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Abstract— Smart homes/offices based on Wireless Sensor Networks (WSNs) can provide an assisted living and working environment to the users. In these applications, the distributed network nodes are made up of low-power low-cost high-energy-efficient electronic platforms equipped with sensors, microcontroller, radio and antenna, able to periodically sense, receive, store, pre-process and transmit ambient data to a remote host station. Conventional nodes are usually supplied by batteries, resulting in a significant limitation to the life time and to the maximum number of deployable devices. To meet the demand of next Internet of Things (IoT) applications, requiring a vast plurality of interconnected wireless network nodes, this paper presents the design and implementation of a WSN platform whose nodes are energetically autonomous thanks to an embedded photovoltaic (PV) panel associated to a rechargeable battery and a power-efficient design with optimized power-management strategy. The implemented node is able to harvest indoor ambient light starting from 100 lux and, according to the available energy, adaptively sets the sensors acquisition and RF transmission rate. Moreover, it provides long-distance data transmission with air data rate from 1 to 500 kbps. The WSN node device is implemented on an 8.6 x 5.4-cm² flexible PCB, being therefore amenable to conform even to curved surfaces. Comparison with commercial IoT nodes reveals a significant improvement in the state of the art.

Index Terms—Energy harvesting, home automation, Internet of Things (IoT), low power, microcontrollers, Wireless Sensor Network (WSN).

I. INTRODUCTION

HOME/OFFICE AUTOMATION consists in the exploitation of micro/nanoelectronic technology within the home/office environment to assist and enhance the quality of life/work of its occupants through the main goals of increasing comfort, saving energy and providing remote surveillance and real time monitoring [1]-[3]. Wireless Sensor Network (WSN) platforms are exploited to implement this paradigm [4]-[6]. At this purpose, each WSN physical node is equipped with multi-sensor devices for heterogeneous ambient sensing and is also able to store, pre-process, transmit and receive data to a host controller. More generally, intelligent wireless interconnected sensing devices are expected to pervade all the emerging applications in the Internet of Things (IoT) area [7]-[10]. In this context, key performances of the WSN nodes are reduced power consumption and maximum throughput at a maximum communication distance [9]. Additional specifications that must be considered are cost, size and ease of configuration and installation [7]-[8].

Presently, to prolong the battery life up to months or even years, WSN nodes are implemented through energy-efficient communication schemes combined with low-power design [7], [11]-[12]. To this end, Wi-Fi, ZigBee, and Bluetooth are popular wireless protocols which use a license-free ISM (Industrial, Scientific and Medical) frequency band. ZigBee, in particular, offers the best trade-off between cost and communication distance, as proven by the several related papers in the literature [12]-[16].

Combination of Wi-Fi and Zigbee are also proposed for power saving [17], [18]. Another solution embeds several radio modules to reduce energy consumption and latency for neighbor discovery and opportunistic networking [19], but at the expense of increasing both the size and cost of devices. Nevertheless, the use of Wi-Fi, Bluetooth and Zigbee as a low power radio is still too costly for WSN applications. Bluetooth Low Energy (BLE) protocol reduces power consumption and provides connection to smart phones with easy setup but has limited operating range and is subject to royalties, which makes BLE unsuitable for WSN ubiquitous low-cost devices.

A last, profitable, approach is offered by Sub-1GHz wireless connectivity schemes providing long distance communication (tens of kilometers, thanks to the lower frequencies exploited) in a less crowded spectrum than ISM band (769 MHz - 935 MHz), while requiring lower power
consumption [20]. The main disadvantage can be related to the dimension of the antenna and the need of an additional transceiver in the concentrator node.

It should be also observed that most researches in the field are just proposals, and very few are complete implementations [10]. To take both the research and implementation a step further, this paper presents a novel design of a WSN platform amenable to home/office automation and, more generally, to IoT applications thanks to its reduced dimension and its energy autonomy. The WSN nodes are able to make available information from several sensor devices (temperature, humidity, presence, etc.) to the user or to a centralized control host.

Low-power operation and energy efficiency are obtained through careful hardware and software co-design. To this end, the microcontroller, which manages the whole system, does not execute a rigid control algorithm but adaptively changes tasks and their timings by taking into account the energy available to the node and the power consumption of each task. Long distance communication is enabled through the use of a specific radio module allowing more flexibility in frequency, modulation schemes and protocols.

