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Adaptive filtering for white-light LED visible light communication

Chin-Wei Hsu,^a Guan-Hong Chen,^a Liang-Yu Wei,^a Chi-Wai Chow,^{a,*} I-Cheng Lu,^b Yen-Liang Liu,^b Hsing-Yu Chen,^b Chien-Hung Yeh,^c and Yang Liu^d

^aNational Chiao Tung University, Department of Photonics and Institute of Electro-Optical Engineering, Hsinchu 30010, Taiwan

^bIndustrial Technology Research Institute, Hsinchu 310, Taiwan

^cFeng Chia University, Department of Photonics, Taichung 40724, Taiwan

^dPhilips Electronics Ltd., N.T., Hong Kong

Abstract. White-light phosphor-based light-emitting diode (LED) can be used to provide lighting and visible light communication (VLC) simultaneously. However, the long relaxation time of phosphor can reduce the modulation bandwidth and limit the VLC data rate. Recent VLC works focus on improving the LED modulation bandwidths. Here, we propose and demonstrate the use of adaptive Volterra filtering (AVF) to increase the data rate of a white-light LED VLC system. The detailed algorithm and implementation of the AVF for the VLC system have been discussed. Using our proposed electrical frontend circuit and the proposed AVF, a significant data rate enhancement to 700.68 Mbit/s is achieved after 1-m free-space transmission using a single white-light phosphor-based LED. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.56.1.016115]

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1 Introduction

The need for low electricity consumption around the world has created rapid growth of the light-emitting diode (LED) market. Apart from illumination, LED is also a good transmitter (Tx) for optical wireless communication, known as visible light communication (VLC).¹⁻⁵ VLC is considered a promising solution for the next-generation 5G wireless communications⁶ since it uses the visible spectrum to solve the congested radio-frequency (RF) communication spectrum. It can be applied in internet-of-thing and indoor positioning, as reported in our previous papers.^{7,8} White-light phosphor-LED is a low-cost solution for VLC and lighting simultaneously. However, the long relaxation time of phosphor reduces the modulation bandwidth and limits the VLC data rate.¹ Several schemes have been proposed to increase the VLC data rate, such as using a blue filter in front of the optical receiver (Rx) to remove the yellow light,⁹ using electrical equalization circuits,¹⁰ and using spectral-efficient discrete multitone or orthogonal frequency division multiplexing (OFDM) modulations.^{11,12} Among the proposed methods, using OFDM modulation is popular since it provides a high spectral efficiency for the bandwidth limited VLC link. In addition, modulate high speed digital-to-analog converter (DAC) and analog-to-digital converter (ADC) for encoding and decoding OFDM signal used in RF communication are commercially available and low cost.¹² Although OFDM provides many advantages, it has a high peak-to-average power ratio (PAPR) and can suffer from signal degradation caused by the nonlinear transfer function of the LED. Using multiple-band OFDM modulations has been demonstrated¹³ to mitigate the LED nonlinearity; however, multiple LED chips are required.

Other schemes such as using semidefinite relaxation or pilot-assisted PAPR reduction have been proposed.¹⁴⁻¹⁶

In this work, we propose and demonstrate the use of adaptive Volterra filtering (AVF) to increase the data rate of a white-light LED OFDM VLC system. In Ref. 17, Volterra decision feedback equalizer (DFE) was used for nonlinearity compensation of phosphor white LED-based VLC. However, the equalizer was used for pulse amplitude modulation and only second-order Volterra DFE was utilized. In Ref. 18, Volterra nonlinear equalizer was applied for the red-green-blue LED-based VLC using carrier-less amplitude and phase modulation. In our work, the designed front-end circuit was first used to increase the modulation bandwidth of phosphor white LED Tx. In addition, the OFDM modulation with bit loading algorithm was used to enhance the spectral efficiency. Finally, we utilized the AVF to compensate for the nonlinear distortion to improve the received signal. Here, we also compare the second- and third-order AVF with different signal amplitudes, and the data rate of >700 Mbit/s using a single phosphor white LED over 1-m free-space transmission was achieved. The algorithm and implementation of the AVF for the VLC system have been discussed.

