Self-Powered Wireless Sensor Network Designed for Energy Saving in HVAC Systems

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Abstract - *Wireless sensor networks (WSN) are a promising technology to monitor the state of large buildings and provide the necessary data for continuous optimization of energy consumption, for instance, related to thermal comfort or lighting control. For these applications, currently available off-the-shelf WSN devices are still too expensive for deployment in large quantities, require considerable amount of work to integrate with specific sensors, usually include many unnecessary components, and most consume too much energy, therefore requiring frequent battery replacement or powering from building's electrical network. The work hereby presented describes the development and testing of WSN nodes based on Ultra-Low-Power components, suitable for energy efficiency related applications in buildings, such as Heating Ventilating and Air Conditioning and thermal comfort control. The proposed nodes are capable of self-powering under frequently available conditions, are small in size, and may be competitive in price, therefore being appropriate for large scale deployment in large buildings.*

Keywords: Energy harvesting; Self-powered wireless sensors; Energy efficiency; Thermal comfort; HVAC control.

1 Introduction

Due to fast economic development affected by industrialization and globalization, energy consumption has been steadily increasing over the last years [1, 2]. Industry, transportation and buildings are the three main economic sectors which consume a significant amount of energy, with buildings accounting for the biggest proportion. For example, in European Union countries, energy consumption in buildings represents about 40% of the total energy consumption [3]. In the USA, more than 44% of domestic energy consumption corresponds to heating, ventilating and air conditioning (HVAC) systems in buildings [4].

It is currently well accepted that the best approach towards energy efficiency of HVAC control for thermal comfort is Model-based Predictive Control (MPC), a technique that requires predictive models related to the controlled process, thus being inherently data intensive to allow accurate dynamic modelling of relevant processes. The authors have used WSNs to support an intelligent MPC approach to energy efficient HVAC and thermal comfort control [5, 6], which is the main motivation for the work presented in this article, although its applicability is not limited to that specific application. For instance, lighting control is another problem where the sensors developed may be applied.

Briefly, in the current intelligent MPC approach, the HVAC system is controlled in such a way that the energy (or its economic cost) spent for ensuring thermal comfort in a room, within a predictive horizon (PH), is minimized. The thermal comfort is measured by the Predicted Mean Vote (PMV) index which approximates the thermal sensation of a large group of people exposed to certain thermal condition. The PMV ranges from -3 (cold) to +3 (hot); typically, when it lies between -0.5 and +0.5, the room is assumed to be in thermal comfort [7].

In order to predict the evolution of the PMV over PH, the evolution (and obviously their measurement) of several variables must be obtained. Of interest to this work are the Inside Air temperature (Tair), Inside Relative Humidity (%RH), Mean Radiant Temperature (MRT), Room Activity, as well as the state of windows or doors (open/close). The use of MPC for HVAC systems is translated in important energy and economic savings [5, 6] but, for its implementation, it requires the usage of additional sensors. In order for HVAC MPC to be an economically valid proposition, this additional hardware must be cheap, easy to install and maintain.

In previous works [5], a network of wireless sensor nodes were used, where each node consisted of one Tmote Sky connected to the required sensors. This platform, as well as most commercial off-the-shelf WSN nodes, are not appropriate for this specific application, due to one or more of the following reasons:

- they are too expensive for large deployments;
- the consumption of energy would require too frequent battery replacement or hardwiring to electric network;
- even if infrequent, changing batteries in large deployments is unfeasible;
- they require a significant amount of work to integrate with specific sensors; and wiring for power would restrict available placement locations;
- they are too big after integration with batteries, sensors and/or other required components

To overcome the limitations presented, the goal is to design, implement and test Self-Powered Wireless Sensors (SPWS) that:

- can harvest energy from the surrounding environment and store it in a battery, to avoid wiring for power or having to periodically change batteries;
- are small in size, therefore being suitable for easy and aesthetically pleasant installation in a wide variety of confined spaces that are commonly found in large buildings (new or existing);
- use only the components necessary for the applications being considered, employing Ultra-Low Power (ULP) components whenever possible and available;
- are cheap to produce, in order to allow a viable and marketable product for energy efficiency of buildings.

