

Passive Nonlinear Compensation Circuits for Photovoltaic Visible Light Communications under Low Illuminance

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Abstract: For photovoltaic nonlinearity, the distortion is much exacerbated at a low illumination level. We propose and experimentally demonstrate a simple passive post-distortion compensation circuit without complex DSP and achieve one-order of magnitude reduction in BER.
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1. Introduction

Photovoltaic (PV) modules are recently used as visible light communication (VLC) receivers for simultaneous energy harvesting and communication, attracting more attention for their low cost and high energy efficiency [1]. Practical VLC systems have been demonstrated with wake-up receivers or audio receivers that use PV modules as the photo detectors [2], [3]. This energy-efficient optical receiver can be used in extensive indoor scenarios, such as capturing information from light sources to update product information on eTags or organic light-emitting diode (OLED) screens in shops or supermarkets [4].

For bandlimited optical communication channels, multilevel modulation formats can be used to achieve a higher data rate. However, multilevel modulation formats are susceptible to nonlinearities in the electrical-to-optical conversion and optical-to-electrical conversion, thus requiring higher device linearity or advanced signal processing for nonlinearity mitigation [5]. In VLC, for a photodiode (PD)-based VLC system, the light-emitting diode (LED) is the major source of nonlinearities as distortion in PD is insignificant [6]. However, for PV-based receivers, signals detected by PV modules suffer from severe nonlinear distortion due to the recombination process in PV cells during the absorption process that gives rise to the logarithmic relationship between the output voltage and the input light luminance [7]. The distortion is more exacerbated under low illumination, which is the typical setting for indoor [8]. Thus, it is important to investigate the PV-based VLC system under low illuminance. In [9], we have investigated nonlinearity-induced degradation in communication performance for PV receivers. Significant performance enhancement in bit-error-rate (BER) by using a local distortion compensation light or post-distortion compensation signal processing has been demonstrated experimentally [9]. To further simplify the distortion compensation circuit and reduce power consumption, passive analog distortion compensation is desirable. This is particularly valuable for Internet-of-thing applications with low-power consumption.

In this paper, we propose a passive distortion compensation circuit based on a simple diode array to realize a low-complexity linear optical receiver. The output of the PV module is connected to a diode array to attain a linear response for signal detection. The experimental results show that there exists an optimum number of serially connected diodes under a given illuminance. Our proposed scheme shows effective mitigation of the PV nonlinear distortion. Under the indoor illuminance of 400 lux, around one-order of magnitude reduction in BER, from 8.2×10^{-2} to 9.5×10^{-3}, is achieved for a 1.0-Mbit/s four-level pulse-amplitude modulation (PAM4) transmission.

2. Principles of nonlinear compensation circuits

The output voltage generated by a PV module is denoted by [7]:

$$V \approx \frac{nk_BT}{q}\ln\left(\frac{\eta L}{I_0}+1\right), \tag{1}$$

where V is the primary voltage generated by the PV module, 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, η is a conversion factor converting illuminance to current, and L is the illuminance in lux. Eq. (1) shows that the output voltage of the solar panel increases logarithmically with light intensity, manifesting the origin of the PV nonlinearity. We propose a simple passive post-distortion compensation circuit consisting of serially connected diodes to mitigate the PV distortion. The compensation circuit's output voltage is the difference between the PV's output voltage and the diode array's voltages. Based on the diode equation, the output voltage is:

$$V_L = \frac{nk_BT}{q}\ln\left(\frac{\eta L}{I_0}+1\right) - N\frac{nk_BT}{q}\ln\left(\frac{I_L}{I_s}+1\right), \tag{2}$$

where I_L is the current flow over the load that depends on the photocurrent and load resistance value, I_s is the reverse-bias saturation current, and N is the number of diodes connected in series. It will be shown in the following that for a fixed illuminance, there is an optimal number of diodes for the distortion compensation. Details of the characterization of the compensation circuit and the optimal diode number will be discussed.