2 Architecture and Experiment

AVF is used to increase the data rate of the white-light LED OFDM-based VLC system. Its implementation can be performed either in time domain (as demonstrated here) or in frequency domain.¹⁹ Solving the AVF coefficients is an estimation problem. By applying the minimum mean-squared error criterion, the problem can be considered a generalization of Wiener filtering.²⁰ For the actual experimental implementation, during the adaptive equalization process, a training sequence is first sent from the LED to the receiver

*Address all correspondence to: Chi-Wai Chow, E-mail: cwchow@faculty.nctu.edu.tw

(Rx); hence, the equalizer at the Rx can adapt to a proper setting to minimize the error rate. When the equalizer is properly trained, the filter function is converted by obtaining the proper filter coefficients. Figure 1 shows the schematic of the AVF, where k is the discrete time and $x(k)$ and $y(k)$ are the input and output signals, respectively. The adaptive algorithm is controlled by the error signal $e(k)$, which is obtained by comparing the equalizer output signal $y(k)$ with a signal $s(k)$, which either represents a known property of the transmitted signal or is a scaled replica of the transmitted signal. The adaptive algorithm then updates the equalizer coefficients, also called the weight function $w(k)$. The AVF can be represented as

$$\begin{aligned}
 y(k) = & \sum_{l_1=0}^{L-1} w_1(l_1)x(k-l_1) \\
 & + \sum_{l_1=0}^{L-1} \sum_{l_2=0}^{L-1} w_2(l_1, l_2)x(k-l_1)x(k-l_2) \\
 & + \sum_{l_1=0}^{L-1} \sum_{l_2=0}^{L-1} \sum_{l_3=0}^{L-1} w_3(l_1, l_2, l_3)x(k-l_1)x(k-l_2)x(k-l_3) + \dots,
 \end{aligned} \quad (1)$$

where L is the memory length. Figure 2 shows the experimental demonstration of the white-LED VLC system using AVF. The LED is from Cree® (XR-E). It is phosphor-based and with a color temperature of 5500 K. The typical forward voltage is 3.3 V at bias-current of 350 mA. The distance between optical lens and the Tx circuit is set to be the focal length of the lens. The lens has a focal length of 4 cm and a diverse angle of 18 deg. An arbitrary waveform generator (AWG, Tektronix, AWG7122) with a sampling rate of 625 MSample/s performs the DAC by launching the OFDM signal to the Tx circuit. The OFDM signal is

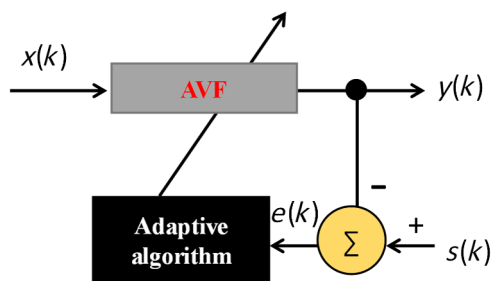


Fig. 1 The schematic of the AVF.

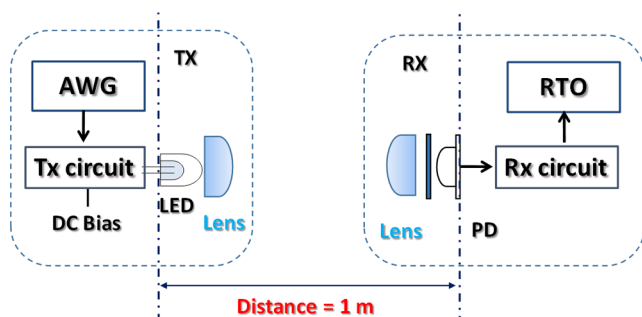


Fig. 2 Experimental demonstration of white-LED VLC system using AVF. AWG, arbitrary waveform generator; RTO, real-time oscilloscope.

generated using off-line MATLAB® program, including serial-to-parallel conversion, quadrature amplitude modulation (QAM) symbol encoding, inverse fast-Fourier transform, and cyclic prefix (CP) insertion. Here the fast-Fourier transform (FFT) size is 256, the CP is about 3%, and the number of subcarrier used is 53. The Tx circuit consists of a pre-equalizer integrated with an electrical amplifier (Texas Instruments, OPA2677), a bias-tee, and a phosphor white-LED.