In particular, comparing the implemented platform with existing similar solutions, the main significant advantages are summarized below:

1) the node is energetically autonomous;
2) highly configurable RF connectivity;
3) the node is implemented on a flexible and compact PCB;
4) a Graphical User Interface (GUI) is developed and provided to the final user.

The first feature is obtained through indoor energy harvesting from an embedded photovoltaic (PV) panel associated to a rechargeable battery and through through innovative energy-aware power managing policy. Consequently, periodic human maintenance required by devices powered by a primary battery is avoided.

As far as the connectivity is concerned, the proposed platform exhibits a high level of flexibility, providing different transmission bands, protocols, and data rates to the designer. In such a way the system can meet the specified energy constraints and cost budget allowing the designer to develop proprietary RF point-to-point and mesh protocols. In particular, the system supports the realization of mesh networks through IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) protocol in which every node has its own IPv6 address, allowing direct connection to the Internet by using open standards.

The use of point-to-point or mesh network architecture depends upon the specific application. Indeed, if the area to be monitored is very large, a mesh architecture would guarantee a better coverage using a single gateway. The proposed platform fits also this scenario by supporting different protocols. Moreover, every node can easily act as an IoT gateway if connected to a processing host that collects and store the data coming from the sensor nodes.

The flexible PCB embeds a flexible PV panel and printed integrated antenna. Thin film batteries and low-profile components are also employed to achieve both compact dimensions (compatible with the size of a credit card: 8.6 x 5.4 cm²) and ability to conform non-flat surfaces.

Finally, the GUI provides an easy configuration tool and allows the user to interact with the system.

The paper is organized as follows. Section II describes the WSN node architecture, energy management strategy and first component selection based on the energy budget specifications (discussed in the Appendix). Example of application and further implementation highlights are presented in Section III, whereas experimental results are shown in Section IV. Finally, a comprehensive performance comparison with other implemented platforms for distributed sensing is reported in Section V. Concluding remarks are summarized in Section VI.

II. ARCHITECTURE OF THE WSN NODE AND ENERGY MANAGEMENT STRATEGY

Since the WSN node must be able to periodically sense, receive, store, pre-process and transmit ambient data to a remote host station, its overall architecture can be divided into the three main functional subsystems, namely: energy, sensor and control, and communication, as shown in Fig. 1.

The energy subsystem includes components and circuits that supersede harvesting, storage and energy management. Sensors aimed to environmental monitoring are part of the sensor and control subsystem. Of course, the type and number of sensors is dictated by the specific application. The microcontroller manages the sensors and oversees the overall system operation. Data from sensors are cyclically sampled and sent to an external base station through the communication subsystem. Starting from these general assumptions and considerations, the proposed platform has been designed as illustrated in Fig. 2 and as summarized in Table I, where the main specifications and functions of the different subsystems are briefly reported. Each subsystem is described in detail below.

A. Energy subsystem

A platform that targets ambitious goals in terms of low power consumption and high energy efficiency must accurately take into account relevant system power managing issues, starting from the early design stage. Indeed, selecting energy-efficient components alone is not enough to achieve the desired goals if an accurate analysis and definition of the system operation and energy management strategies is not accomplished.
As an example of these strategies, the proposed platform allows switching-off the power supply of specific circuit sections, provided that this does not compromise the system functionality. In addition, a careful partitioning of the supply voltage levels allows an optimized trade-off between performance and power consumption from each single component to be achieved.

The energy subsystem includes as main elements the PV panel, a rechargeable thin film battery, as well as some blocks constituting the Power Management Unit (PMU) for optimized use of the available harvested energy.

The PV panel is made up of six flexible 26.6-mm x 20.75-mm PV modules which are interconnected in two parallel strings of three series-connected modules, as exemplified in Fig. 3a-b.

If exposed to a radiation of 300 lux, each PV module provides the following nominal electrical parameters: short-circuit current 26.8 μA, open-circuit voltage 2.8 V and maximum output power of about 46 μW with conversion efficiency greater than 8%. Therefore, the overall PV panel is able to provide about 275 μW at 300 lux.