Section 2 of the paper discusses the design of the system; section 3 describes the prototype, in section 4 validation results are presented; section 5 discusses energy harvesting and finally in section 6 conclusions are drawn.

2 System design

To design a low energy-consumption, possibly perpetual, device, two main strategies were followed. On the one hand, the circuit includes a power management stage that harvests, conditions and stores energy in a battery. On the other hand, the firmware shuts down unused components and microcontroller sub-systems during operation and takes the microcontroller to deep-sleep state for the part of the duty-cycle with no tasks.

A SPWS which harvest energy from the environment can be synthetized by the blocks diagram present in Fig. 1. The primary power supply contains the environmental energy, energy transducer, power management and battery blocks; all these blocks act like a power supply for the remaining essential circuit, built with a transceiver, microcontroller and sensor.

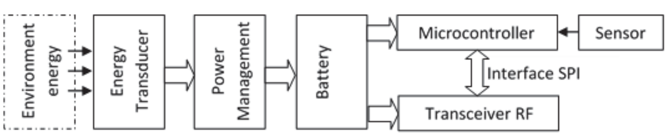

Fig. 1. Autonomous WSN diagram that harvests energy from the environment, adapted from [8]

Energy can be extracted from different sources, namely radiant, mechanical, thermal, magnetic and biochemical [8]. Considering the type of application and the scale at which the devices are meant to be deployed, light is the form of environment energy more readily available. Therefore, the design considers the use of an adequate size photovoltaic panel as the energy transducer. The harvested energy is not constant, therefore the voltage level must be adjusted. Additionally, as there are times when there is no energy available, a capacitor or a battery is required to store the energy, which can be used later when necessary [9]. The SPWS implemented in this work uses an 850 mAh lithium polymer battery.

In the following subsections more information and details are given about the components used, their selection, and integration into the prototype developed.

2.1 Transceiver

The most important points taken into account were the current consumption, the transmission range and finally the price The devices considered were AT86RF231-ZU, AT86RF233 and AT2564RFR2 from Atmel, 22M10 and 22M00, from Dresden Elektronik, MC13202, MC1322, MC1323x and C13234/37, from Freescale, JN5168-001-M03Z, JN5148-001-M00 and JN5148-001-M03, from Jennic, NRF24L01+ and NRF24LE1, from Nordic, MRF24J40MA, MRF24J40MB, MRF24J40MC and MRF24J40, from Microchip, LPR2430A from Murata, STM32W108HB and STM32W108C8 from ST Microeletronics, and CC2533, CC2530 and CC2531 from Texas Instruments.

Fig. 2 compares the current consumption, as reported by the manufacturers, when the RF transceivers are used with maximum power transmission.

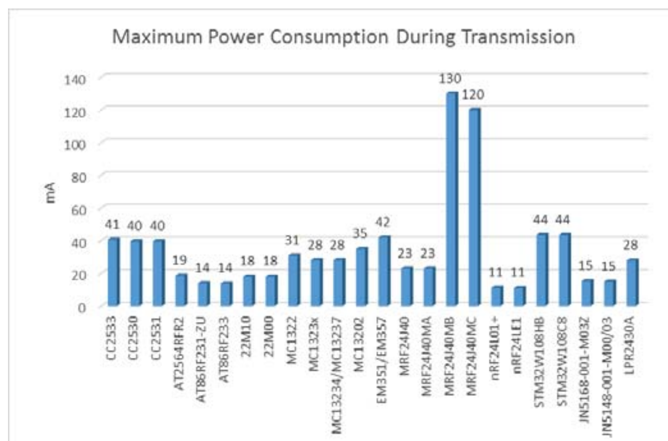

Fig. 2. Energy consumption at maximum power transmission.

Although the Nordic devices were considered at first, because of their low consumptions, they were discarded as they are not 802.15.4 compliant devices. A number of other devices with current consumption above 28 mA were also discarded by considering the low-power consumption goal for the SPWS. From the remaining 9 alternatives, the Microchip MRF24J40MA device presents the most interesting compromise between current consumption, transmission range, integration level, and price. As it is an integrated module without microcontroller, the selection of one was the next requirement for the development of the SPWS.

