A Real-Time RGB PAM-4 Visible Light Communication System Based on a Transceiver Design with Pre- and Post-equalizations

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Abstract. VLC is becoming a trending of next-generation communication because of its broad-spectrum range and unique application scenario. The transmission speed is limited because of the LED bandwidth. Equalization technology on analog frontend or digital baseband can broad the bandwidth of the whole system. High order modulation scheme is also an effect way to improve the data rate under a fixed bandwidth. This work presents a novel RGB PAM-4 transceiver employing digitally controlled asymmetric FFE and cascaded CTLE. The PAM-4 signal with one-tap FFE is composed of six OOK signals with different delays in the optical domain. Delay control is implemented in digital baseband and no DAC is needed in the system. The transceiver achieves 250% increase in bandwidth extension ratio in VLC links using ordinary RGB LEDs by allowing independent PAM-4 eye-height tuning.

Keywords: VLC · PAM-4 · FFE · CTLE

1 Introduction

Visible light communication (VLC) technology based on LEDs has demonstrated significant potential towards the next generation optical wireless interconnection for Internet-of-Things (IoT) devices due to its wide spectrum resources, huge bandwidth capacity, high security, and negligible electromagnetic interference. With the wide application of LEDs in every aspect of human life, VLC becomes a promising technology in various application scenarios such as illumination, display backlights and near field communication. Recent studies have demonstrated system, modulation scheme and optical link level innovations to achieve higher bandwidth efficiencies or wider bandwidth extensions. High level modulation schemes such as pulse amplitude modulation (PAM) [2, 3, 7], carrierless amplitude phase modulation (CAP) [4, 10] and orthogonal frequency division multiplexing (OFDM) combined with various bit and energy allocation algorithms [1, 8, 12] have been thoroughly investigated to

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significantly improve the bandwidth efficiency. Additionally, circuit and system level innovations in physical layers have been proposed to achieve real-time VLC systems by employing various pre- and post-equalization methods [5, 6, 9, 11].

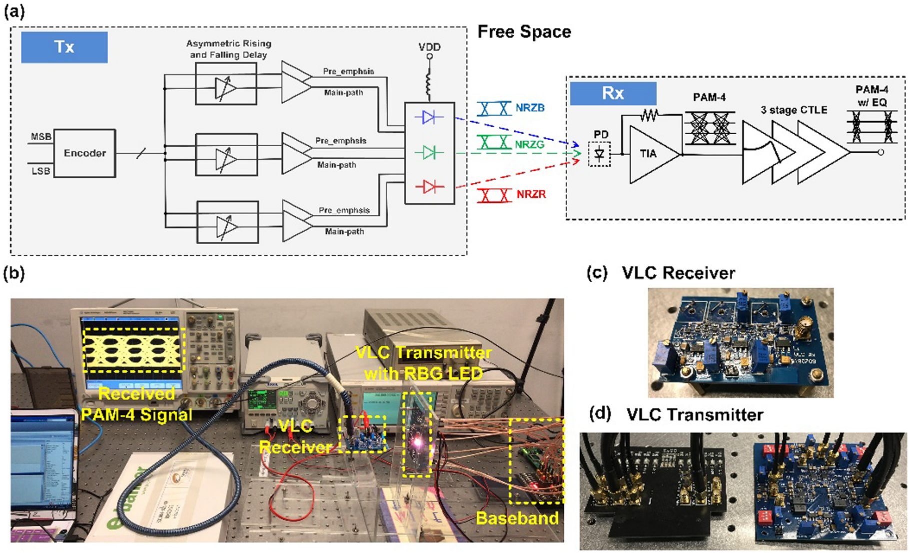

Fig. 1. (a) System architecture of the proposed PAM-4 VLC system. (b) Experimental setup. (c) VLC receiver. (d) VLC transmitter.

However, there are several physical layer challenges that severely limit the data transmission quality of real-time VLC systems, such as the nonlinearity optical responses to driving current and the limited bandwidths of LEDs, especially when a high-level modulation scheme such as PAM-4 is applied. So far, there has been a lack of investigation into the practical and compact implementation of the transceiver front-end design supporting PAM-4 modulation to serve as an electrical-to-optical and optical-to-electrical interface.

