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Programmable Anti-Logarithm Linearization Circuits (PALC) for Self-Adaptive Signal-to-Noise Ratio Optimization in Photovoltaic Visible Light Communications

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Abstract *A programmable anti-logarithm linearization circuit (PALC) for linearizing photovoltaic modules is proposed and implemented. With the investigation of an optimal number of diodes required in PALC under different scenarios, a BER reduction from 1.4×10^{-1} to 8.2×10^{-3} is achieved under 1000 lux with self-adaptation.*

Introduction

Photovoltaic (PV) modules are promising devices that offer energy harvesting and visible light communication (VLC) reception simultaneously [1]. Unlike VLC receivers using photodiodes (PD), PV-based VLC receivers do not require external power during the optical-electro (OE) conversion process. Additionally, the relatively large physical area of PV modules significantly alleviates the alignment requirement and can accommodate a large diverged optical beam. However, when PV modules are used in optical signal detection without reverse bias, its OE response suffers from logarithmic nonlinearity [2]. That nonlinear response severely degrades the performances of multilevel modulation communication that is commonly used in bandlimited channels to achieve a higher data rate. Therefore, device linearity enhancement or nonlinear distortion compensation is critical for high-performance PV receivers.

The nonlinear distortion in PV modules is exacerbated at low illuminance [3] or when the received signal amplitude (modulation index) is relatively large [4]. PV modules in VLC are also susceptible to the fluctuation of environmental illuminance as it results in different operation regions, consequently different nonlinearity, of the OE response. Two compensation methods, local light compensation [3] and passive diode compensation [5], have been proposed for PV modules. Both schemes are suitable for fixed illuminance and fixed received signal amplitude scenarios, but not applicable for mobile devices or when received illuminance varies due to shading from passing by humans/objects. Thus, a self-adaptive linearizer that can flexibly adjust the effective OE response curve with respect to illuminance is highly desirable for PV-based VLC systems.

In this paper, we propose a programmable anti-logarithm linearization circuit (PALC) to achieve linear OE response for PV photodetectors. We investigate the effectiveness of nonlinearity compensation in terms of signal-to-noise ratio (SNR) for four-level pulse-amplitude modulation (PAM4) signals. Experimental results show that the PALC can maximize the SNR by adaptively adjusting the compensation under different illuminance and modulation indexes. A significant BER reduction from 1.4×10^{-1} to 8.2×10^{-3} is achieved by self-adaptive linearization.

Principle of PALC

The instantaneous output voltage generated by a PV module is denoted by [3]:

$$V = h(L) = \frac{nk_BT}{q}\ln\left(\frac{\eta L}{I_0}+1\right), \quad (1)$$

where V is the primary voltage generated by the PV module, $h(L)$ denotes the OE transfer function of a PV module, and L is the incident illuminance in lux. I_0 is the reverse saturation current of the diode, n is the diode ideality factor, k_B is Boltzmann's constant, T is the temperature in Kelvin, q is the electron charge, and η is a conversion factor converting illuminance to current. Eq. (1) shows that the output voltage of the solar panel increases logarithmically with illuminance, manifesting the origin of the PV nonlinearity.

For the purpose of linearizing the OE response of PV, we propose a linearizer based on the antilog response [6], as shown in the inset of Fig.1 (a). An antilog circuit is mainly based on operational amplifiers (op-amp) where the non-inverting input terminal of the op-amp is connected to the ground, and the inverting input is connected with a diode. Diodes have been used for third-order distortion compensation in CATV systems as well [7]. In order to digitally tune the antilog curve, we propose to use *N* serially connected diodes at the inverting input.

