Faster-Than-Nyquist Precoded CAP Modulation Visible Light Communication System Based on Nonlinear Weighted Look-Up Table Predistortion

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The Weighted Look-up Table

\[ \text{Index } i+n \]
\[ \text{Index } i+1 \]

\[ X'(k) = X(k) - WLUT \cdot e(k) \times w \]

\[ WLUT(i) = WLUT(i) + e(k) \]
\[ N(i) = N(i) + 1 \]
\[ e(k) = Y(k) - X(k) \]

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Faster-Than-Nyquist Precoded CAP Modulation Visible Light Communication System Based on Nonlinear Weighted Look-Up Table Predistortion

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Abstract: In this paper, we have experimentally demonstrated faster-than-Nyquist carrierless amplitude and phase modulation quadrature phase-shift keying visible light communication system over 1.5-m free space transmission. Weighted look-up table is used to mitigate nonlinear impairment caused by amplifiers and electro-optical components. At the receiver side, recursive least square is employed to improve the decision precision. By combining these techniques, a data rate of 1.01 Gb/s is experimentally achieved with a bit error rate less than 7% forward error correction limit of $3 \times 10^{-3}$. To the best of our knowledge, this is the first time that weighted look-up table is proposed and used in visible light communication system.

Index Terms: Faster-than-Nyquist (FTN), carrierless amplitude and phase modulation (CAP), weighted look-up table (WLUT), RLS.

1. Introduction

In recent years, light-emitting diode (LEDs) based visible light communication (VLC) system has attracted more and more attention due to its advantages of license-free, immunity to electromagnetic interference, low cost, low power consumption, security and so on [1], [2]. VLC can provide simultaneous illumination and communication through high-speed shading LED lights and is considered to be a promising technology [3], [4]. However, in high-speed visible light communication system, how to improve the system spectral efficiency (SE) [5] and mitigate the nonlinearity [6] are still two key challenges.

In VLC systems, bandwidth of commercial LEDs is very limited and one of the important ways to improve the transmission data rate is to adopt advanced modulation technology, such as orthogonal frequency division multiplexing (OFDM) [2], pulse amplitude modulation (PAM) [7] and carrierless amplitude and phase (CAP) [8] modulation. Among them, CAP is highly advocated due to simple structure, low computational complexity and high spectral efficiency [2]. In [9], an 8 Gbps
transmission data rate is experimentally demonstrated in a high-order CAP modulation VLC system over a 1 m free-space. In order to further improve SE, faster-than-Nyquist (FTN) [10] modulation formats can be used in high speed VLC systems. In [11], a novel FTN pre-coded multiband CAP modulation scheme is proposed. Compared with traditional CAP, FTN pre-coded CAP shows better SE performance. But this system does not take the nonlinearity of VLC system into account. Electrical amplifiers (EA) and electro-optical components in VLC systems will cause nonlinear distortion. Many efforts have been made to compensate this nonlinearity. In [12] and [13], volterra series based post nonlinear equalizer and in [14], polynomial based adaptive pre-distorter are used to mitigate the impact of nonlinearity. However, the computational complexity of these methods is relatively high. Besides, nonlinear Volterra equalizations is applied in the receiver (Rx)-side. Because the complexity of the Volterra equalizations, post-compensation will increase the computational load of the receiver. Otherwise, pre-distortion enable receiver side with low complexity. Alternatively, in [15]–[18], nonlinear look-up table (LUT) pre-distortion to intensity modulation and direct-detection (IM/DD) systems and coherent detection systems has been proved to be effective to overcome the nonlinearity impairment.

In this paper, we propose and experimentally demonstrate a weighted look-up table (WLUT) pre-distortion based FTN pre-coded CAP modulation visible light communication system. At the transmitter side, FTN coding is used to generate FTN CAP data. WLUT is employed to mitigate the nonlinearity impairment of opto-electronic components and LED and the pre-distortion performance of WLUT is studied by calculating bit error rate (BER). At the receiver side, recursive least square (RLS) [19] is employed to realize post-equalization and FTN decoding is used to recover the original data. By using RLS and WLUT, a data rate of 1.01 Gb/s is experimentally achieved by FTN CAP4 over 1.5-m indoor free space transmission with the BER below the 7% forward error correction (FEC) limit of $3.8 \times 10^{-3}$ [20]. This result obviously show the feasibility of WLUT for indoor high speed VLC systems. To our best knowledge, this is the first time that WLUT is proposed and used in VLC system.