3. Experimental setup

Fig. 1 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 5162), 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 0.5-m or 0.7-m free-space transmission, the optical signal is detected by a PV module (ANYSOLAR SM301K09L) and then compensated by a distortion compensation circuit. The inset shows the equivalent circuit of the PV module and the distortion compensation circuit. The compensated voltage on the load R_L is recorded by a mixed-signal oscilloscope (MSO, Tektronix MSO 4054) for subsequent offline signal processing. A lux meter (Smart sensor, AS823) is used to estimate the illuminance. For performance evaluation, we estimated the BER performance with a forward-error-correction (FEC) threshold value of 2.0×10^{-2}.

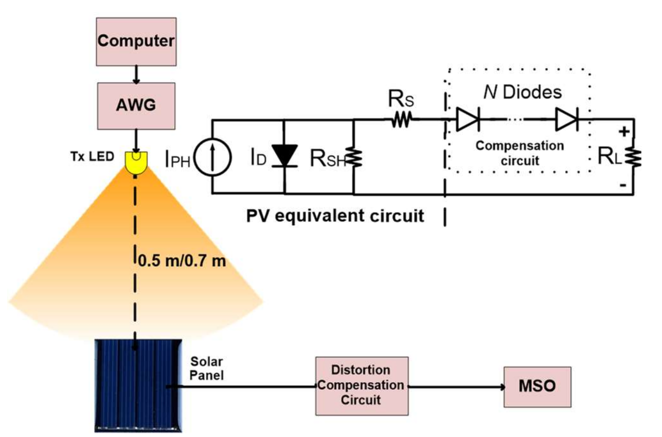

Fig. 1. Experimental setup for solar panel VLC system with diode array. AWG: arbitrary waveform generator, MSO: mixed-signal oscilloscope. The inset shows the equivalent circuit of the PV module and the distortion compensation circuit.

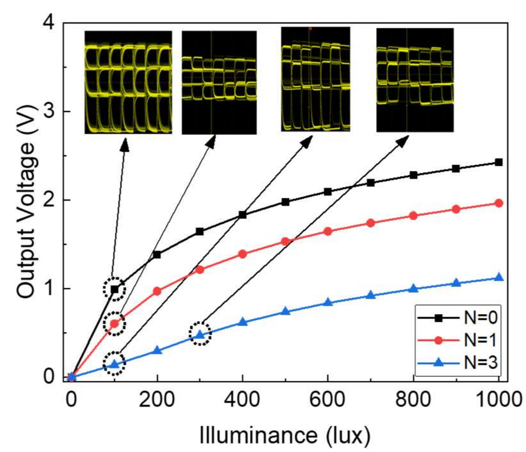

Fig. 2. DC response curve and signal distortion. N: number of diodes serially cascaded. The inset shows the eye diagram examples of PAM4 signals under different illuminance and with different *N*.

4. Results and discussions

Before transmitting data, we first measure the receiver *V-L* curve to characterize its optical-electro (OE) response. As shown in Fig. 2, the *V-L* curve with a different number (*N*) of diodes is illustrated. From Eq. (1), it can be shown that the nonlinear distortion is more severe at low illumination [9]. Eye diagrams of PAM4 signals for different *N* and *L* are illustrated in the inset of Fig.2. Without using diodes, the PAM4 signals suffer severe nonlinear distortion under the illuminance of 100 lux. The distortion is compensated when connecting one diode in the circuit. However, additional distortion is introduced when three diodes are used. The 3-diode circuit exhibits better distortion compensation under an increased illuminance of 300 lux than that under 100 lux. Considering a specific indoor scenario, the illuminance level may be fixed and is not a free parameter. In the following, we will investigate the effect of the number of diodes on the communication performance to find the optimal number for different illuminance.