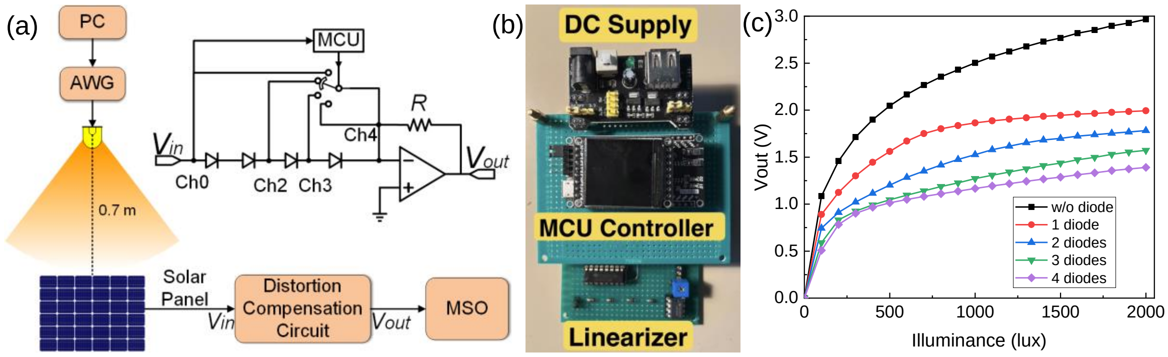

Fig. 1: (a) Experimental setup for solar panel VLC system with PALC, The inset shows the circuit of the PALC module. (b) Snapshot of PALC. (c) DC response curve with *N* numbers of diodes activated in PALC. AWG: arbitrary waveform generator, MSO: mixed-signal oscilloscope, MCU: microcontroller unit.

The number of diodes employed can be modified by a switch to bypass some diodes. More details of the PALC will be given in the following. With *N* diodes connected, the relationship between the input voltage V_{in} and the output voltage V_{out} is:

$$V_{out} = g(V_{in}) = -R\, I_S \exp\left(\frac{V_{in}}{NV_T}\right), \qquad (2)$$

where R is the op-amp load resistor, I_S is the reverse-bias saturation current, and V_T is the thermal equivalent voltage.

With Eq. (1) and Eq. (2), we can obtain the OE transfer function of a PV module cascaded with a PALC as:

$$V_L = g\big(h(L)\big), \qquad (3)$$

where V_L is the load voltage.

Experimental setup and PALC design

Fig. 1 (a) illustrates the experimental setup of the PV-based VLC systems. On the transmitter side, a random data sequence generated by a computer is first converted to PAM4 signals by an arbitrary waveform generator (AWG, Siglent SDG 6022X), with a direct current (DC) bias superimposed. The output electrical signals drive a light-emitting diode (LED, OSRAM LUW W5AM) to generate visible light signals. After 0.7-m free-space transmission, the optical signal is detected by a PV module (ANYSOLAR SM301K09L) and then compensated by a PALC module, as shown in Fig. 1 (b). The compensated voltage is recorded by a mixed-signal oscilloscope (MSO, Tektronix MSO 4054) for subsequent offline signal processing in MATLAB. A lux meter (Smart sensor, AS823) is used to estimate the illuminance. The offline processing procedure includes frame synchronization, recursive least squares (RLS) linear equalization, and PAM4 demodulation. For performance evaluation, we estimated the BER performance with a forward-error-correction (FEC) threshold value of 2.0×10^{-2}.

The linearizer module in Fig.1 (b) contains an op-amp (TI, LM258P), collaborating with four diodes (Risym, 1N4148). For nonlinearity evaluation, the signal generated from the PV module is tapped into the analog-to-digital converter (ADC) port of an MCU (STM32F401CC) MCU that controls a digitally-controlled analog switch (TI, CD4053B) to adjust the desired number of diodes in the circuit. The required DC operation voltage of the whole system is 5 volts. This simple PALC module costs less than 4.75 USD (or 4.5 EUR).

Experimental results

Before transmitting data, we first measure the receiver *V-L* curve to characterize its OE response. As illustrated in Fig. 1 (c), the V-L curve with a different number (*N*) of diodes activated in PALC is illustrated. It is shown that when more diodes are connected in the circuit, the OE response will be more linear, but the slope becomes flatter, implying a smaller output signal amplitude. We will show in the following that under a certain indoor illuminance, there exists an optimal number of diodes that maximizes the SNR for different modulation indexes.