After 1-m free-space transmission, the VLC signal is launched into the Rx, which consists of a PIN photodiode (PD) (Hamamatsu, S10784) and a trans-impedance amplifier (Texas Instruments, OPA657). A blue filter can be included to attenuate the optical signal to avoid the PD saturation and to extend the analog bandwidth. The PD has the photosensitive area size of 7 mm², optical-to-electrical response bandwidth of 250 MHz, responsivity of 0.45 A/W, and dark current of 0.01 nA at reverse bias voltage of 2.5 V. It has the spectral response range of 340 to 1040 nm. Then the received electrical signal is digitized by a real-time oscilloscope (RTO, Tektronix, CSA 7404) at a sampling rate of 625 MSample/s. It acts as an ADC. The OFDM demodulation consists of off-line synchronization, FFT, CP removal, and QAM symbol decoding. The signal-to-noise ratio (SNR) of each OFDM subcarrier is analyzed to determine the bit-error rate (BER) based on the error vector magnitude. Furthermore, depending on the measured SNR of different OFDM subcarriers, different bit-loading can be applied.

3 Results and Discussion

Before applying the proposed AVF, the modulation bandwidth of VLC Tx can be increased using an electrical front-end Tx circuit. It consists of a pre-equalizer integrated with an amplifier and a bias-tee. The detailed implementation of the Tx circuit can be found in Ref. 12. By adjusting the resistance and capacitance to match with the impedance of the LED, the available modulation bandwidth of the Tx can be extended to about 100 MHz. Then, the proposed AVF is applied to the Tx. The first term in Eq. (1) is a linear equalizer; we have also analyzed and experimentally evaluated the second-order and third-order terms of the AVF. Figure 3(a) shows the measured SNR of each OFDM subcarrier without and with the AVF. When the AVF is not applied, the measured maximum and minimum SNRs are 23.7 and 11 dB, respectively. By applying the first-order (linear filtering) and second-order (nonlinear filtering) of the AVF, the measured maximum and minimum SNRs are increased to 25.2 and 12.6 dB, respectively. By applying the first-order (linear filtering), second-order (nonlinear filtering), and the third-order (nonlinear filtering) of the AVF, the maximum SNR are slightly enhanced to 25.3 dB. As also shown in Fig. 3 (a), before applying the AVF, the bandwidth with SNR > 19 dB is 31.74 MHz. When the first- and second-order AVF is applied, the bandwidth with SNR > 19 dB is extended to 68.36 MHz, which is a more than two times increase in the bandwidth. When the first-, second-, and third-order AVF is applied, the bandwidth with SNR > 19 dB is further enhanced to 83.01 MHz. Figure 3(b) shows the corresponding bit-loading to different subcarriers without and with the first-, second-, and third-order AVF. It is observed that the numbers of OFDM subcarriers that can carry 7 and 6 bits are only 2 and 7, respectively, without

