# Harvesting artificial light indoors to power perpetually a Wireless Sensor Network node

David Pubill, Jordi Serra and Christos Verikoukis, Senior Member, IEEE

*Telecommunications Technological Center of Catalonia (CTTC), 08860 Castelldefels, Spain*

*E-mails: {dpubill,jserra,cveri}@cttc.es*

*Abstract*—Wireless Sensor Networks (WSN) devices are usually battery powered and thereby their lifetime is limited. This issue leads to lose data measurements and thus to a performance loss of the underlying WSN application. It also increases the maintenance cost in Internet of Things (IoT) scenarios with a huge number of WSN devices. Energy harvesting (EH) is one of the key technologies to solve this issue. In this paper, energy harvesting by artificial light is proposed to power WSN devices in indoor scenarios. Contrary to the state-of-the-art related work, this paper experimentally demonstrates that it is possible, under certain conditions, to achieve energy neutral WSN devices by harvesting energy from artificial light. The experimental setup consists of an EH module, which powers a WSN source data acquisition node, and a WSN sink node which receives the data sent by the first. The EH module consists of a photovoltaic (PV) cell, a boost converter and a 3V coin battery.

*Index Terms*—Energy harvesting, photovoltaic cell, boost converter, Wireless Sensor Networks, Internet of Things.

## I. INTRODUCTION

WSN devices are key components of the upcoming IoT revolution, where billions of devices with sensing, communications and actuating capabilities will setup a huge geo-distributed perception system to interact with the background. Thereby, IoT creates a plethora of applications such as air quality monitoring in smart cities, self-driving cars, etc. However, IoT benefits may be impaired by the limited energy budget of battery-powered WSN devices. Energy constraints limit the WSN devices lifetime, which leads to a performance loss in an IoT application. Moreover, the limited energy budget provokes the battery replenishment of a huge number of WSN devices and increases the maintenance cost. EH is envisaged as the key technology to circumvent this issue.

EH systems capture energy from different environmental sources. A variety of EH sources exist depending on the scenario and the application, e.g. light, motion, vibration, wind, heat or electromagnetic waves [1]. Moreover, EH systems transform the harvested energy into electrical energy and store it in a battery. A power management subsystem, within the EH module, defines a proper electrical interface to power a WSN device with the harvested energy. Thereby, EH is the cornerstone to extend the WSN devices' lifetime. This work investigates EH for indoor environments and, in particular, we focus on EH from artificial light. EH in indoor environments is a challenging scenario since the average power that can be harvested from ambient light, is 10 to 100 times lower than in outdoor environments [2].

Several works deal with EH from ambient light in the literature. In [2] a hybrid EH module is proposed, which gathers energy from both thermal and ambient light. They propose a single power management unit for both sources of energy. The authors in [3] characterize the indoors light energy availability and they develop energy allocation algorithms for EH devices. The work in [4] considers WSN devices that harvest ambient light energy, both from solar and artificial light sources. Each WSN device is equipped with presence and light sensors, and their measurements are used by a central controller to adapt the illumination of the indoor light system. In [5] the authors characterize the indoor light conditions not only in terms of light intensity, but in terms of its spectral information. This leads to a precise estimation of the output power that a photovoltaic panel can obtain from the given ambient light conditions.

This paper proposes and experimentally demonstrates energy neutrality in WSN devices based on energy harvested from artificial light. The proposed solution consists of an EH module that powers a WSN source node which is transmitting data to a WSN sink node. The EH module consists of a PV cell that harvests artificial light from a nearby lamp, a boost converter that transforms the gathered energy into the proper electrical features of the WSN node and a 3V rechargeable coin battery that stores the electrical energy.

## II. RELATED WORK

Several related works have been presented in the literature, though some of them focus on harvesting solar light in outdoor scenarios. In [6] the authors present a low cost solar harvesting system constituted by WSN MICAz nodes and the MAX1724EZK33 boost converter, by Maxim Integrated, which achieves a perpetual power supply. Unlike in [6], our work focuses in an indoor scenario. In [7] the authors study the performance of different type of PV cells. To test the cells, they design a prototype based on the Texas Instruments bq25504 boost converter. In our work the use of this boost converter is different, as in this work it is used to design an EH module to power perpetually a WSN node. Finally, in [8] the same boost converter is used to build an EH WSN device. Their conclusion is that the consumed power is higher than the harvested one. In this paper we present a way of powering perpetually a WSN node in three different scenarios: 1) no activity in the data acquisition device, 2) performing a simple computation and 3) periodically transmitting temperature measured values to

another device. We consider several transmission time periods and we conclude that it is possible to extend the device's lifetime when the frequency of the transmissions is above a certain threshold.