The distortion of PV-based VLC system depends on two factors: (i) the operation region of V-L curve and (ii) the signal modulation index. The first factor is less significant at high illuminance as shown both in indoor [3] and outdoor scenarios [4]. In Fig.2, we investigate the performance of a 1.2-Mbit/s PAM4 signal under 1200 lux, where the first distortion factor is less severe. Fig.2 (a) shows that with no diodes activated, SNR maximizes when the modulation index is 0.16. Below 0.16, SNR will degrade due to a smaller signal swing. Above 0.16, nonlinear distortion exacerbates, leading to degrading SNR with the increase of modulation index. By using three-diode or four-diode PALC, higher maximal SNR can be achieved at a larger modulation index, demonstrating the effectiveness of the PALC for distortion mitigation. With the increase of modulation index, the optimal number of diodes for distortion compensation will increase.

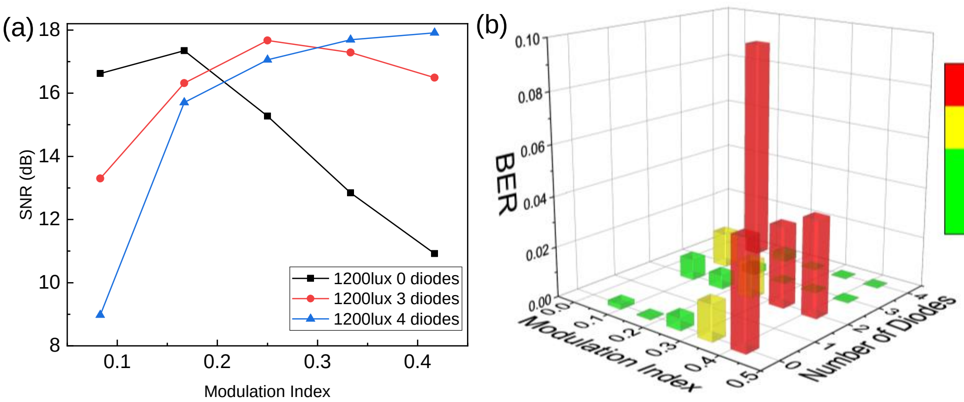

Fig. 2: (a) SNR with respect to modulation index for a 1.2-Mbit/s PAM4 communication with different numbers of diodes activated in PALC. (b) BER with respect to modulation index and number of diodes for a 1.2-Mbit/s PAM4 communication.

The BER results illustrated in Fig.2 (b) further attest to this trend. We have also conducted experiments under 800 lux, and 1600 lux, and the trends are similar to that for 1200 lux.

Albeit the modulation index can be adjusted to attain the maximal SNR for different receiver illuminance, it may not be practical as it requires a feedback link to the transmitter. Therefore, adjusting the linearization circuit at the receiver would be more feasible and desirable. Based on the above characterization, we implemented a self-adaptive algorithm in the MCU to support automatic optimization for a robust photovoltaic VLC system. The MCU-ADC port periodically samples the received signal every two seconds and maps its value according to Tab.1 to deduce a suitable number of diodes for linearization. Fig. 3 shows the self-adaptive performance with respect to time. The modulation index was 0.333,

Tab. 1: PALC Diode Selection algorithm

Received DC voltage	Received AC Voltage V_{pp}	Number of diodes
< 2 V	< 50 mV	0
< 2 V	> 50 mV	2
> 2 V	< 100 mV	0
> 2 V	> 100 mV	3

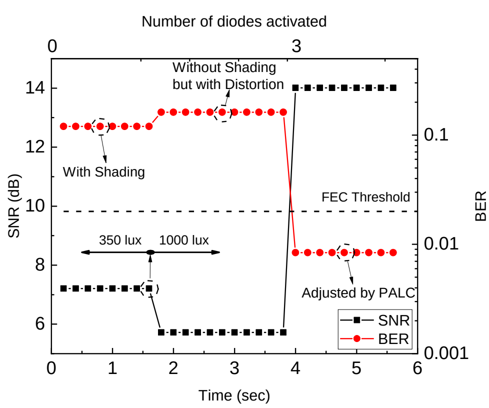

Fig. 3: SNR and BER status when a shading is removed between the communication link.