The PMU is made up of a battery charger SPV1050 [21] that charges the thin film lithium battery EFL700A39 [22] by monitoring the charging profile. It integrates over-charge, over-discharge and over-current protection circuitry to prevent the battery from being damaged under fault conditions and hence prolonging its life. The SPV1050 device integrates a DC-DC converter stage suitable for PV cells harvesting sources, as it covers the input voltage range from 75 mV up to 18 V and guarantees high efficiency in both buck-boost and boost configuration. Moreover, it implements the Maximum Power Point Tracking (MPPT) algorithm, to extract the maximum power from the PV module under different operating conditions of light and temperature [21], [23]-[25].

Taking into account the PV panel and the SPV1050 electrical characteristics, as well as the battery features, the PMU is able to ensure full system functionality from harvested light down to 100 lux. In particular, the SPV1050 device acts as a power manager also by making available one unregulated output voltage on the STORE pin and two LDO regulators, providing 1.8 V and 3.3 V. Each LDO can be selectively enabled or disabled through the associated enable pin. More specifically, the LDOs are managed by the microcontroller and supply the sensors according to the state of the system and the operating scenario to minimize power dissipation. Moreover, the microcontroller also enables the voltage regulator that provides power supply to itself. This means that if long periods of inactivity are predicted, the microcontroller can bring the WSN node into a very low-power state, turning off all the circuits, including the microcontroller itself, after programming its wake-up time on the Real Time Clock (RTC). In this state, only the RTC module is on, which is responsible to wake up the system as the programmed sleep time is elapsed.

Finally, the PMU implements a pre-charge circuit and a supercapacitor which provides the current peaks absorbed by the communication RF subsystem during the data transmission phase. This solution allows sustaining the current absorption peaks required by the RF transceiver and allows reducing the required battery capacity as well.

B. Sensor and control subsystem

The Sensor and control subsystem can be customized according to the features required by the WSN node. The implemented reference platform includes on board sensors for ambient light, temperature, humidity, pressure and acceleration monitoring. Additional sensors could be connected to an extension header which provides I2C bus and power supply.

All the adopted sensor devices are off-the-shelf components manufactured by STMicroelectronics, except for the ambient light sensor. These components have been chosen mainly because of their good trade-off between performance and power consumption.

Temperature and acceleration sensing are both provided by the LIS3DH component [26], an ultra-low-power high-performance 3-axis linear MEMS accelerometer. The relative value of humidity is sensed by ultra-compact HTS221 device [27]. Pressure is detected by ultra-compact absolute piezoresistive pressure sensor LPS25H [28].

All the sensors are managed by STM32L052 [29], an ultra-low-power microcontroller that incorporates: a high-performance Arm® Cortex®-M0+ 32-bit RISC core operating at a frequency of 32 MHz, a memory protection unit (MPU), high-speed embedded memories (64 Kbytes of Flash program memory, 2 Kbytes of data EEPROM and 8 Kbytes of RAM) plus an extensive range of enhanced I/Os and peripherals. The
microcontroller supervises and monitors the whole system behavior according to the energy management strategy.

C. Communication subsystem

In ultra-low power systems, RF communication is undoubtedly burdensome as far as the energy management is concerned, in terms of both peak and average current consumption. For these reasons it is necessary to carefully handle the duration of the states where the system exchanges data with the base station as well as the power transmission level (i.e., the transmission distance to be covered and data rate) in order to keep the consumption within the specified constraints and to ensure the system energy sustainability.

The communication subsystem is made up of the radio module, the antenna and, if required, the matching circuit. The SPIRIT1 low data rate, low power Sub module, [7] was adopted, mainly because it is a very low-power RF transceiver [30]. It is designed to operate in both the license-free ISM and SRD frequency bands at 169, 315, 433, 868, and 915 MHz, and can also be programmed to operate at other additional frequencies in the 300-348 MHz, 387-470 MHz, and 779-956 MHz bands.

The air data rate is programmable from 1 to 500 kbps, and the channel spacing is 12.5/25 kHz, complying with the EN 300 220 standard [31]. The data management handles the data in the proprietary fully programmable packet format.

The radio can perform Cyclic Redundancy Checks (CRC) on the data as well as Forward Error Correction encoding/decoding on the packets. It provides an optional automatic acknowledgement, retransmission and timeout protocol engine in order to reduce overall system costs by managing all the high-speed link layer operations. Moreover, the radio supports an embedded Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) engine as well as different modulation schemes, namely: 2-FSK, GFSK, OOK, ASK, and MSK.