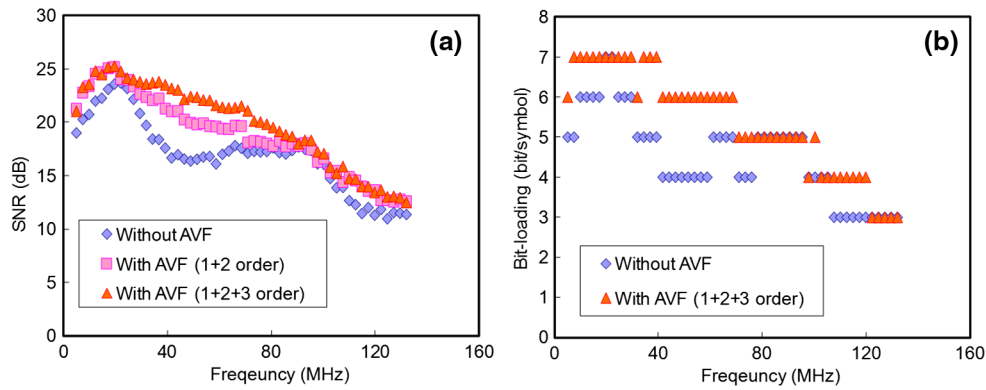


Fig. 3 (a) Measured SNR of each OFDM subcarrier without and with the proposed scheme and (b) the corresponding bit-loading can be achieved in the bandwidth.

the proposed scheme. Using the proposed scheme, the numbers of OFDM subcarriers that can carry 7 and 6 bits are significantly enhanced to 13 and 14, respectively.

Figures 4(a)–4(d) show the experimental constellation diagrams without the proposed scheme at 8-QAM, 16-QAM, 32-QAM, and 64-QAM, respectively. They represent the bit-loadings of 3, 4, 5, and 6 bits/symbol, respectively. Figures 4(e)–4(h) show the corresponding experimental constellation diagrams using the proposed first-, second-, and third-order AVF. It is interesting to note that using the proposed scheme, the SNR of the system has been improved, so more subcarriers can be modulated with higher order modulation format, such as 64-QAM. Therefore, when comparing Figs. 4(d) and 4(h), Fig. 4(h) is denser than Fig. 4(d). Since more subcarriers with AVF have loaded with high order modulation format, when comparing Figs. 4(a) and 4(e), the constellation of Fig. 4(e) is less dense.

Finally, the data rates of the white-light LED VLC system are evaluated. Figure 5 shows the net experimental data rates

achieved without and with the proposed AVF after a free-space transmission of 1 m. The measured signals satisfy the 7% forward error correction BER requirement (i.e., $BER \leq 3.8 \times 10^{-3}$). For a linear VLC system, if the amplitude of the driving signal increases, the received SNR will increase, and the system can achieve a higher data rate. However, from the experimental results shown in Fig. 5, it is observed that without the AVF, the data rate will decrease when the driving signal is increased larger than 78.4 mV; showing the nonlinearity issue degrading the data rate. After applying the first- and second-order AVF, the driving signal amplitude achieving the highest data rate is increased to 87.5 mV. After applying the first-, second-, and third-order AVF, the driving signal amplitude achieving the highest data rate is increased to 98 mV. The experimental results also illustrate that when there is no AVF, the optimum LED driving voltage is 78.4 mV to achieve data rate of 603.03 Mbit/s. The optimum LED driving voltages are increased to 87.5 mV (achieving a data rate

