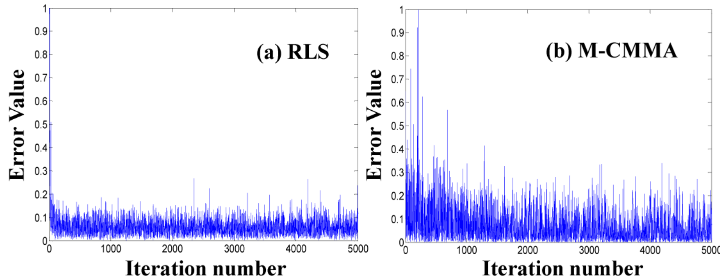

Fig. 2. The error value vs. different iteration number of (a) RLS, (b) M-CMMA

Table 1. The required computation of M-CMMA and RLS in one interation.

Algorithm	M-CMMA	RLS
Multiplier	8N + 16	$4N^2 + 4N + 1$
Adder	8N + 20	$3N^2 + N$
Comparator	28	0
Required interation	All the symbols	About 200

3. Experimental setup

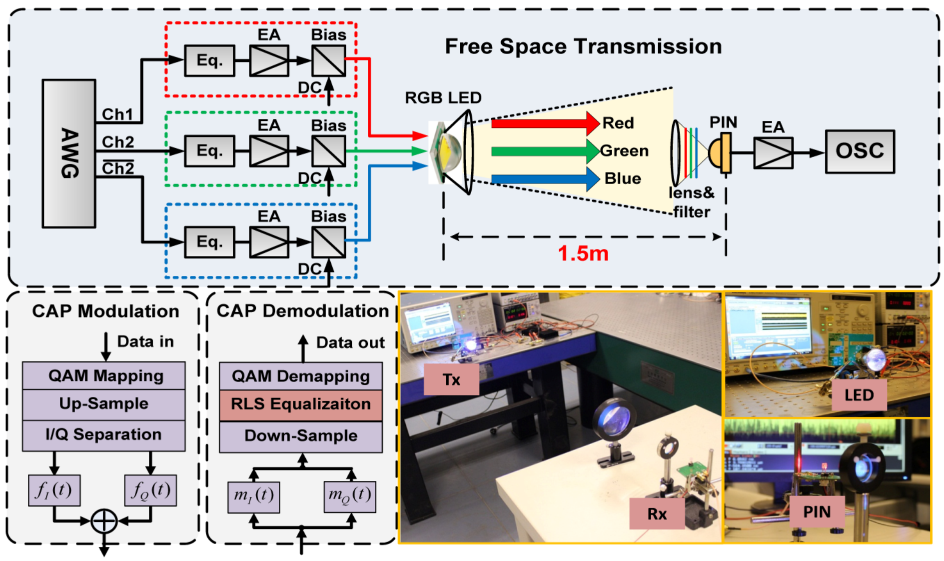

Fig. 3. The experimental setup of the WDM VLC system employing CAP and RLS

Figure 3 shows the experimental setup of the RGB-LED based WDM VLC system employing CAP modulation and RLS adaptive equalization. At the transmitter, the original bit sequence is firstly mapped into complex symbols for 64QAM. Then the QAM signals are sent for CAP modulation. The detail of the CAP modulation and demodulation has been well described in [12]. 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 0.02 for a high spectral efficiency. Although the energy efficiency of CAP modulation is lower than OFDM, the advantage of CAP modulation is that no electrical or optical complex-to-real-value conversion is necessary. Neither does it require the discrete Fourier transform (DFT) that utilized in OFDM signal generation and demodulation. The CAP signal can be generated by employing a digital filter with several taps and detected by a matching digital filter. So it can reduce the complexity of computation and system structure considerably.

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In this experiment, Tektronix AWG 7122C is used to generate the CAP signals for the three color chips of the RGB LED. The modulation bandwidth of each color chip is set at 250MHz. The AWG 7122C have 2 independent outputs, so we use the output of channel 1 for the red chip, while the output of channel 2 and its inverted copy are used as the signal sources for green and blue chip respectively. The generated CAP signal is then pre-amplified by a self-designed bridged-T based pre-equalizer to compensate the frequency attenuation at high frequency component [13]. 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 respectively applied to the three color chips of the RGB LED. The three color chips of the RGB LED are simultaneously used to carry signals. Here a commercial RGB LED (Cree PLCC, output power: 1W, red: 620nm; green: 520nm; blue: 470nm) 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. So the divergence angle of the beam after the reflection cup is 60°.

At the receiver, a commercially available PIN photodiode (Hamamatsu 10784) are used as the receiver. Before the PIN, lens (70-mm diameter and 100-mm focus length) are used to focus light, and optical R/G/B filters are also employed to filter out different colors. The outputs of the receiver is amplified by an EA and then recorded by a digital storage oscilloscope (Agilent DSO54855A) for further offline demodulation and signal processing.