The rest of the paper is organized as follows. Section III describes two setups, the proposed photovoltaic cell setup and a baseline one to compare the results obtained. Section IV presents in detail the components of the setups and Section V shows the experimental results. Finally, Section VI concludes our work.

## III. ARTIFICIAL LIGHT EH SETUP

In this section the block diagram of the proposed energy harvesting system and the two setups deployed are presented. Fig. 1 shows the energy harvesting block diagram, it consists of a Raspberry Pi, a WSN node, a PV cell, a boost converter and a 3V coin battery. The last three elements constitute the EH module. Next, Fig. 2 displays the photovoltaic cell setup based on the block diagram. This implementation is constituted by three WSN nodes (source, sink and auxiliary). The function of the WSN source node is to send temperature measurements to the WSN sink node while the WSN auxiliary node collects the battery level and the Raspberry Pi gathers the data for later analysis. All the experiments of this work have been carried out in an indoor environment.
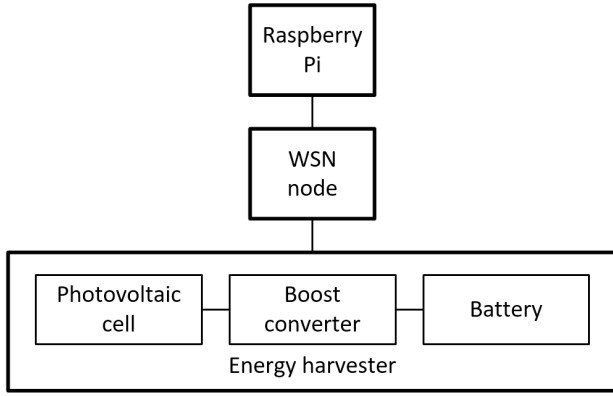


Fig. 1. Energy harvesting block diagram

The light generated by a common desk lamp is the energy source used to recharge the battery, see Fig. 3. According to the manufacturer, the power of the lamp is around 50 watts and 400 lumens. Taking into account that a lux is the unit of illuminance equal to 1 lumen per square meter and that the distance between the lamp and the photovoltaic cell was around 25cm for all the experiments, equation (1) can be used to calculate the illuminance in lux, $E_v(lx)$:

$$E_v(lx) = \frac{\phi_v(lm)}{4\pi r^2} \qquad (1)$$

where $\phi_v(lm)$ is the illuminance in lumens and $r$ is the spherical radius which corresponds to the distance between the lamp and the PV cell. Therefore, the illuminance is around 500 lux.
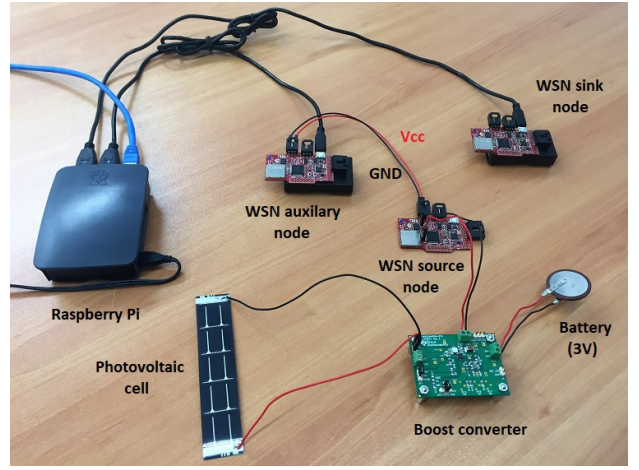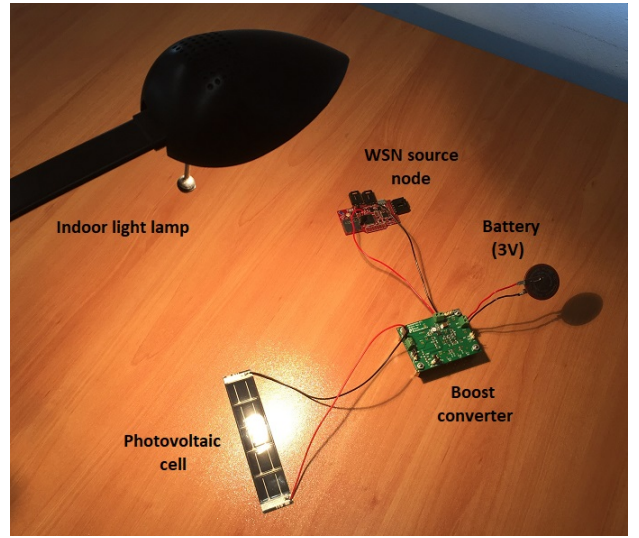