and the time information was extracted from MSO. From 0 to 1.8 sec, a piece of translucent plastic sheet was randomly chosen as an obstacle to block the light between the transmitter and the receiver. The resultant incident illuminance was 350 lux, and the optimal number of diodes activated was zero, resulting in a BER of 1.2×10^{-1}. After 1.8 sec, the obstacle was removed, and the incident illuminance became 1000 lux, with a received peak-to-peak voltage (V_{pp}) larger than 100 mV. The received signal was severely distorted with a BER of 1.4×10^{-1}. Within around 2 sec, the PALC activated three diodes, and the signal was well linearized with an improved BER of 8.2×10^{-3}. It is worth noting that the PALC can achieve a faster adjustment speed by reducing the ADC sampling intervals.

The proposed scheme is applicable to other PV devices, such as gallium arsenide (GaAs) solar cells that have a larger energy conversion efficiency for satellite applications. Our measurement showed that the GaAs cell also has a logarithm OE response and thus can be linearized with PALC. This will facilitate inter-satellite free-space optics communication [8].

Conclusions

In this paper, we proposed and experimentally demonstrated a simple, inexpensive, yet effective programmable anti-logarithm linearization circuit that can adaptively optimize the linearization circuit under changing environments, such as temporary shading by passing by humans/objects. A self-adjusted BER reduction from 1.4×10^{-1} to 8.2×10^{-3} is demonstrated under 1000 lux in real-time.

Acknowledgments

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References

[1] Z. Wang, D. Tsonev, S. Videv and H. Haas, "On the Design of a Solar-Panel Receiver for Optical Wireless Communications With Simultaneous Energy Harvesting," in IEEE Journal on Selected Areas in Communications, vol. 33, no. 8, pp. 1612-1623, Aug. 2015, DOI: 10.1109/JSAC.2015.2391811.

[2] J. Nelson, "Photons In, Electrons Out: Basic Principles of PV," in Physics of Solar Cells. London: Imperial College Press, 2003, ch2, pp. 43-45. ISBN:978-1-84816-823-7.

[3] S. Chen, L. Liu and L. -K. Chen, "On the Nonlinear Distortion Characterization in Photovoltaic Modules for Visible Light Communication," in IEEE Photonics Technology Letters, vol. 33, no. 24, pp. 1467-1470, 15 Dec.15, 2021, DOI: 10.1109/LPT.2021.3128680.

[4] N. Lorrière, N. Bétrancourt , M. Pasquinelli, G. Chabriel , J. Barrère, L. Escoubas, J. Wu, V. Bermudez, C. Ruiz , and J.Simon, "Photovoltaic Solar Cells for Outdoor LiFi Communications," in Journal of Lightwave Technology, vol. 38, no. 15, pp. 3822-3831, 1 Aug.1, 2020, DOI: 10.1109/JLT.2020.2981554.

[5] S. Chen, L. Liu, and L. Chen, "Passive Nonlinear Compensation Circuits for Photovoltaic Visible Light Communications under Low Illuminance," in Optical Fiber Communication Conference (OFC) 2022, Technical Digest Series (Optica Publishing Group, 2022), paper W2A.32.

[6] A. J. Skinner and M. F. Lambert, "A Log-Antilog Analog Control Circuit for Constant-Power Warm-Thermistor Sensors— Application to Plant Water Status Measurement," in IEEE Sensors Journal, vol. 9, no. 9, pp. 1049-1057, Sept. 2009, DOI: 10.1109/JSEN.2009.2024057.

[7] Yudhi S. Trisno, Lian K. Chen, and David R. Huber "Linearized external modulator for analog applications", Proc. SPIE 1371, High-Frequency Analog Fiber Optic Systems, (1 February 1991); https://doi.org/10.1117/12.24876

[8] S. Zarbakhsh and A. R. Sebak, "Multifunctional Drone-Based Antenna for Satellite Communication," in IEEE Transactions on Antennas and Propagation, DOI: 10.1109/TAP.2022.3145463.