In this work, we propose a complete system-on-board RGB PAM-4 transceiver design with feed-forward equalization (FFE) and cascaded continuous-time linear equalization (CTLE). The PAM-4 optical signal is constructed by linearly combining the three serial NRZ optical signals from the red, green, and blue LEDs in the optical domain. The transceiver design can tune the three eye-heights of the PAM-4 optical signal independently to compensate for the differences in the LED optical responses. Experimental results of the RGB PAM-4 system demonstrate that PAM-4 data transmission can be achieved with high quality, and the LED bandwidth can be extended 2.5 times using pre- and post-equalization.

2 System Architecture and Operating Principle

The system architecture of the proposed RGB PAM-4 VLC system is presented in Fig. 1(a). The transmitter system consists of a baseband encoder implemented in a field programmable gate array (FPGA) and a transmitter circuit board with 1-tap FFE function as Fig. 2 shows. The baseband encoder receives two serial bits: one most significant bit (MSB) and one least significant bit (LSB). The MSB and LSB serial bits are encoded into three channels of serial data, which separately contribute to the three eyes of the PAM-4 signal. For each of the three channels, the data is duplicated into two paths, with one data path going through an inverter and a digitally controlled asymmetric rising and falling delay. On the transmitter circuit board, three serial data-pairs control the main and 1-tap FFE drivers of each of the red, green, and blue LED. The output NRZ optical signals from the red, green, and blue LEDs are linearly combined in the optical domain and generate the PAM-4 optical signal, with each NRZ optical signal contributing to one part of the PAM-4 eye. On the receiver side, the PAM-4 optical signal is converted into an electrical signal using a photo detector and a trans-impedance amplifier (TIA). The converted electrical PAM-4 signal is then equalized using a three-stage cascaded CLTE to compensate for the limited bandwidth and is delivered to the output with a unit gain buffer. The experimental setup is shown in Fig. 1(b). The receiver and transmitter circuit are shown in Fig. 1(c) and (d), respectively.

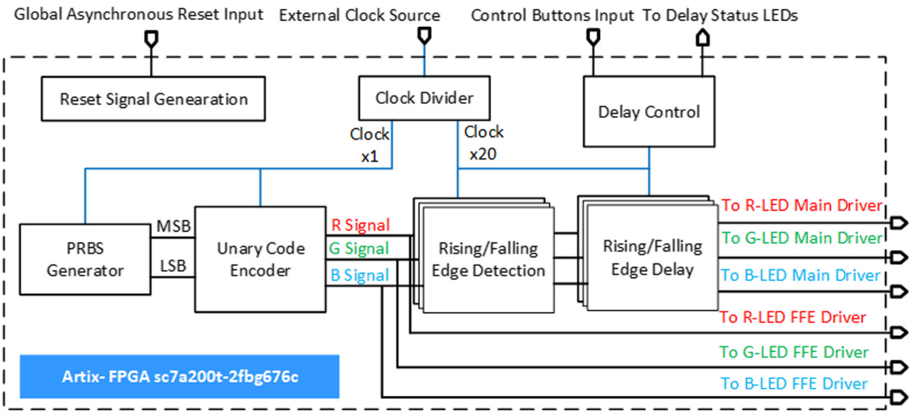

Fig. 2. Structure of digital baseband of the transmitter

The light source employed here is a commercially available RGB LED with each of the red, green, and blue LEDs capable of providing a maximum of 0.5 W output light. The optical responses and bandwidths of the three LEDs are different, which causes the eye-widths to be unequal and the eye quality to be degraded. To solve this problem, three VLC drivers with independently driving current controls and FFEs with asymmetric digitally controlled edge delays are separately implemented for the red, green, and blue LEDs. The delays for the rising and falling edges of the FFE data path can be controlled separately using digital code to compensate for the asymmetric rising and falling times of the LEDs, as shown in Fig. 3(a). The driving current of the three drivers are carefully adjusted so that the three eye heights of the PAM-4 signal are equal. On the receiver side, three-stage-cascaded CTLE with an R-C degeneration structure is implemented to compensate for the bandwidth limitation of the RGB LED and the TIA. The cascaded CTLE features variable peaking frequency, height, and slope, which can provide compensation to a wider bandwidth.

