

Powering a Sensor Node with an Organic PV Module Under Low-Light Indoor Conditions

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Summary: This work presents an optical harvesting system to power a wireless sensor node operating under low-light indoor conditions. By integrating an organic photovoltaic cell with an optimized power management and storage sizing, self-sustained operation is achieved at low-light indoor conditions. Experimental and in-situ testing demonstrate continuous functionality, offering a robust, battery-less solution for sustainable indoor IoT deployments under indoor illuminance levels as low as 182 lx.

Keywords: autonomous sensors, energy harvesting, low illuminance, photovoltaic cell.

Introduction

The massive deployment of wireless sensor nodes (WSN) is currently transforming fields such as healthcare, Industry 4.0, and residential monitoring. With approximately half of these devices expected to operate in indoor environments, sustainable powering remains a critical challenge [1]. Transitioning away from conventional batteries is essential to reduce maintenance costs and environmental impact. In that sense, Energy Harvesting (EH) systems have emerged as a robust alternative by scavenging ambient energy. Among them, optical EH stands out, in part due to the emergence of novel photovoltaic (PV) technologies such as perovskite and organic (OPV). However, developing PV-based EH systems for indoor applications is challenging, as indoor light sources provide significantly lower irradiance than outdoor sunlight. Furthermore, these systems must balance small form factors with high sensitivity to artificial spectra. Despite previous research has extensively explored the use of PV cells to power WSN [2], this work presents the development of a complete EH system optimized to power a WSN under low-light indoor conditions by using an OPV cell. Its functionality is validated through lab and in-situ testing, proving the system ability to maintain operation of the WSN under real-world, low-illuminance conditions.

Optical Energy Harvester and Sensor Node

Fig. 1 shows a block diagram of the proposed EH system to power an indoor WSN. This comprises three main blocks: an OPV cell, a power management circuit (PMC), and an energy storage unit (ESU). The OPV cell (Dracula Tech.), with an area of 22 cm², was selected for its high sensitivity under indoor LED lighting [3]. As for the

PMC, the AEM30940 (e-peas) was chosen. This features a Maximum Power Point Tracking (MPPT) stage relying on the Fractional Open Circuit Voltage (FOCV) method [4], an energy storage control circuit, and a regulated voltage output. On the other hand, the ESU was implemented by an array of low-cost electrolytic capacitors.

The SHT43 (Sensirion), with a nominal supply voltage of 3.3 V, was used as a WSN to demonstrate the feasibility of the EH system. This WSN is capable of measuring temperature and humidity while transmitting data via Bluetooth Low Energy (BLE) and displaying results on an integrated LCD.

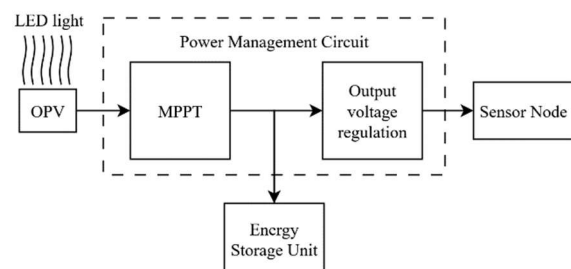


Fig. 1. Block diagram of the EH system powering a WSN.

Experimental Results

Fig. 2 shows the profile of the current consumption of the WSN at 3.3 V. Four distinct operational phases were identified. Phase 0 corresponds to a start-up pulse, whereas phase 3 to steady-state conditions in terms of measurement and communication. The intermediate phases (1 and 2) are similar to phase 3, but the frequency of measurement and communication is higher than that in phase 3. The energy metrics for each stage are summarized in Table 1.

Tab. 1: Charge (Q), energy (E), and mean power (P) consumption of the WSN per phase.

Phase	Interval (s)	Q (mC)	E (mJ)	P (μ W)
0	0-1	2.979	9.791	9791
1	1-32	2.840	9.356	309.4
2	32-303	4.749	15.65	58.38
3	303-500	1.998	6.582	33.11

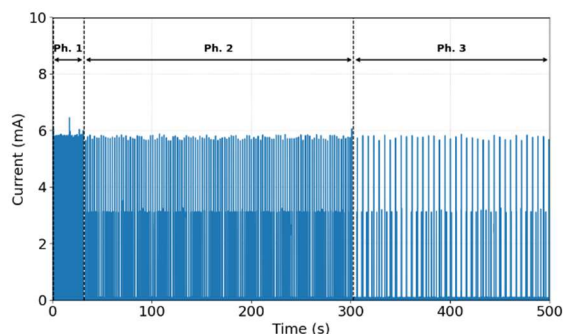


Fig. 2. Profile of the WSN current consumption.