2. Principle of Weighted Look-Up Table (WLUT) Pre-Distortion

WLUT pre-distortion is employed to mitigate the nonlinearity impairments of opto-electronic components. The channel of VLC system has very serious frequency fading phenomena and the 3 dB bandwidth of the system is limited, which will decrease demodulation accuracy seriously. To solve this problem, pre-equalization can be used to compensate the frequency fading and the spectrum of the received signal can be flat after the channel, but this method will reduce the signal-to-noise ratio (SNR) in low frequency band. A better way to solve this problem is to multiply pre-equalization data by a weight so as to optimize the overall performance of the system [21]. Compared with LUT pre-distortion used in [15], [16], WLUT pre-distortion is modified by introducing a compensation weight. Fig. 1 illustrates schematic diagram of WLUT pre-distortion that is employed in FTN CAP VLC system.

WLUT pre-distortion can be divided into two steps: table generation and routing WLUT to mitigate nonlinear impact. Firstly, the symbol sequence $X(k - N : k : k + N)$ contain the certain pattern extracted from the FTN pre-coded data and the length of the pattern is $2N + 1$. Each pattern has a certain address, namely WLUT index $i$. A sliding window is used to select $2N + 1$ symbols. Correspondingly, $Y(k - N : k : k + N)$ is the received signal with the same index $i$ that can be compared with transmitted data. The amplitude correction for middle symbol is defined as $e(k)$:

$$e(k) = Y(k) - X(k)$$  \hspace{1cm} (1)

$e(k)$ is placed in the corresponding address $i$. When the sliding window moves forward, the amplitude of the middle symbol for each pattern is corrected and the amplitude error is stored in the corresponding address. When all symbols are calculated, the average value of the amplitude error for every symbol is obtained and stored finally.

Secondly, the transmitted data $X(k)$ can be pre-distorted by finding the generated WLUT at the transmitter side. For a certain $N$, the transmitted FTN pre-coded signal can be pre-distorted as $X'(k)$.
according to WLUT index $i$ correspondingly.

$$X'(k) = X(k) - WLUT_e(k) \times w$$

(2)

Where $w$ is the weight that used in this system. By using WLUT, the nonlinear impairment can be mitigated effectively with simple calculation and high accuracy.

3. Experimental Setup

Fig. 2 shows the experimental setup of the VLC system employing FTN pre-coding CAP with WLUT pre-distortion and RLS post equalization. At transmitter side, firstly the original sequence is mapped into QPSK signals, then the complex signal is divided into real part and imaginary part and FTN pre-coding is done to improve the SE. The detail of the FTN pre-coding has been well described in [11]. After that, WLUT pre-distortion is employed to mitigate the nonlinearity impairments. After upsampling, the signal passes through a pair of orthogonal shaping filter [22]. The roll-off coefficient
Fig. 3. Spectral envelope diagram versus different roll-off coefficient of the square-root raised-cosine function for CAP modulation.

Fig. 4. Measured V-I curve of the red chip.

of the square-root raised-cosine function for CAP modulation is a key parameter to determine the roll-off speed and the shape of the filter. The roll-off coefficient determines the bandwidth of the signal. The time domain and frequency domain responses of the shaping filter are different under different roll-off coefficients. When the roll-off coefficient is reducing, the sideband fading of the shaping filter is faster and the signal bandwidth is narrower. To render the system working at the optimal condition, the influence of roll-off coefficient of the square-root raised-cosine function for CAP modulation is studied. The spectral envelope of FTN pre-coded CAP signal at the modulation bandwidth of 500 MHz with different roll-off coefficient is shown in Fig. 3. It can be seen from Fig. 3 that when the roll-off coefficient is decreasing, the degree of spectrum compression is increasing, and the SE of the system is improving accordingly. The roll-off coefficient of the square-root raised-cosine function in this system is set to 0.02 for a high spectral efficiency [12], [21].