As mentioned before, the power supply of the radio module is connected to a pre-charge circuit which, before each transmission phase, stores the energy required for the transmission. This relieves the battery energy load and allows the microcontroller to handle more effectively the transmission phase.

The communication subsystem includes also the M24LR64-E-R device [32] and the associated antenna. M24LR64E-R is a dynamic NFC/RFID (Near Field Communication/Radio Frequency Identification) tag IC with a dual-interface EEPROM. Optionally, the memory can be

<table>
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<th>Subsystem</th>
<th>Feature</th>
<th>Main components</th>
<th>Functionality</th>
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<tbody>
<tr>
<td>Energy</td>
<td>Energy harvesting, storing and delivering to the different subsystems</td>
<td>Flexible PV panel</td>
<td>Harvesting of light energy down to 100 lux</td>
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<tr>
<td></td>
<td></td>
<td>EFL700A39 Rechargeable Thin Film Battery</td>
<td>Storage of harvested energy needed to supply the system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPV1050 Power Management Unit</td>
<td>It embeds a battery charger and a DC-DC converter, implementing MPPT algorithm, and two LDOs. It optimizes the harvested energy and the charge stored in the battery. It provides power to the system</td>
</tr>
<tr>
<td>Sensor and Control</td>
<td>Data acquiring and storing from sensors Adaptive acquisition and transmission rate to fit the energy budget</td>
<td>STM32L052 Microcontroller</td>
<td>It enables the different devices and implements the power management strategies according to the available energy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Real Time Clock</td>
<td>It regulates the activity and inactivity status of the system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M24LR64E-R EEPROM memory</td>
<td>Storage of system configuration and sensor data to be transmitted to the base station</td>
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<tr>
<td></td>
<td></td>
<td>LIS3DH</td>
<td>3-axis MEMS accelerometer sensor with temperature</td>
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<td></td>
<td></td>
<td>HS221</td>
<td>Humidity sensor</td>
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<td></td>
<td>LPS25H</td>
<td>Pressure sensor</td>
</tr>
<tr>
<td>Communication</td>
<td>Communication to the base station using different bands, protocols, and transmission rates</td>
<td>SPIRIT1</td>
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<td>M24LR64E-R</td>
<td>Dynamic NFC/RFID tag IC with dual-interface and EEPROM</td>
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<tr>
<td></td>
<td></td>
<td>Antenna</td>
<td>Printed dipole antenna</td>
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powered in contactless mode by the received carrier electromagnetic wave. This allows the user to change the system settings by simply placing in its proximity an NFC/RFID device.

Since a full-size patch antenna operating in the ISM band, possibly with circularly polarization for optimal reception, would occupy an excessive area [33], low profile miniaturized antennas have been considered. Specifically, two types of antenna were developed, both suitable for the application, and whose layouts are illustrated in Fig. 4a and 4b, respectively: 1) integrated monopole slot antenna, made up of a half magnetic slot fed by a microstrip line placed next to the short side credit-card-size module and 2) printed dipole antenna, derived from a full size half wavelength dipole exploiting harm folding to reduce the occupied area.

The second antenna is placed along the long side of the credit-card-size module (see layout in Fig. 4b) and does not require a balun, but only lumped loss-less components for impedance transformation and matching.

III. PROTOTYPING

Two subsequent prototypes were designed and fabricated in order to validate the proposed platform and the energy management strategies. The first prototype is shown in Fig. 5 and was originally conceived to allow easy monitoring and testing as well as easy comparison of different solutions and components in terms of performance and power consumptions. It implements the architecture discussed in the previous section by distributing the various devices on two different PCBs: a motherboard and a daughterboard.

Among the possible alternatives, a point-to-point communication protocol with acknowledgement, directly accessing the link layer of the SPIRIT1, was adopted. This design choice has been adopted for a proficient transmission of short messages from different nodes to a single centralized control host.

The mother board includes the components constituting the sensor and control subsystems as well as the main components of the energy subsystem. The daughter board includes the PV panels, ambient light sensor and the integrated monopole slot antenna. It is fed by a 50-Ohm microstrip and requires transformation from balanced to unbalanced mode at the output of the SPIRIT1 radio through the ultraminiaturized balun BALF-SPI-01D3 [34]. The antenna input impedance can be controlled by choosing the slot dimensions and the distance, $d$, between the 50-Ohm microstrip line and the substrate edge.