Fig. 2. Photovoltaic cell setup



Fig. 3. Indoor light lamp and photovoltaic cell

In order to compare the results of the experiments with the photovoltaic cell setup, a baseline setup (see Fig. 4) has been defined. It consists of three WSN nodes, a 3V coin battery and a Raspberry Pi. In this case the 3V battery is connected directly to the WSN source node without considering energy harvesting. The aim of the baseline scenario is to characterize the discharge behavior of the battery for different ways of operation of the WSN source node, these are the three possible scenarios:

1) *No activity:* there is no activity in the WSN source node. This scenario represents a lower bound on the energy consumption of the WSN device.
2) *Computing:* simple computation is running in the WSN source node; it simply increments a sequence number in an infinite loop.
3) *Computing + transmission (Computing+Tx):* the RF transceiver of the WSN source node is active and, therefore, transmitting packets to the WSN sink node

every certain time periods.

The voltage output pin of the WSN source node ($V_{cc}$) is connected, for both setups, to the data input pin of the WSN auxiliary node with the aim of collecting the battery level. The maximum battery level is around 3V. However, when it is discharging, the voltage on the output $V_{cc}$ pin drops. This data is transferred and stored on the Raspberry Pi. Note that the WSN sink node is only used in the *Computing+Tx* scenario since it is used as a receiver of the temperature measurements transmitted by the WSN source node. Therefore, it does not play any role in the *No activity* and *Computing* scenarios.
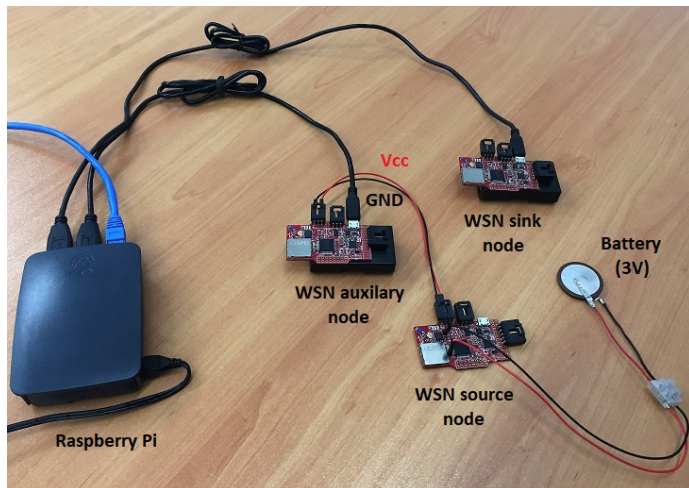


Fig. 4. Baseline setup

## IV. SETUP COMPONENTS

In this section we explain more in detail the components of the setups proposed in section III and their features.

### A. WSN node: Z1

The WSN nodes used are the Zolertia Z1 devices (see Fig. 5) [9]. The Z1 is a low power wireless module compliant with IEEE 802.15.4 and Zigbee protocols. It is equipped with a second generation low-power microcontroller, which features a 16-bit RISC CPU @16MHz clock speed, a built-in clock factory calibration, 8KB RAM and 92 KB flash memory. It also includes the CC2420 transceiver, operating at 2.4GHz frequency band with a data rate of 250Kbps. It supports Contiki OS, an open-source operating system for the IoT, which connects tiny, low-cost, low-power microcontrollers to the Internet. It is worth noting that each node can operate as either a source or a sink. According to [9] the consumption in transmission mode is around 17.4mA for a transmission power of 0dBm, 18.8mA in reception mode, less than 10mA when the micro-controller is active and the consumption of the memory circuit is up to 15mA. The Z1 can be powered with two AA batteries (1.5V each one). However, in this work it has been powered using the EH module.