2.2 Microcontroller

Microchip development kits used for evaluation and development for IEEE 802.15.4 applications use the PIC18F46J50 microcontroller. Choosing this PIC enables the use of the same libraries employed for microchip RF kits,

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being therefore a safe choice, offering low cost and low power consumption, as the PIC belongs to the eXtreme Low Power (XLP) family.

2.3 Sensors

Two sensors were considered for the measurement of air temperature and relative humidity: Silicon Labs Si7021; and Sensirion SHT25. In both cases, the two quantities are measured by the same sensor, which allows decreasing the Printed Circuit Board (PCB) size. Although the Si7021 and SHT25 have similar features, the Si7021 was designed having HVAC applications in mind and its energy consumption is smaller than that of the SHT25, therefore it was the chosen sensor for the SPWS. The temperature and relative humidity values provided by the sensor have to be converted to the corresponding units accordingly to the following equations:

$$T_{air}\left({}^{o}C\right) = \frac{175{,}72 \times T_s}{65536} - 46{,}85 \quad (1)$$

$$\%RH = \frac{125 \times RH_s}{65536} - 6 \quad (2)$$

where T_s and RH_s are the 16 bit words provided by the sensor. The accuracy is ±0.4ºC for temperature and ±3% for relative humidity.

To detect movement in rooms a Passive Infra-Red (PIR) motion sensor was employed. The selection privileged the Panasonic EKMC1601111 sensor, which shows a good compromise between size, warm-up time, and current consumption. It requires 30 seconds to warm-up and 170µA to operate. The room activity is given as the fraction of time in one minute, during which the sensor output is in a high state.

The detection of the state of doors and windows (open or closed) is made by means of magnetic reed switch sensors. When prototyping the system, two sensors, the Hamlin 59150-030 and the Comus S1372, were employed. The Hamlin was selected because it is cheaper and is easier to mount on a surface using screws.

The MRT is estimated by recurring to wall temperature measurements. As the Si7021 sensor cannot be coupled directly to a wall, a common PT1000 surface contact temperature sensor is employed. As the sensor is analog, a complementary Wheatstone bridge and amplifier circuit is implemented in order to adjust its terminals differential voltage to the microcontroller's ADC input range. The amplifier circuit considered is the Texas Instruments INA126UA instrumentation amplifier, designed for differential data acquisition in battery powered systems. The wall temperature is then determined as a function of the PT1000 resistance, as:

$$T_{Wall} = \frac{\left[R_{PT1000} - R0_{PT1000}\right]}{3{,}85} \quad (3)$$

where R_{PT1000} is the sensor impedance at the moment of the microcontroller's ADC sampling, and $R0_{PT100}$ is a baseline impedance of 1000 Ohms, which is observed by the PT1000 at 0ºC. The R_{PT1000} value is computed as a function of the voltage measured by the ADC at the sensor terminals.

The last sensor incorporated in the SPWS PCB was a N5AC-50108 photo-resistor from Low Power Radio Solutions (LPRS). As the sensor is included to enable an energy conservation mechanism rather than providing the most accurate measurements, accuracy was not a factor when selecting it. The idea is to detect if the room is illuminated, in order to complement the SPWS firmware with a policy to determine if the room is not being used. In this case the periodic sensor data transmission may be interrupted for a given amount of time, therefore preserving battery charge.

2.4 Power Management

The power management circuit supports three modes of operation: battery charging and powering; powering from an USB port; or, charging the battery while powering from the USB. The energy harvest is done by a Solems 10/072/048 photovoltaic panel built with amorphous substrate. This substrate is able to convert light into current even in low light environments (20 - 100 lx), making it more appropriate for indoor operations.

The power supply has to be constant at 3.3 Volts, as all the sensors, the transceiver and the microcontroller work at this voltage. In order to use a solar panel, there are two ways to accomplish this: use a step-up boost converter or a step-down converter. As on the one hand it was found that a step-up boost converter needs a high current, and on the other hand by using a step-down converter allows using a lithium battery with higher load capacity and lighter properties, the second approach was followed. Fig. 3 shows a block diagram of the circuit employed for the SPWS power management.