In this experiment, AWG 710 is used to generate the CAP signals, where the signal voltage peak-to-peak value (Vpp) is adjustable. The generated CAP signal then passes through T-based hardware pre-equalizer [23] to compensate the frequency attenuation. Then, the signal is amplified with an electrical amplifier (EA), the amplified signal and direct current (DC) bias voltage are combined by a bias tee. After amplified and DC biased, the signal is used to drive the red LED. In this paper, a commercial RGBA LED (LZ4-00MA00) is utilized as the transmitter. The maximum output power of red LED is 2 W. The receiver used in the experiment is silicon-based PIN photodiode. The optimal frequency response band of the receiver is in the range of red light wavelength. Therefore, the receiver’s frequency response to red light LED will be more sensitive than green and blue LED. A higher transmission rate can be achieved by using red light LED. A reflection cup with a 60° divergence angle is applied to decrease the beam angle of the LED and lens are used to converge the beam. The transmission distance is fixed as 1.5 m.

LEDs also have nonlinearity. To illustrate the LED nonlinearity, the V-I curve of the red chip of the RGBA LED is measured, as shown in Fig. 4. The U-I curve of red LED is obviously nonlinear, which
will bring distortion to the modulated signal. Therefore, two factors dominate the nonlinear effects: bias voltage and the input signal peak-to-peak value (Vpp). The nonlinearity of modulation curve severely limits the Vpp of input signal and the modulation depth of signal is decreased. Besides, the power efficiency of the system will also be decreased and the nonlinearity will have an adverse effect on the detection of the receiving signal.

At the receiver, a commercial differential outputs PIN photodiode [24] is used to detect the optical signals. EAs are employed to amplify the differential output signals and the signals are recorded by two different channels of a digital storage oscilloscope for further offline demodulation and signal processing. In offline signal processing, the signal is sent into a pair of matched filters to separate the in-phase and quadrature components of the signal. After down-sampling, RLS post-equalization is employed. Then a simple modular operation is used to realize FTN decoding and QAM decoder is followed to further recover the original bit sequence and calculate BER.

4. Experimental Results and Discussions

In WLUT, the computational complexity is increased with the increase of pattern length, although the accuracy of nonlinearity estimation is improved. The real part and imaginary part of WLUT with 3-symbols and 7-symbols patterns for FTN CAP QPSK signal via training sequence as shown in Figs. 5 and 6.
Then, in order to choose the appropriate pattern length and pre-distortion weight of the system, BER versus pattern length and pre-distortion weight is measured in VLC system and shown in Fig. 7. From Figs. 5 and 6 respectively, it can be observed that longer pattern symbols estimate larger nonlinear distortion. Besides, it can be clearly seen that the symbol distortion value is zero in some pattern index due to FTN pre-coding used in this system and this situation will be more obvious with the increase of the pattern length. The FTN signal is obtained by duobinary encoding of the real and imaginary parts of the original QPSK signal. When the table is being set up, the index value $i$ of each pattern is obtained based on the coded signal. The index value $i$ is the address of each pattern. When the pattern length is $2^N + 1$, theoretically, the number of pattern index for the real parts and imaginary parts of FTN CAP QPSK signal should be $3^2^{N+1}$ respectively. But, because of the duobinary encoding, some pattern will not appear. According to Fig. 7, when the WLUT pre-distortion weight is fixed, with the increasing of pattern length, the BER of this system is decreasing correspondingly. But when pattern length is set as 9, BER of this system is higher than that pattern length is set as 7. Besides, when the pattern symbol length is fixed, larger nonlinear pre-distortion weight of the system cannot get a lower BER. For example, comparing with pre-distortion weight of 0.6 and 0.8, BER of the system with pre-distortion weight of 1 is higher when pattern symbols is set as 7. The BER performance is better as the number of patterns increase. At the situation of 3-pattern, the BER with weighted of 0.2 is higher than the threshold while other BERs (i.e., weighted of 0.6, 0.8 and 1) are less than the threshold. When the pattern symbol is 7, we can obtain a better BER performance, wherein, the system reliability is the best when the weight factor is 0.8, it also can be seen from the constellation D shown in Fig. 7. In this system, BER is the lowest when the pre-distortion weight is 0.8 and pattern symbols is 7. Considering the computation complexity and the accuracy of nonlinear estimation, it is appropriate to set pattern symbols as 7 and pre-distortion weight as 0.8 in our experiment.