Fig. 5. Z1 WSN node

### B. Raspberry Pi 3

Fig. 6 shows a Raspberry Pi 3 which is a single-board computer with wireless LAN and Bluetooth connectivity. It is equipped with a Quad Core 1.2GHz Broadcom BCM2837 64bit CPU and 1GB RAM. Its role is mainly to gather data from the WSN source node's lifetime for the different scenarios and setups.



Fig. 6. Raspberry Pi 3 Model B

### C. Rechargeable coin batteries

Two coin type rechargeable lithium batteries of 50 and 100mAh capacity have been chosen for the experiments. They correspond to the VL series provided by Panasonic [10], see Fig. 7. Although there are smaller capacity batteries in the market they are not considered for this work because they cannot assume the power consumption of the WSN node and the boost converter. The 100mAh coin battery is the one with the most capacity in the market considering such small dimensions. Its nominal voltage is 3V, which is the voltage needed to power the WSN node.

### D. Boost converter

Fig. 8 shows the boost converter used for the experimental setup, it is the bq25504 evaluation module, by Texas Instruments. According to [11] the $V_{BAT\_OK}$ parameter defines high/low thresholds programmed at 2.8V and 2.4V, respectively. A $V_{BAT\_OK}$ high signal would typically indicate that the battery is ready to be used. If it is low, it would indicate that the battery is discharged and the system load should be reduced or disabled. The $V_{BAT\_OK}$ signal is checked every 64ms.

### E. Photovoltaic cell

Fig. 9 shows the MP3-25 photovoltaic cell by PowerFilm Solar [12]. It is created by depositing amorphous silicon on a

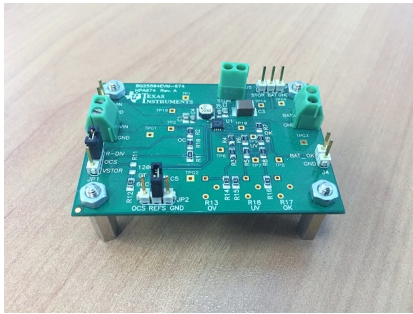Fig. 7. Rechargeable coin batteries



Fig. 8. Boost converter

thin plastic substrate, operates at 3V and generates a current of 31mA. Its dimensions are 24x114mm. This module is lightweight, paper-thin and durable. In order to connect it to the boost converter a cable has been welded to every tin-coated copper tape.
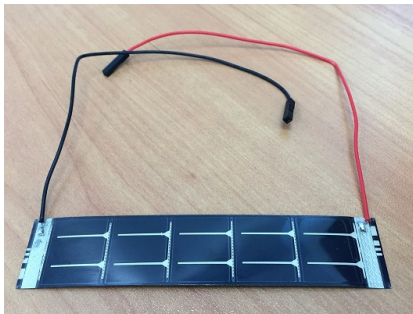


Fig. 9. Photovoltaic cell

## V. EXPERIMENTAL RESULTS

This section is divided in two subsections. The first subsection considers the baseline setup and shows the performance of both 50 and 100mAh capacity batteries (see Fig. 10 and Fig. 11, respectively). The purpose of these experiments is to evaluate both batteries and decide whether the 50mAh capacity battery is enough to achieve a perpetual power supply of the WSN node under study or a higher capacity battery is needed, i.e. the 100mAh battery. Then, once decided the most

appropriate battery, the second set of experiments (see Fig. 12 and Fig. 13) demonstrates how we achieve the main objective of this work, evaluating the battery for the different scenarios described in section III.