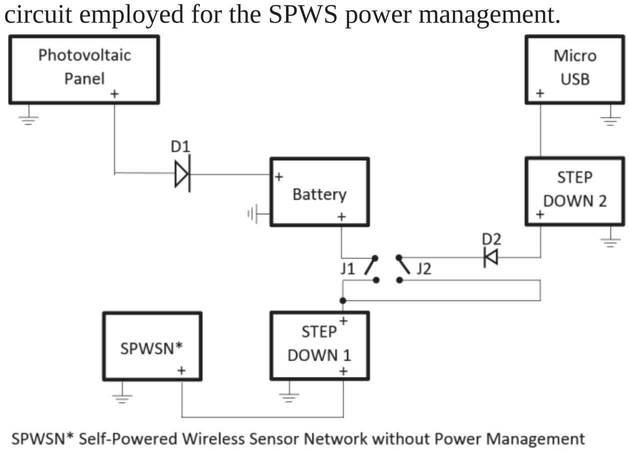

Fig. 3. Block diagram of the circuit employed for the SPWS power management.

The Microchip MCP1700T-33 and Texas Instruments TPS79901 low quiescent current voltage regulators are employed as step-down 1 and 2, respectively. As the different types of nodes are configured before being deployed and then are kept working for very long periods of time, a simple configuration method using two jumpers (J1 and J2) is used to select the power management mode of operation. In the case that J1 is closed and J2 open, the battery is connected to the input of the MCP1700 step-down, whose output is used to provide the voltage regulation for the SPWS circuit. Another mode of operation is selected by closing J2, resulting in powering from the USB connection. Finally, the third and last mode of operation is selected by closing both jumpers, allowing to simultaneously charge the battery and power the SPWS. The battery requires 4.2 V for charging and for that reason step-down 2 was selected. The diodes D1 and D2 prevent the battery current dissipation by the photovoltaic panel or by the step-down 2 component.

3 Prototype SPWS

3.1 Prototyping Hardware

The first prototype was built using discrete components and had the purpose of validating the design options that had been made. It consisted of two breadboards, one with the base circuit, including all the components required to transmit a packet (microcontroller, crystal, and the MRF24J40MA transceiver), and the other one containing all the sensors and their auxiliary components.

In order to accommodate the PCB board and the battery, and to allow an adequate placement of sensors, an enclosure was modelled and printed in a 3D printer. In Fig. 4 a picture is given for an open SPWS, showing the battery and the PCB.

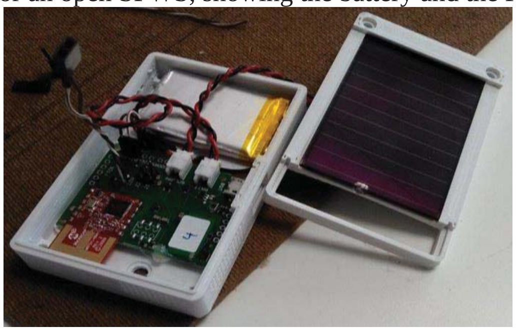

Fig. 4. An opened SPWS showing the PCB., battery and PV panel

3.2 Prototyping Software

The prototype firmware was developed under the MPLAB X IDE application, which is recommended for developing and debugging for the family of Microchip microcontrollers that was employed. Three firmware versions are implemented, one for each type of node: transmitter; receiver and repeater.

The PCB transmitter device follows a strict operational sequence of actions in order to minimize the energy consumption:

1. setting the microcontroller initial configuration;
2. acquiring the values of connected sensors;
3. configuring SPI pins;
4. turning the MRF24J40MA module on and configuring the radio;
5. loading the MRF24J40 radio registry with data to transmit;
6. transmitting the data;
7. waiting for the TX interrupt pin;
8. switching off the RF module, and;
9. finally, putting the device in deep sleep mode.

On the receiver type of node the sequence of operations is off-course different:

1. set the microcontroller initial configuration;
2. setup USART communication;
3. configure microcontroller SPI pins;
4. configure MRF24J40 radio;
5. cycle waiting for transmitter's data;
    a. activate RX interrupt pin;
    b. read MRF24J40 data;
    c. send data to the RPI collector;
    d. d. turn ON interrupts; and
    e. e. go back to wstep 5a.