Fig. 3 shows the power-voltage (P - V) characteristics of the OPV cell under different illuminance levels (from 100 lx to 1500 lx) of cold LED (C-LED). The maximum power (highlighted with circular markers) is 40.4 μ W at 100 lx and 585 μ W at 1.5 klx. Therefore, assuming an ideal scenario without losses, the selected PV cell should be able to power the WSN in phase 3 at an illuminance as low as 100 lux. Regarding the PMC, this was set to provide a FOCV ratio of 0.8.

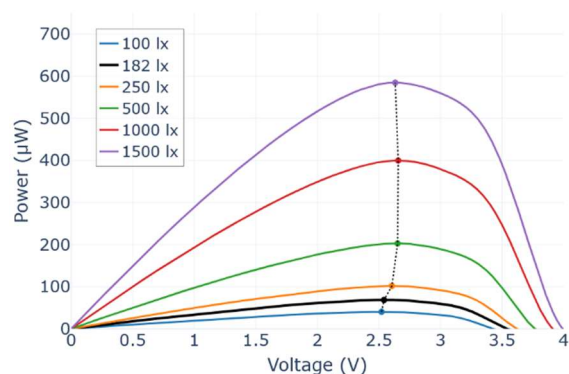


Fig. 3. P - V characteristics for the OPV cell under different C-LED illuminance levels.

The ESU was selected to cope with the more power demanding phases (i.e., phases 0, 1, and 2). In other words, once the WSN is activated (and phase 0 starts), the ESU capacitance should be able to maintain the voltage across it within a given interval. This capacitance was computed as $Q/[V_{\text{CHRDY}} - V_{\text{OVDIS}}]$, where V_{CHRDY} is the voltage (across ESU) at which the PMC output regulator starts powering the WSN, and V_{OVDIS} is a undervoltage protection limit for the

ESU. On the other hand, Q is the charge required during phases 0, 1 and 2 minus the charge already provided by the PV cell assuming that it delivers a power equivalent to that required in phase 3 in the first 303 s (i.e., 3.04 mC). Since $V_{\text{OVDIS}} = 3.6$ V and $V_{\text{CHRDY}} = 4.04$ V, the minimum capacitance is 17.1 mF, although a value of 21 mF was selected.

The complete system in Fig. 1 was validated. Fig. 4 shows the voltage waveforms under 250 lx of C-LED. The WSN starts (supply voltage in blue rises to 3.28 V) when the ESU reaches 4.045 V (in green). Afterwards, during the first 32 s (phases 0 and 1), there is a transient voltage drop at the ESU, but not sufficient to be below V_{OVDIS} . Next, the OPV successfully sustains both the node operation and the recharging of the ESU. This behavior was verified down to 182 lx, which is higher than that determined before theoretically. This is due to the power losses, especially the leakage of the selected capacitor. A capacitor with less leakage could make the system autonomous at lower levels of illuminance.

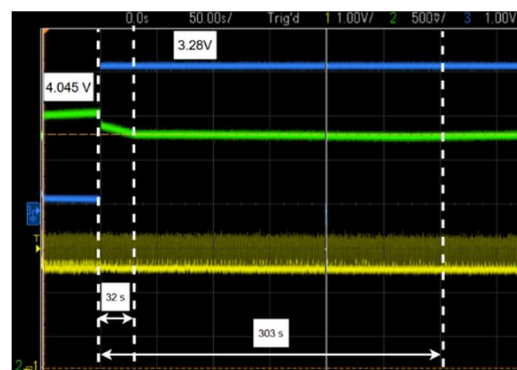


Fig. 4. Voltage across the PV cell (yellow), ESU (green), and WSN supply (blue) at 250 lx. The ground reference of channel 2 is at -1 V.

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