Fig. 3 shows the BER results for different numbers of diodes connected in serial under 300 lux and 400 lux with different modulation indexes at the transmitter. It is shown that under 300 lux, the optimized number of cascaded diodes is two, whereas three diodes are required under 400 lux. Further increase in diode number than the optimal one induces overcompensation as well as reduced signal strength due to the flatter slope (as shown in Fig. 2), thus resulting in BER degradation. In Fig. 4, we investigate the BER of a 1.0-Mbit/s PAM4 signal with respect to its modulation index under different illuminance when the optimized diode array is employed. Two communication distances at 50 and 70 cm, corresponding to different illuminance, are used in the transmission. For both illuminances, without compensation, the signal amplitude increases when modulation index is increased from 0.1 to 0.2, resulting in BER reduction. However, a further increase in modulation index leads to BER degradation due to escalated nonlinear distortion. Comparing the two cases with and without distortion compensation, we can see from Fig. 4 that with compensation, the BER is reduced for all modulation indexes. In addition, for the two cases with compensation, the BERs always decrease with the increment of the modulation index, showing the effectiveness of the proposed passive compensation scheme. When the modulation index is larger than 0.4 for compensated cases, both 300 lux and 400 lux BER is below FEC threshold thus efficient for decoding. While 400-500 lux is a typical office illuminance, we further investigate communication performances in dim scenarios. At 280 lux, BER reduction from 1.6×10^{-2} to 1.3×10^{-3} is achieved for 0.8-Mbit/s transmission using a 3-diode array compensation circuit. In addition, at a dimming condition with an illuminance of 120 lux, BER reduction from 6.5×10^{-2} to 1.4×10^{-2} is realized for 0.8-Mbit/s transmission using a 2-diode array. With the effective passive compensation scheme, the BERs also decrease with the modulation index increment for the two dim illuminance cases.

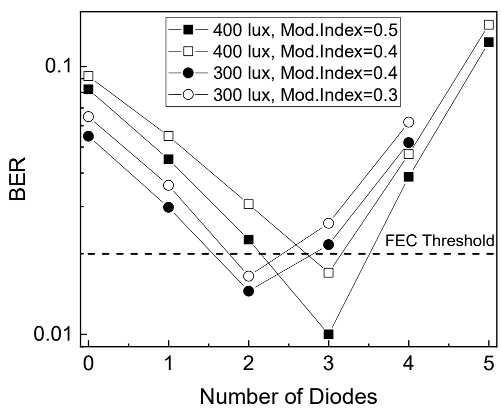

Fig. 3. BER with respect to the numbers of diodes cascaded for a 1.0-Mbit/s PAM4 communication.

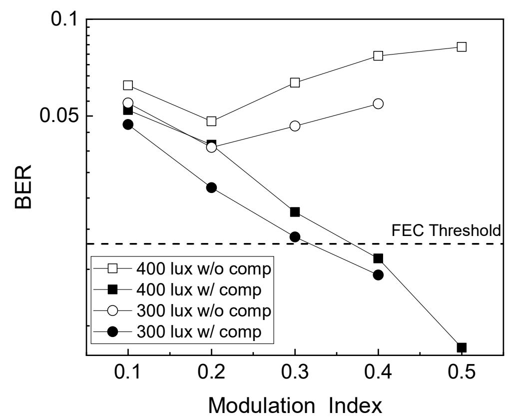

Fig. 4. BER with respect to modulation index for a 1.0-Mbit/s PAM4 communication signal under (i) 300 lux/2 diodes and (ii) 400 lux/3 diodes .

5. Conclusion

In this paper, we propose and experimentally demonstrate an effective and simple passive post-distortion compensation circuit using a serially-connected diode array to mitigate the nonlinearity in the PV-based VLC system. BER reduction is achieved without additional digital signal processing that consumes power. With the proposed scheme, a 1-Mbit/s transmission link is realized with BER reduced from 8.2×10^{-2} to 9.5×10^{-3} under the illuminance of 400 lux. This work is supported in part by HKSAR RGC GRF 14207220 and 14204921.

6. References

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