Finally, the repeater node operates according to the following procedure:

1. set the microcontroller initial configuration;
2. configure SPI pins;
3. turn on the MRF24J40MA module;
4. configure MRF24J40 radio (PAN id, channel id, source ID);
5. cycle waiting for transmitter's data;
    a. activate RX interrupt pin;
    b. read MRF24J40 data;
    c. load MRF24J40 radio registry with data to transmit;
    d. transmit Data;
    e. wait on TX interrupt pin; and
    f. go back to step 5a.

As mentioned above, in order to decrease transmission energy consumption, all the information is sent as is. Conversion to physical variables units is done on the RPI collector device.

4 SPWS Validation

The SPWS devices were tested in order to validate their operation in terms of packet loss. Although this was not accomplished using a systematic approach, it was well verified that within the expected range of communication, reception is almost perfect, making a more detailed analysis unnecessary.
In previous work, Tmote Sky based sensors were enclosed in a large box with plenty air circulation. Fig. 5 shows several Tmote based sensors, as well SPWS based systems, left under different conditions. The numbers inside red squares are the device ids of the following sensors: device 43 is a Tmote inside a closed box; device 44 is a Tmote inside an open box, where a SPWS device with id 2 is also placed; device 45 is a Tmote outside the box; device 1 is a SPWS outside the box; and device 3 is a SPWS inside the enclosure shown in previous section.

The devices recorded the air temperature and relative humidity inside the room during one day. The result is presented in Figures 6 and 7.

Regarding air temperature, there is clearly an offset of about 1.5ºC between Tmote devices and the SPWS devices. Part of this deviation may be explained by the fact that the Tmote temperature conversion equation depends on the power supply. As the SHT11 datasheet does not have the factor for 3.3 V power supply, the choice was to employ the 3 V factor. Nevertheless, the temperature trend is the same among the two types of sensors. On a separate experiment, not detailed here, the SI7021 sensor employed in the SPWS was compared to the SHT25 sensor (new Sensirion sensor) and in this case very similar readings were obtained. The comparison among SPWS devices shows good agreement of the measurements. Importantly, by looking at the device 1 (red) and device 3 (dark blue), it is concluded that there is no significant difference between the measurements made by sensors inside or outside the box, which validates air circulation in the sensor area of the PCB.

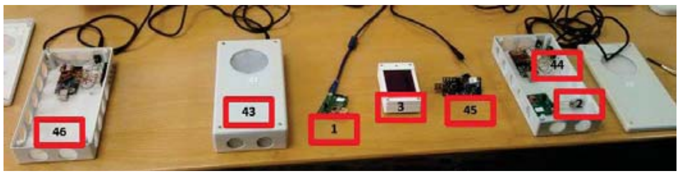

Fig. 5. Tmote Sky based sensors and SPWS based nodes.

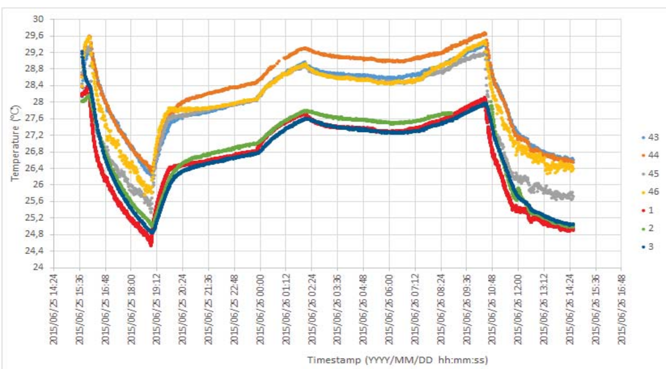

Fig. 6. Air temperature measured by Tmote Sky sensors and the SPWS developed.