Without substantially modifying the principles and strategies that addressed the design of the first prototype, the second demonstrator, shown in Fig. 6, was aimed at optimizing the whole system form factor and at exploiting the photovoltaic panel flexibility, with all the components soldered on the same credit-card-size (8.6 x 5.4-cm$^2$) flexible PCB. Starting from the scheme in Fig. 2, several optimizations were carried out involving the DC-DC converter section, the firmware of the microcontroller, the radio transceiver and the antenna. In this second version the antenna is a printed dipole antenna (as in Fig. 4b) which does not require a balun, but only lumped loss-less components for impedance transformation and matching.

Fig. 7 shows a screenshot of the graphical user interface (GUI) that was developed to allow easy interfacing between the sensor nodes and a concentrator connected to a computer through the USB port. The GUI allows to retrieve data from the various WSN nodes and to store them into a MySql database. Moreover, it allows the user to set the configuration of each node by enabling its sensors and, if required, to force the acquisition and transmission rate.

The energy sustainability of the system has been tailored for indoor operating environments. As an example, an “office” application case is considered, with the following three operating scenarios, denoted as WD, WN and WE and illustrated in Fig. 8:

- **WD.** Working day, hours 8am-4pm (Monday-Friday).
  An 8-hour artificial lighting environment (300 lux,
The strategies adopted above were implemented according to the flow chart illustrated in Fig. 9. When the microcontroller wakes-up, it initializes the WSN node by also powering up those subsystems that were disconnected during the low-power mode. Subsequently, it checks the reason of the awakening event by asking to the base station a new configuration and synchronization, in the case data and time are not valid. Then, it processes the sensors environmental parameters by either storing them in the non-volatile memory or sending them, together with those data collected previously, to the base station.

The power consumption of the RF transceiver is influenced by several configuration parameters, but it mainly depends on the transmission distance to be covered along with the transmission data rate. To meet functionality and power consumption requirements, the RF transceiver has been configured to enable data transmission in the range of tens of meters. At the end of a data transmission the system checks if a new configuration is received, taking the consequential actions. In particular, the RTC is programmed according to the acquisition time/rate, then the system switches in the low power mode. If energy is not enough to complete the assigned tasks, the system goes into the low-power mode.

Fig. 8. Light and dark time patterns in the case of a typical “office” application.

![Fig. 8](image)

Fig. 9. Simplified WSN node firmware flow diagram.

from 8:00 am to 4:00 pm) was assumed;

- WN. Working night, hours 4pm-8am (Monday-Friday).
  Lights of the office are turned off;
- WE. Weekend (Saturday-Sunday). Lights of the office are turned off.

On the basis of the expected harvested energy and estimated power consumption, as explained in the Appendix, the three following functional modes have been implemented:

- During WD scenario, the WSN node wakes up and performs a complete measurement cycle every 10 minutes storing acquired data. Then the node returns to sleep mode. The data are transferred to the base station every 6 measuring cycles (i.e. every hour).
- During WN scenario, the WSN node wakes up and performs a complete measurement cycle every 30 minutes storing acquired data. Then the node returns to sleep mode. The data are transferred to the base station every 8 measuring cycles.
- During WE scenario, the WSN node wakes up and performs a complete measurement cycle every 60 minutes storing acquired data. Then the node returns to sleep mode. The data are transferred to the base station every 8 measuring cycles.

The overall system was then evaluated. With reference to the flow chart shown in Fig. 8, two main sequences were considered: the former includes the system awakening, initialization, after-awakening controls, and a complete cycle of sensor data acquisition (sequence A); the latter includes, in addition to the previous phases, also the final power-hungry phase of data transmission to the concentrator node (sequence B). As previously stated, the transmission phase requires a relatively long period to charge the supercapacitor with the energy required for two transmissions (the first one, optional, for synchronization purposes and the other, mandatory, for data transmission). The use of the supercapacitor allows sustaining the current absorption peaks required by the RF communication without relying on the battery.

Fig. 11 shows the measured current consumption during the two aforementioned operating sequences. Sequence A, as illustrated in Fig. 11a, starts at 1.6 s and ends at 4.4 s. Its average current consumption is 662 μA, with an average charge consumption of 0.52 μA/h. Assuming an average operating battery level of 3.9 V, the average power consumption is 2.58 mW.