In offline signal processing, the received signal is firstly sent for CAP demodulation. Accordingly, $m_I(t)$ and $m_Q(t)$ are the matching filter pair for demodulation. Then the RLS based adaptive post-equalization is employed to eliminate the ISI. In our system, 1000 training symbols are used to update and converge the filter weights. Subsequently QAM decoder is utilized to further recover the original bit sequence.

4. Experimental results and discussions

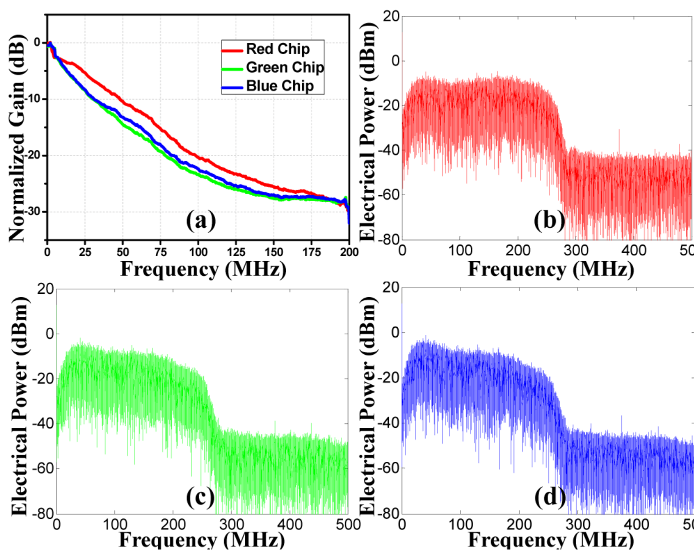

Fig. 4. (a) The measured frequency response of the three individual VLC links, (b) the electrical spectra of the red chip, (c) the electrical spectra of the green chip, (d) the electrical spectra of the blue chip

First of all, we measured the frequency response of the overall system including the RGB LED, bias tee, electrical amplifier, and PIN. The results are shown in Fig. 4(a). It can be found that there are large attenuations at the high frequency component, and the gradients of the frequency response of the three color chips are different. The frequency response of the red chip is more flat, while the green and blue chips behave a little worse. Furthermore, we use a self-designed bridged-T based pre-equalizer to compensate for the frequency attenuation of the three color chips and optimize the system performances. The electrical spectra of the three color chips with pre-equalization are depicted in Fig. 4(b)-(d). In this experiment, 250-MHz 64QAM CAP signals are respectively applied to the three color chips, so that the aggregate data rate of the WDM VLC system is reach to 4.5Gb/s (1.5Gb/s per wavelength).

The optimal number of taps for RLS equalization is then investigated in red link. In this investigation, the number of taps is ranging from 10 to 70. The BER performance versus the number of taps is shown in Fig. 5. The system performance can be improved with the increasing tap number of the RLS equalizer. When the number of taps is larger than 27, the BER performance is below the 7% FEC limit of $3.8x10^{-3}$. Considering the system performance and computational complexity, the proper number of taps is fixed at 35.

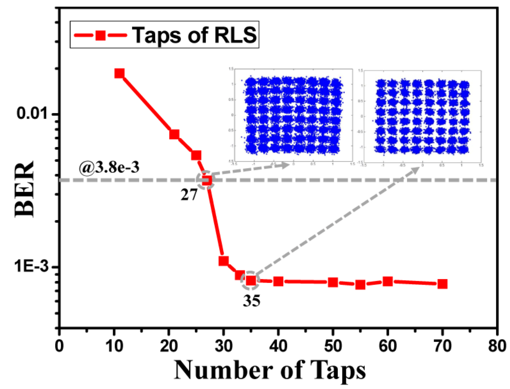

Fig. 5. The BER performance versus the number of taps in the red chip

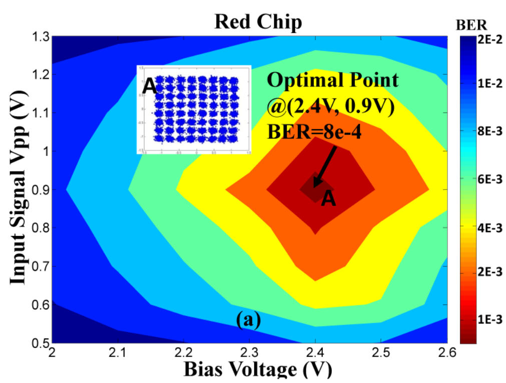

Fig. 6. Measured BER versus different bias voltages and input signal Vpp of the red chip.