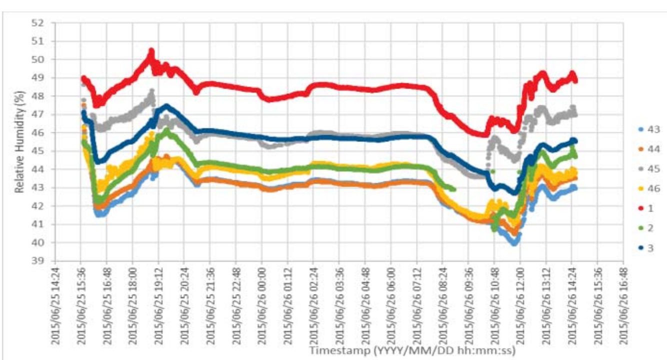

Fig. 7. Relative humidity measured by Tmote Sky sensors and the SPWS developed.

For relative humidity, shown in Fig. 7, all sensors exhibit the same trend, with slight differences with short durations for sensors inside boxes. These are most probably caused by the isolation provided by the boxes. The offset among the SPWS devices, with a maximum value around 4%, is well within the accuracy margin of the Si7021 sensor specifications.

5 Energy Harvesting

For a battery powered device that employs energy harvesting with the aim of attaining perpetual autonomous operation, there is one rule that, on average, must hold within a given period of time: the amount of energy harvested must be larger than the energy consumed. A number of tests were carried out in order to find the conditions in which this rule holds for the SPWS transmitter type node.

5.1 Average energy harvest

The first test was conducted in order to find the average current produced by the photovoltaic panel employed, under conditions typically found, and actually recommended, in large buildings rooms. Illuminance may depend on the type of activity being executed in a given space but will usually lie in the range from 500 to at least 2500 lux.

To this end, 10 panels were subject to different illuminance levels while the output current was measured. The illuminance was provided by a Philips 1250 lumens, 220V, 20W, fluorescent lamp and measured by an Avago Technologies APDS-9007 sensor. The current was computed by means of Ohm’s law, after measuring the voltage at the terminals of a 10kΩ resistance, using a multimeter. The results for the 10 panels are presented in Fig. 8. The illuminance levels considered were 637, 1493, 1998, and 2492 lux, and the corresponding average instantaneous currents produced were 185.3, 264.2, 321.6, and 382 µA. If this production holds for a period of 8 hours per day, the average production decreases to 61.8, 88.1, 107.2, and 127.3 µA for the illuminance values considered.

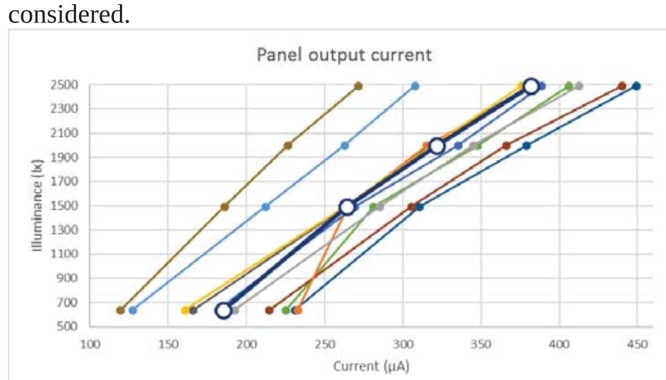

Fig. 8. Current provided by 10 photovoltaic panels. The thicker line with the larger marker identifies the average response.

5.2 SPWS energy consumption

Due to the small currents involved a Tektronix TDS2024 oscilloscope was employed to measure the voltage across the terminals of one resistance placed in series between the battery and the SPWSN. The voltage acquired was recorded for later current calculation by means of Ohm’s law.

The results presented are relative to a fully integrated SPWS as shown in Fig. 4. To get a realistic consumption measure, the photovoltaic panel was removed. Calculations were based on an application note available from Jennic

Company. Except for the room activity sensor, as soon as the radio transmits a packet, the microcontroller enters deep sleep mode, and the current drawn becomes constant, equal to 7μA. The experiments considered duty cycles of 34 and 135 seconds. Figure 9 presents the current consumption during the active part of the duty cycle of a doors/windows state sensor.

The instants marked with a square and corresponding yellow box, show the consumption at interesting times that are used to divide the graph into sections. Assuming that the current is constant in each section, to calculate the average power consumption during a given section, the following equation is employed:

$$I_{Avg} = \frac{I_{section} \times t_{section}}{t_{total}} \quad (4)$$

where $I_{section}$ is the current of the section concerned, $t_{section}$ is the duration of the section, and t_{total} is the total time of a duty cycle including the deep sleep period and the active period where the microcontroller performs data acquisition and the radio transceiver sends the data.

