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Performance of a Photovoltaic Module for Energy Harvesting and Optical Wireless Communications

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Abstract — In this article, we present the simulation model of a photovoltaic module (PVM) used in an optical wireless communication system for both data reception and energy harvesting. A light-emitting diode placed at the center of a 4×4×2.85 m room transmits a 10 kbps Manchester-encoded on-off keying data stream, that is received and decoded by a PVM moving across a reception plane 2 m from the source. We obtained a null bit error rate whatever the PVM position, and a maximum harvested power of 0.42 mW.

Keywords — Optical wireless communications, energy harvesting, photovoltaic module

I. INTRODUCTION

Communications needs are growing at an extremely rapid pace, and so is the deployment of new wireless technologies to meet them, including radio frequency, future terahertz and optical wireless communications (OWC) [1]. In a context of strong environmental concerns [2], such technologies must be sustainable, especially in terms of energy efficiency and power consumption. One solution addressing the later issue is to collect the energy carried by the data signals received by communication systems and the ambient energy: this is energy harvesting [3-6].

In the optical field, such a solution can be implemented using photovoltaic modules (PVM), designed to convert optical energy into electrical energy, rather than conventional photodiodes, although the latter may provide higher data rate as they usually have larger bandwidth [1]. For example, in [4], the use of a PVM is demonstrated experimentally and a data rate of 11.84 Mbps is achieved simultaneously with a harvesting power of 30 mW when the distance between the emitter and the PVM is 0.75 m. However, these results were obtained at a given distance without considering other crucial metrics like the communication coverage.

In this paper, we simulate with MATLAB an end-to-end OWC system using a state-of-the-art PVM for both energy harvesting and optical signal reception, and we study its performance in terms of data rate, energy harvesting and communication coverage. To that extent, we first detail the system and PVM models (Section II) and then the simulation results obtained (Section III), before concluding the paper (Section IV) with final remarks and future works.

II. STUDIED SYSTEM ARCHITECTURE AND MODELLING

Figure 1 shows the architecture of the simulated system. The data transmitted in the form of light radiation from the light emitting diode (LED) propagates through the OWC channel before being collected by the PVM. This data is transmitted using on-off keying (OOK) modulation with Manchester coding (i.e. a bit '1' corresponds to the symbol '10' and a bit '0' to '01'). The PVM, on its side, is composed of a photovoltaic panel along with a receiver circuit that recovers the data and the electrical power they carry.

To simulate the communication performance of such a system, it is necessary to model its frequency response, which links the optical signal emitted (ϕ_e , in [W]) to the load terminal voltage of the PVM ($v(f)$, in [V]), and is given by:

$$v(f) = \phi_e H(0) \mathcal{R} H_p(f), \quad (1)$$

where $H(0)$ (without units) models the OWC channel gain, \mathcal{R} (in [A/W]) is the PVM responsivity and $H_p(f)$ (in [V/A]) models the PVM frequency response.

Then the energy harvesting performance of the system, i.e. the electrical power P_e collected on the terminals of the load R_L of the harvesting branch, can be evaluated by calculating the DC current across R_L while assuming the AC source of the circuit is off (as the AC part is strongly attenuated by the energy harvesting branch). This leads to:

$$P_e = \frac{\left(\frac{r R_{SH} H(0) \phi_e \mathcal{R}}{r + R_{SH}}\right)^2 R_L}{(R_L + R_S)^2}, \quad (2)$$

with r , R_{SH} , R_L and R_S as defined in Table I.

In practice, we can model the OWC channel using Lambert's emission law, which relates the optical power ϕ_e emitted by an LED to the optical power ϕ_r incident to a photoreceiver of area S , and is given by [1]:

$$H(0) = \frac{\phi_r}{\phi_e} = \frac{(m+1)S}{2\pi d^2} \cos^m(\phi) \cos(\psi), \quad (3)$$

with m the Lambertian order, defined as $m = -\ln 2 / \ln(\cos \theta_{1/2})$, $\theta_{1/2}$ the semi-angle at half power of the LED source, ϕ the radiation angle, ψ the incidence angle and d the distance between the LED and the PVM.

In parallel, we can model the PVM frequency response $H_p(f)$ as $H_p(f) = \frac{v(f)}{i_{ph}(f)}$, where $i_{ph}(f)$ is the AC part of the photocurrent generated by the PVM from the incident optical power ϕ_r . Although the literature lists three main electrical models for PVMs – with one, two or three diodes –, our study is restricted to the use of the one-diode model as it remains accurate [4] and requires less simulation time when estimating parameters or evaluating the PVM performance. In Fig. 1, the PVM is thus represented following the equivalent one-diode model proposed in [4], which includes multiple passive dipoles modelling each specific physical behaviors, as detailed in Table I. According to this model:

$$|H_p|^2 = \left[\frac{\frac{R_{LC} R_C}{R_S + j\omega L + R_{LC} \frac{1}{j\omega C_0} + R_C}}{\frac{1}{r + j\omega C + \frac{1}{R_{SH} + R_S + j\omega L + R_{LC}}}} \right]^2, \quad (4)$$

with $R_{LC} = \frac{1}{\frac{1}{R_L + j\omega L_0} + \frac{1}{R_C + 1/j\omega C_0}}$ an equivalent impedance.

Finally, when converting ϕ_r into $v(f)$, the PVM also adds shot and thermal noise, which expressions are not detailed here but were simulated following the same model as in [4].