The influence of different bias voltages and input signal peak-to-peak value (Vpp) is also studied to render the RGB LED work at the optimal condition. The measured BER performance of the red chip versus bias voltages and input signal Vpp is shown in Fig. 6. According to the measurements, the optimal working point of the red, green and blue chip is respectively at (2.4V bias voltage, 0.9V input signal Vpp), (4.1V, 0.55V) and (4.1V, 0.5V). At the optimum point, all the BER of the three color chips can below the 7% FEC limit of $3.8x10^{-3}$.

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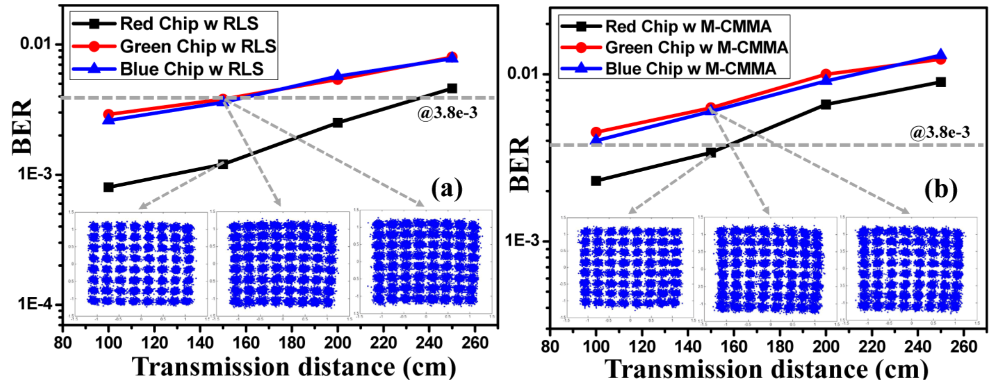

Fig. 7. The BER performance versus transmission distance with (a) RLS equalization, (b) M-CMMA equalization

The BER performance versus different distances employing RLS based equalization is presented in Fig. 7(a). We respectively measure the BER performances at 1m, 1.5m, 2m and 2.5m. It can be observed that at the distance of 1.5m, BER of the three color chips can below the 7% FEC limit of $3.8\text{x}10^{-3}$, so that the aggregate data rate of 4.5Gb/s is successfully achieved at common indoor distance. We also measure the BER performance employing M-CMMA based equalization for comparison, as shown in Fig. 7(b). It can be found that with M-CMMA, the BER performances become worse in all the three color chips, and the BER of green and blue chip cannot meet the FEC threshold at 1.5-m distance. For a clear comparison, we measure the Q factor versus transmission distance with RLS, M-CMMA and CMMA respectively, as shown in Fig. 8. The results show that RLS can outperform M-CMMA by Q factor of 1dB and outperform CMMA by 2.1dB at the distance of 1.5m.

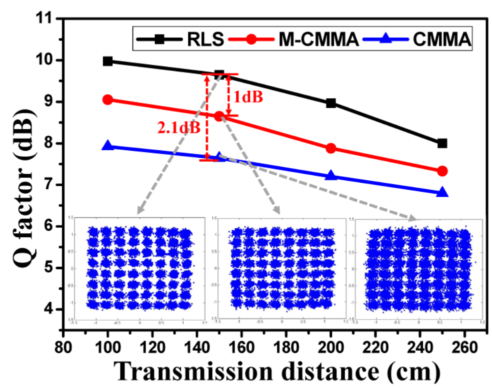

Fig. 8. The Q factor comparison between RLS, M-CMMA and CMMA equalization

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 combined white light at 1.5m is about 400lx. The lamination 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. Moreover, considering the multipath induced by LED array, there have been many schemes proposed to reduce the effect of the multipath, i.e. adaptive equalizer [14], receiver diversity technology [15] and advanced coding techniques [16]. Therefore, the multipath effect induced by deploying a LED array can be well reduced by these schemes, and the transmission distance will be obviously increased with the LED array.

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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 a high-speed RGB-LED based WDM VLC system employing CAP modulation and RLS based adaptive equalization. The optimal number of taps for RLS equalization has been investigated, and the influence of bias voltages and input signal Vpp is also studied to find the optimal working condition. On the basis of RLS equalization, an aggregate data rate of 4.5Gb/s is successfully achieved over 1.5-m indoor free space transmission with the bit error rate (BER) below the 7% forward error correction (FEC) limit of 3.8×10^{-3}. Moreover, we make a comparison between RLS and M-CMMA equalization scheme, and RLS can outperform M-CMMA by Q factor of 1dB. To the best of our knowledge, this is the highest data rate ever achieved in RGB-LED based VLC systems at common indoor distance. The results clearly show the benefit and feasibility of RLS based adaptive equalization scheme for indoor high-speed VLC systems.

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