### A. Baseline setup experiments

This set of experiments has been performed using the baseline setup described in Section III (see Fig. 4). The main objective here is to study the behavior of the batteries without considering the EH module and, therefore, connecting directly the battery to the WSN source node. It should be noted that the operating range of the WSN device micro-controller ranges from 1.8 to 3.6V, this means that below 1.8V the WSN source node may not work properly. Fig. 10 and Fig. 11 shows the baseline results for the 50 and 100mAh capacity battery for the scenarios described in section III: *No activity*, *Computing* and *Computing+Tx* (with a transmission period of 5 seconds). A first observation is that as the activity in the WSN source node increases, the operating time of the battery decreases. Namely, the power consumption due to the computational and communication resources usage is greater in the *Computing+Tx* scenario than in the *Computing* one and, in the same way, in the *Computing* scenario than in the *No activity* one. In fact, in Fig. 10, which shows the performance of the 50mAh battery, can be appreciated that there is a substantial difference between the *No activity* scenario (69 hours of operation) and the *Computing+Tx* (only 11 hours). This last result makes us glimpse that with the 50mAh battery it will be very difficult to obtain a perpetual power supply for the WSN source node because, as it can be seen in Fig. 10, the voltage drops very quickly for the *Computing+Tx* scenario. This leads us to consider the 100mAh capacity battery as the best candidate for the photovoltaic cell setup. Fig. 11 shows that the operating time using this battery, compared to the 50mAh capacity battery, is significantly better for all the scenarios. Therefore, the next set of experiments considers only the 100mAh capacity battery and compares the results obtained for the photovoltaic cell setup with the ones obtained for the baseline setup.

### B. Photovoltaic cell setup experiments

The photovoltaic cell setup described in section III (see Fig. 2) has been considered for this set of experiments. Namely, here the WSN source node is powered from the EH module while the artificial light is being harvested. As concluded in the previous subsection, we have chosen the 100mAh capacity battery since it is the most appropriate for this setup. The experiments of this subsection have been focused on two of the scenarios: *Computing* and *Computing+Tx*. In particular, Fig. 12 shows the results for the *Computing* one. Unlike what happened with the 50mAh capacity battery, the 100mAh battery presents encouraging results since the WSN source node is continuously powered. This can be seen in Fig. 12, the level of the voltage is not decreasing with the time. Since the *Computing* scenario is more restrictive than the *No activity* one, there is no point in testing this scenario; the result
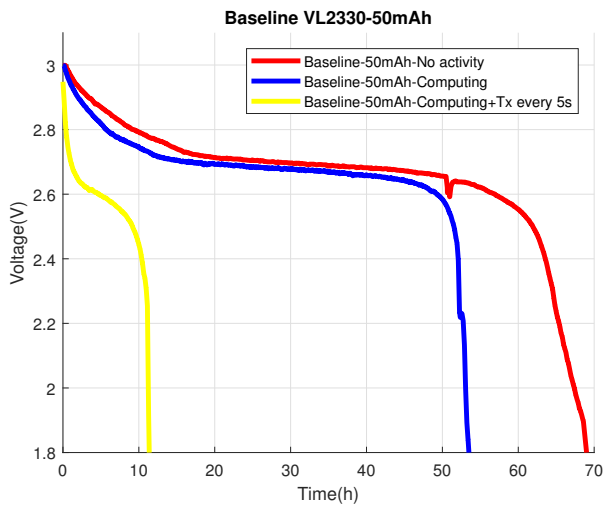
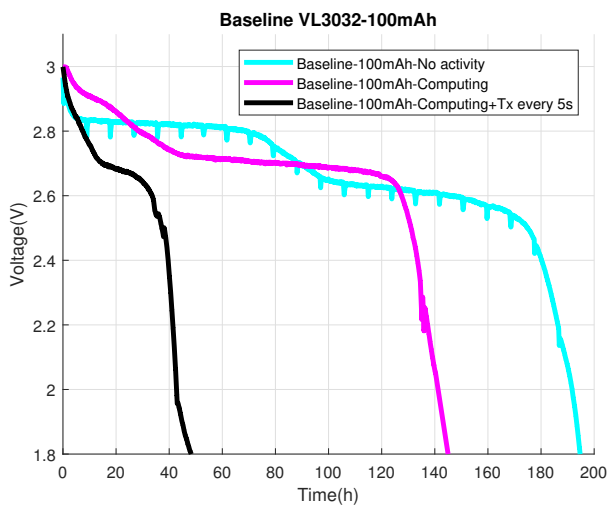Fig. 10. Baseline setup, 50mAh, 3 scenarios