Fig. 8 shows the constellation of FTN pre-coded at transmitter and obtained at receiver. From Fig. 8, because the WLUT estimates the nonlinearity of the system and compensates for the amplitude of the original pre-coded signal, it can be clearly seen that the constellation of the transmitted FTN pre-coded signal is larger than the standard constellation when WLUT is used in this system. Signal with better performance can be received at the receiver. Moreover, the larger the pre-distortion weight is, the larger the constellation at receiver side becomes. Compared with systems that do not use WLUT pre-distortion, it is obvious that the received constellation is more convergent and clear when WLUT is used in VLC systems.

In order to specifically clarify the influence of WLUT, when the system bandwidth is fixed at 495 MHz, BER of the system with different input signal Vpp and bias currents is measured and shown in Fig. 9. In Fig. 9(a), the bias current is fixed at 150 mA and input signal Vpp is measured from 0.7 V to 1.1 V. At this time, the output power of the red LED is 0.35 W. Then, when the input signal Vpp is fixed at 0.9 V, bias current is measured from 130 mA to 170 mA and the result is shown in Fig. 9(b). The output power of the red LED is from 0.3 to 0.41 W. The measured BER
Fig. 8. The constellation of FTN pre-coded when (a) without WLUT pre-distortion (b) WLUT pre-distortion weight is 0.2 (c) WLUT pre-distortion weight is 0.8 and received when (d) without WLUT pre-distortion (e) WLUT pre-distortion weight is 0.2 (f) WLUT pre-distortion weight is 0.8.

Fig. 9. Measured BER versus (a) different input signal and (b) different bias current.

Fig. 10. Q factor versus different signal bandwidth employing RLS post equalization and RLS post equalization & WLUT pre-distortion.
performance is the best when the input voltage Vpp is 0.9 V and the current is 150 mA. When the system is working at the optimal condition, compared to using only the linear RLS equalizer, it can also be found that the best BER performance can be obtained by the WLUT pre-distortion and RLS post equalization. When WLUT pre-distortion is employed in the experiment, BER of the system is below the 7% forward error correction (FEC) limit of $3.8 \times 10^{-3}$. These results demonstrate the feasibility of the proposed WLUT scheme for mitigating the nonlinear impairment in VLC systems.

At the optimal working point, the Q factor versus different signal bandwidth employing RLS post equalization and RLS post equalization and WLUT pre-distortion is presented in Fig. 10. From Fig. 10, it is shown that when the bandwidth of the system is 505 MHz, RLS post equalization and WLUT pre-distortion equalizer can outperform the RLS post equalization equalizer by Q factor of 1.09 dB. Finally, a data rate of 1.01 Gbps is experimentally achieved by FTN CAP QPSK over 1.5-m indoor free space transmission.

5. Conclusion

We have posed and experimentally demonstrated 1.01 Gbit/s FTN CAP QPSK signal generation and 1.5-m free space transmission based on WLUT pre-distortion and RLS post equalization. WLUT pre-distortion has small amount of computational load and the nonlinear impairments can be effectively mitigated. RLS post equalization is employed to mitigate the inter symbol interference to improve the decision precision at the receiver side. The experimental results show that RLS equalizer and WLUT equalizer can outperform the RLS post equalization equalizer by Q factor of 1.09 dB and a data rate of 1.01 Gbps is experimentally achieved. These results demonstrate the feasibility of the proposed WLUT scheme for mitigating the nonlinear impairment in VLC systems.

References