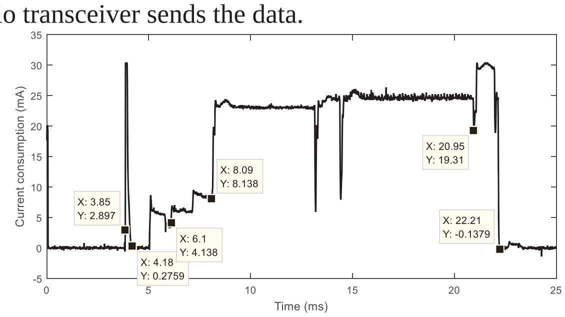

Fig. 9. Current drawn from the SPWS battery during the active part of the door/windows state sensor duty cycle, when reading the sensor and transmitting the result. The square dots and the corresponding yellow squares show the current consumption at relevant instants.

The consumption profiles are similar for all the sensors except for the room activity sensor. This sensor demands more current during the microcontroller deep-sleep period, because the sensor has to be powered at all times due to its 30 seconds warm-up delay. This means that the consumption varies during this period depending whether movement is detected or not. Movement is measured at 2.1 second intervals during 30 interrupts and on the 30th, transmission is done.

By using the worst case scenario consumption values determined as sketched above, the average power consumption for each transmitter type SPWS over a duty cycle is presented in Table 1.

The motion detection sensor is the one demanding more energy, followed by the temperature and relative humidity sensor, the wall temperature sensor, and finally the doors/windows state sensor. By knowing the battery capacity, the sensor life time can be calculated. Results show that wall temperature sensor and door/window sensor can operate approximately during 5 years without any energy harvested (850 mAh / 18.9μA ≈ 44,270.8 h ≈ 1844.6 days ≈ 5.1 years). For the temperature and relative humidity sensor the duration is approximately 3 years, whereas the motion detection sensor achieves 112 days (permanent movement) or 224 days (no movement). As this sensor is more energy demanding, the photo resistor was added to the SPWS to enable a software policy with the aim of decreasing the sensor use in periods that the rooms are not being used.

TABLE I. AVERAGE CURRENT CONSUMPTION OF SPWSS OVER A DUTY-CYCLE.

Sensor	***Deep sleep 2.1 s***	***Deep sleep 34 s***	***Deep sleep 135 s***
Doors/ windows	-	18.9 μA	10.0 μA
PT1000	-	19.2 μA	10.1 μA
SI7021	-	32.4 μA	13.4 μA
Motion detection	Sensor ON Sensor OFF 315.3 μA 157.8 μA	-	-

By confronting the results in Table 1 with the average current produced by the PV panels, as given in section 5.A, it may be concluded that besides being able to sustain operation over very long periods without any battery recharging, mild charging conditions are enough to guarantee perpetual operation. Even in the lowest level of illuminance considered, and assuming that the battery is charged only for a period of 8 hours per day, the doors and windows state sensor, the wall temperature sensor, and the air temperature and relative humidity sensor, consume less energy than that necessary to operate 24 hours per day. The motion detection sensor does not verify the perpetual operation rule for operation over a full day. Nevertheless, if the 8 hours charging period is considered also as the period of operation for this sensor, by assuming that the photo resistor and the policy implemented prevent its use in unnecessary conditions, its average consumption would drop to 105.1 μA (sensor ON) and 52.6 μA (sensor OFF). In this scenario, the motion detection SPWS achieves perpetual operation at various combinations of illuminance and movement level within the monitored space. Only in the unlikely scenario of permanent movement at all times, perpetual operation would not be possible at the two first levels of illuminance.