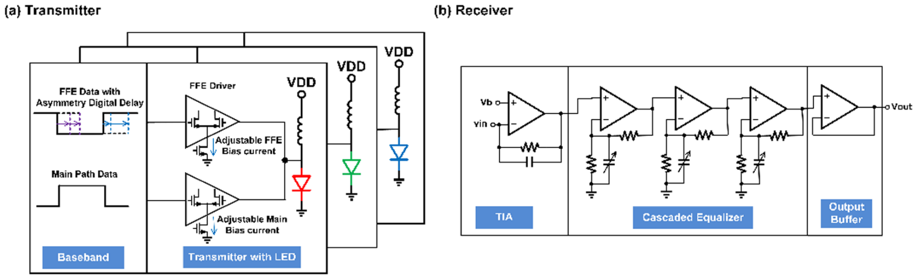

Fig. 3. (a) Transmitter implementation with 1-tap FFE. (b) Receiver implementation with three-stage cascaded CTLE.

3 Experimental Results and Discussion

Based on the designed RGB PAM-4 VLC transmission system, the data transmission performance was verified at a 5-cm transmission distance by measuring the bit-error-rates (BERs), bathtub curve (BC) and eye diagrams. The measured BERs versus data rate under the conditions of red LED NRZ transmission, PAM-4 without equalization (EQ), PAM-4 with FFE only, PAM-4 with one stage CTLE, and three stage CTLE are plotted and compared in Fig. 4(a). Compared to NRZ data transmission, by applying the PAM-4 modulation scheme, the highest achievable data rate was increased from 22 Mbps to 32 Mbps, which was further extended by 2.5 times to 80 Mbps using the FEE and CTLE functions. The FFE on the transmitter side and the cascaded CTLE on the receiver side contributed to a 2.1- and 1.2-times extension ratio, respectively. The bathtub curve at 68 Mbps shows a 0.3–UI margin for a BER less than 3.6×10^{-3}. The eye diagrams under the three different equalization conditions are shown in Fig. 4(a), which demonstrate the functions of the pre- and post-equalizations.

Due to the different optical responses of the red, green, and blue LEDs, the three eye-heights of the received PAM-4 signal were uneven and thus led to very narrow decoding margin. By tuning the driving current of the RGB LEDs independently, a much-improved PAM-4 data eye with almost equal eye-heights can be achieved, as shown in Fig. 4(c) and (d).

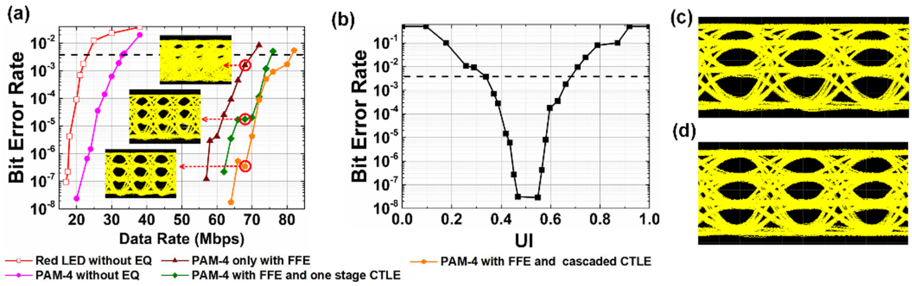

Fig. 4. (a) Measured BER versus data rate for a red LED without EQ, PAM-4 without EQ, PAM-4 with only FFE, PAM-4 with FFE and first stage CTLE, PAM-4 with cascaded CTLE, and eye diagrams at 68 Mbps for the three different equalization conditions. (b) Measured bathtub curve at 68 Mbps. (c) Measured eye diagram without independent driving current tuning. (d) Measured eye diagram with independent driving current tuning.

4 Conclusions

An RGB PAM-4 VLC transceiver system with 1-tap FFE and three-stage-cascaded CTLE was presented. The PAM-4 optical signal is constructed by linearly combining three independent NRZ signals from the RGB LEDs, respectively. The experimental results validate the independent eye-height tuning feature enables high-quality PAM-4 signal transmission resulting in 2.5-times increase in bandwidth extension ratio.

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