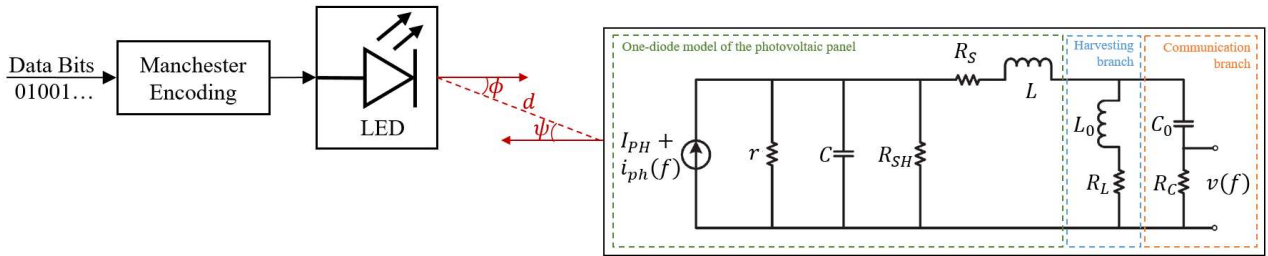


Fig. 1. Block diagram of the simulated system with the equivalent electrical model of the PVM.

III. SYSTEM PERFORMANCE

Table I lists the parameters used in our simulations, defined as in [4]. With these parameters, the PVM frequency response has a flat -3 dB bandwidth from around 350 Hz to 110 kHz, which strongly limits the achievable data rate, unless bandwidth enhancement or equalization techniques are used [5]. Therefore, we set the OOK data rate to 10 kbps for the rest of the simulations, which consist in evaluating the spatial distribution of the bit error rate (BER) and energy harvested when the LED is at the centre of the ceiling of a $4 \times 4 \times 2.85$ m room, and the PVM moves by steps of 20 cm along the x and y axis of a reception plane 2 m from the source.

TABLE I. PARAMETERS VALUES USED.

Description	Symbol	Value
Serial resistor	R_s	1Ω
Shunt resistor	R_{sh}	$20 \text{ k}\Omega$
Small signal equivalent resistor	r	720Ω
Branch resistance for energy conversion	R_L	$1 \text{ k}\Omega$
Resistor of the data reception branch	R_c	50Ω
PVM capacitive effect	C	34 nF
Capacitance to block the DC component of the photo-generated current	C_0	$1 \mu\text{F}$
Serial inductance	L	120 nH
Inductance to attenuate the AC component of the photo-generated current	L_0	10 mH
PVM sensitive area	S	432 cm^2

Figure 2 shows on the one hand an example of transmitted optical signal (in blue) and the resulting voltage signal output by the PVM (orange). We observe the output signal has a very low amplitude because of the OWC channel path loss, and that its shape is not square anymore because of the low-pass and high-pass effects of the PVM frequency response. However, the noise level is so low that the signal-to-noise ratio (SNR) remains high enough at any position of the PVM in the room (around 40 dB), so that the BER spatial distribution remains null (after transmitting 1000 bits) and the whole room is thus correctly covered. Such a high SNR also shows that more advanced modulations could be used to reach higher data rate.

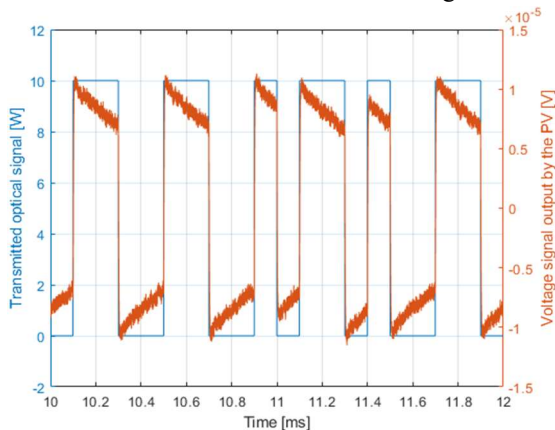


Fig. 2. Example of time evolution of the transmitted optical signal (blue) and voltage signal output by the PVM (orange).

On the other hand, Fig. 3 shows the spatial distribution of the power harvested by the PVM, which is higher when the PVM is closer to the transmitter. This is due to the effect of the OWC channel gain (3), which depends on the distance between transmitter and receiver. The maximum value is eventually 0.42 mW at a distance of 2 m (at 0.75 m, it reaches 21.3 mW, which is line with the 30 mW measured in [4]), but it drops quickly as the PVM moves away from the optical axis of the emitter.

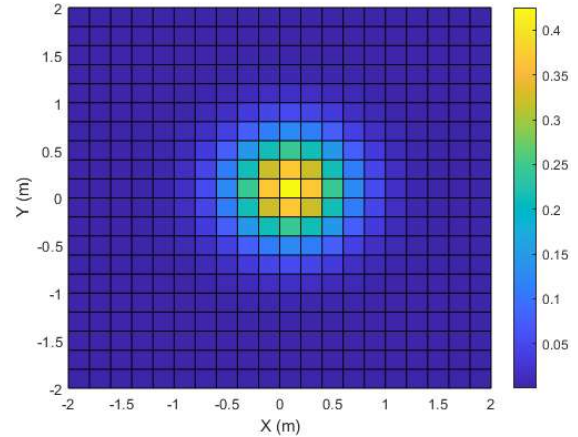


Fig. 3. Spatial distribution of the electrical power harvested (in [mW]).

IV. CONCLUSIONS AND FUTURE WORKS

In this paper, we evaluated the communication coverage and energy harvesting performance of an OWC system using a PVM as receiver. We concluded that at 10 kbps, the communication is error-less across the whole room, but that the energy harvested drops quickly as the PVM moves away from the source. In future works, we will investigate the interest of beamsteering (i.e. real-time alignment between the source and PVM) to optimize the energy collected and validate these results through experimental measurements.

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