Fig. 11. Baseline setup, 100mAh, 3 scenarios

would be the same, a perpetual supply of the WSN source node. However, the objective of this work was to find the scenario in which a WSN source node could transmit data to a WSN sink node every certain periods of time indefinitely, this corresponds to the *Computing+Tx* scenario. In this regard, Fig. 13 shows the results of this experiment. It compares the photovoltaic cell setup (for two different transmission periods, 5 and 10 seconds) with the baseline setup (around 50 hours of operation). For a transmission period of 5 seconds, the voltage at the input of the WSN source node decreases with the time, although its operating time increases until 135 hours. At this point the boost converter (used in the photovoltaic cell setup) presents a constraint. Once the battery level is under the $V_{BAT\_OK}$ threshold (which is a functionality of the boost converter itself, see Section IV-D) the voltage provided to the WSN source node is drastically reduced in order to protect it. When this happens, the WSN source node stops working

properly and it stops the communication with the WSN sink node. Instead, for a transmission period of 10 seconds the WSN source node is powered infinitely. Experiments with transmissions periods of 30 seconds, 1 minute and 2 minutes have been performed with the same result. These experiments show that the threshold (i.e. the transmission period between two consecutive transmissions) above which the WSN source node can be perpetually powered is 10 seconds.
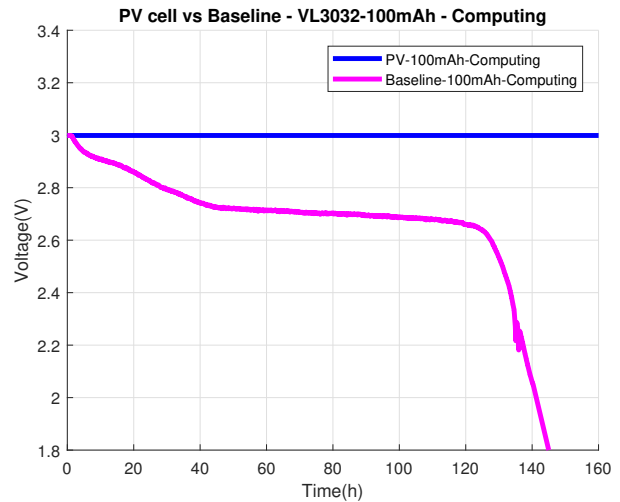


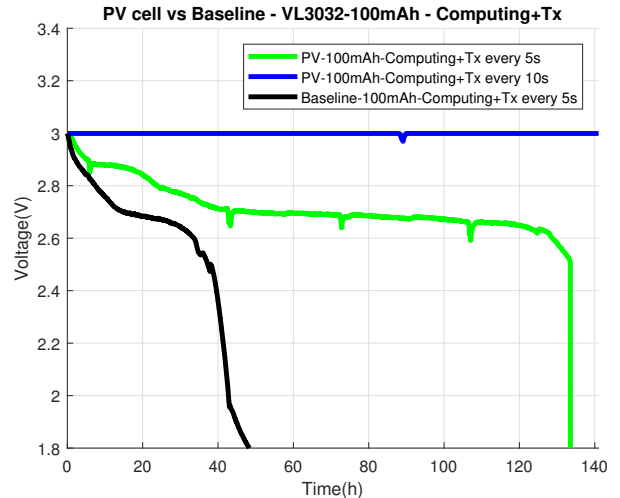Fig. 12. Photovoltaic cell vs Baseline setup, 100mAh, Computing



Fig. 13. Photovoltaic cell vs Baseline setup, 100mAh, Computing+Tx

## VI. CONCLUSION

This paper presents a setup able to power perpetually a WSN node using a 100mAh capacity battery, a PV cell and the bq25504 boost converter in an indoor environment for a transmission period equal or greater than 10 seconds. The energy source for the energy harvester is a common desk lamp which is 25cm from the PV cell generating an illuminance of 500 lux. In future work, more test should be done increasing

the distance between the source of light and the PV cell and, for instance, using other sources of energy such as fluorescent light; always considering a realistic scenario for the WSN source node, for example locating it next to a light on the roof of an office.

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