5.3 Battery charging in research room

The Solems 10/072/048 photovoltaic panel was connected to the 850 mAh lithium polymer battery. The current supplied to the battery was measured with an ammeter and the room illuminance by an Avago Technologies APDS-9007 sensor. Therefore, the charging circuit is a closed loop containing the photovoltaic panel, a diode, the ammeter and battery, all connected in series following this order. The APDS-9007 sensor measures illuminance within the range of 3 to 70000 lux. The relation between current and illuminance is given by:

$$I_{OUT} = 10\mu A \times \log(L) \quad (5)$$

where I_{OUT} is the current measured at the sensor output and L is the corresponding illuminance. Figs 10 and 11 present the panel output current and illuminance measurements within a 6 by 3 by 3m, ground floor working room, for a 24 hours summer period. The room has a window facing north that receives shading by a number of pine trees and very small windows facing south near the ceiling.

The test was executed on the 2nd of June, 2015, and lasted 24 hours starting at 14:46, in broad daylight. As it may be observed, both charts have the highest peak around 15:36, showing approximately 110 μA for 900 Lux. Between sunset and dawn, from 20:40 till 6:31, the panel output is zero due to the absence of light. There are 4 instants where a sudden large increase or decrease occurs, caused by the opening or closing of window shutters. A pair of these occurrences clearly detects lunch time. During lunch, the panel production is generated from the few light entering the small windows facing south.

The average current presented in Figure 10 was 27.4 μA, corresponding to an average illuminance value of 198.8 Lux. Still, this small charge, corresponding to low, and not recommended, illuminance levels, allows the sensor to operate perpetually in the majority of the cases. Only the Si7021 sensor with a sampling time of 34 s and the motion detection sensor would not achieve that goal.

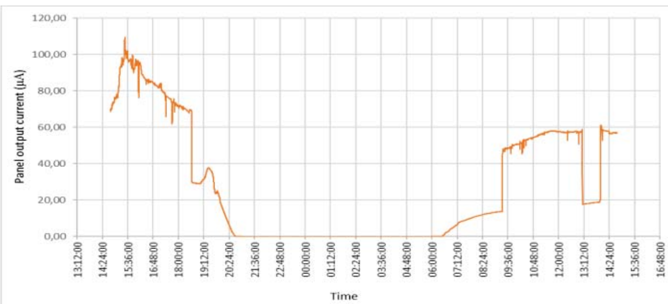

Fig. 10. PV panel current charged to the 850 mAh battery, over 24 hours.

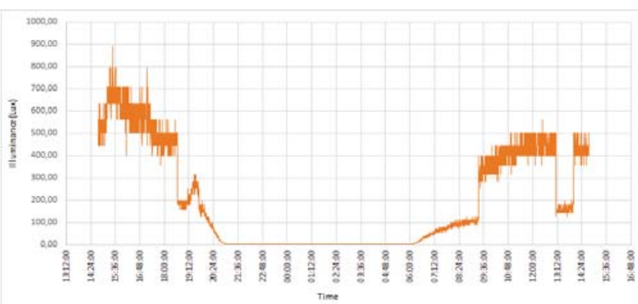

Fig. 11. Illuminance detected for the period of time shown in Figure 12.

6 Conclusions

This paper presents the design and development of a new self-powered wireless sensor device designed specifically for the energy efficiency in buildings related, for instance, to thermal comfort and HVAC control. Three node types were developed: transmitter, repeater and collector. The devices are small, fully integrated for targeting buildings energy efficiency applications, easy to setup and install, cheap when compared to other off-the-shelf generic alternatives, and, most importantly, allow perpetual autonomous operation under reasonable and common conditions in the majority of large buildings.

It was shown that the devices can operate at a fast sampling interval (34 sec) from a charged small 850 mAh battery, without any recharging, from 4 months up to 5 years, depending on the sensed quantity. It was also shown that under mild lighting conditions, the wall temperature, air temperature and relative humidity, and doors/windows state sensors, can operate autonomously and perpetually. The PIR sensor based motion detector, in its current state of design, may also achieve perpetual operation if a software policy is used to turn off the PIR at times when its use is unnecessary. To relax these restrictions, a larger or more efficient PV panel is required.

Future work will look into the modularization of the device, i.e., breaking the design into a base system and easily installable plug-and-play modules that will define the node behavior. This will further decrease the device cost and increase its easiness of deployment. On the data side, work has to be done on the fusion of data into virtual soft-sensors using sampling intervals in accordance with the specifications of the system employing the SPWSs.

Acknowledgments

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