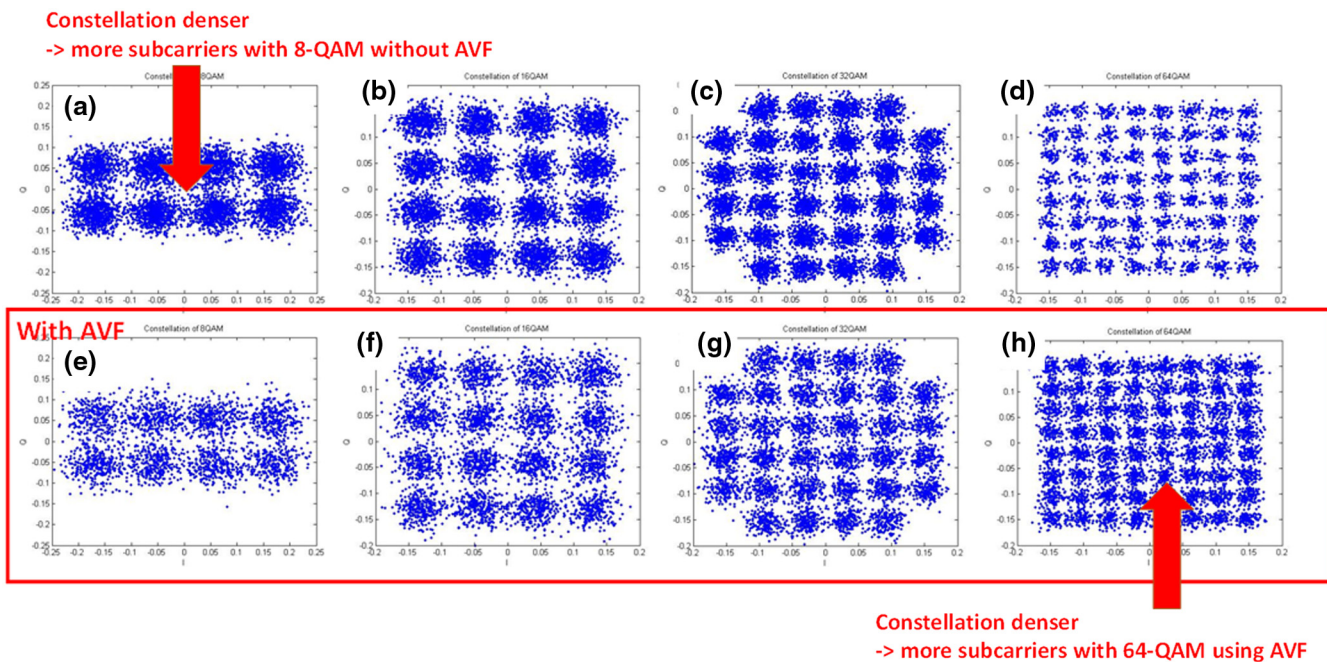


Fig. 4 Experimental constellation diagrams (a)–(d) without using the proposed scheme and (e)–(h) with the proposed first-, second-, and third-order AVF.

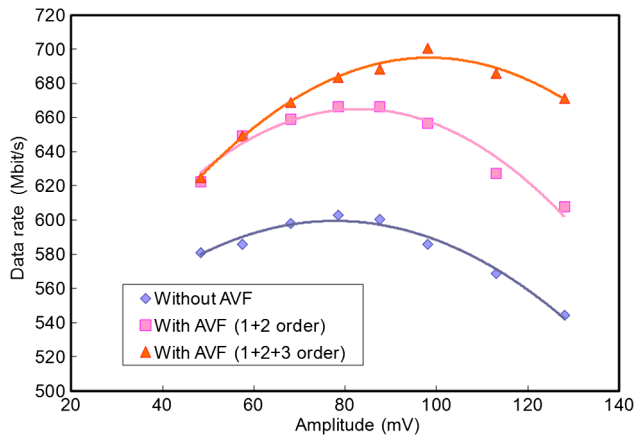


Fig. 5 Experimental data rates achieved without and with using the proposed scheme with free-space transmission of 1 m.

of 666.50 Mbit/s) and to 98 mV (achieving a data rate of 700.68 Mbit/s) after the application of the first- and second-order AVF; and the first-, second-, and third-order AVF, respectively. The interference caused by the nonlinearity is mitigated after using the proposed scheme.

4 Conclusion

Using white-light LED is a cost-effective solution for providing VLC and lighting simultaneously. Here, we proposed and demonstrated using AVF to increase the data rate of white-light LED VLC system. The detailed algorithm and implementation of the AVF for the VLC system have been discussed. In a free-space transmission distance of 1 m, when there was no AVF, the optimum LED driving voltage was 78.4 mV to achieve data rate of 603.03 Mbit/s. The optimum LED driving voltages were increased to 87.5 mV (achieving a data rate of 666.50 Mbit/s) and to 98 mV (achieving a data rate of 700.68 Mbit/s) after the application of the first- and second-order AVF and the first-, second-, and third-order AVF, respectively. The interference caused by the nonlinearity was mitigated after using the proposed scheme.

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Biographies for the authors are not available.