Sequence B, as illustrated in Fig. 11b, starts approximately at 2 s. After initial sensor data acquisition, the supercapacitor...
is connected to the battery at 5 s. The charging phase is then stopped at 19.3 s, i.e., when a suitable voltage of 2.8 V is reached across the supercapacitor.

During this sequence, the average current consumption is 2.21 mA, with an average charge consumption of 10.6 µA/h. Note that this is a worst case, since the supercapacitor is considered as completely discharged at the beginning of the charge phase. When the system is in the low power mode (sleep mode) the average current consumption was found to be 3.3 µA in the worst case.

Additional experimental measurements were carried out during a 4-day test campaign in which a WE scenario was followed by two alternated WD and WN scenarios (WE+WD+WN+WD). Temperature, pressure, humidity and ambient light sensors data were periodically acquired and transmitted to the base station at a distance of around 20 m, according to the transmission rates associated to the scenarios. These measurements, obtained from the received signals, are illustrated in Figs. 12a, 12b, 12c and 12d, respectively; showing in x axes the real time calendar. It is shown that ambient data are correctly sensed and transmitted, without never completely discharge the battery.
V. COMPARISON WITH THE STATE OF THE ART

The main features of the proposed platform were compared to those of other solutions designed for distributed sensing. The evaluation is carried out by considering [8] and [35], where an extensive survey of the state of the art of IoT nodes is performed. In order to make a fair comparison, we considered a number of 58 IoT commercial devices that are implemented on PCB, out of 142 included in [8] and [35] at the date of writing.

First of all, it is worth noting that the proposed sensor node is the only one exploiting energy harvesting based on PV cells.

It also follows from the comparison that the maximum size (along three dimensions) of the proposed device (86 mm) is slightly higher than the average value, equal to 62 mm, of the considered 58 devices. Nonetheless, it is worth noting that the overall volume of the proposed node, equal to 13 932 mm$^3$, is much lower (about an order of magnitude) than the average value, equal to 130 360 mm$^3$ [35]. This is mainly due to the low thickness of the overall assembled system in Fig. 6, which is equal to 3 mm only. Fig. 13a shows the distribution of the sensitivity of RF receivers of the IoT devices (in this case, all the 142 devices in [35] are considered). It is apparent that the transceiver adopted in this work exhibits the best performance, which is 21 dBm lower than the average value. In addition, the proposed node shows the highest value of the maximum transmit power, equal to 16 dBm (the average value is 6 dBm). Finally, the proposed system has the highest level of configurability in terms of RF carrier frequency, as detailed in Section II.C, whereas most of the commercial products (nearly 60%) adopt Bluetooth, ZigBee or WiFi protocols operating in the ISM 2.4-GHz band. Only Waspmote shows a similar level of flexibility and, moreover, is the only other device equipped with NFC interface.

Regarding power consumption, the standby current of the proposed device, equal to 3 μA, is only 30% of the average value of 9.6 μA [35].

Finally, Fig. 13b illustrates the number of devices embedding different types of sensors. The histogram shows that the proposed solution embeds four of the sensors, namely temperature, humidity, accelerometer, and pressure that are mostly present in all devices. It is worth noting that other sensors can be easily added to the node by exploiting the onboard I2C interface.

As a result, the comparison with the state of the art shows that the proposed platform has remarkable advantages in terms of system configurability, dimensions and standby power that allows to satisfy many potential different applications with better performance than other similar commercial solutions.

VI. CONCLUSIONS

An innovative WSN platform expressly conceived for ambient monitoring in indoor environments, but which could be efficiently applied also in other IoT applications, has been proposed, designed and experimentally tested.

It consists of a self-powered autonomous sensor node that exploits embedded PV panels to harvest the energy, a microcontroller, a RF transceiver (plus antenna) and different sensors.

The main strength of the prototype is to achieve the desired (complex) functionality in a small volume with very low power consumption while ensuring ambient monitoring even during night hours. As an example of application, the proposed system was tailored for measuring ambient light, temperature, humidity and pressure inside a typical office that alternates working hours with artificial light and dark hours during night, week-ends or holydays.

The implemented node can harvest indoor ambient light starting from 100 lux and, according to the available energy, adaptively sets the sensors acquisition and RF transmission rate. Moreover, it provides relatively long-distance data transmission (tens of meters) with air data rate from 1 to 500 kbps. The WSN node device is implemented on a flexible PCB and occupies the same area of a credit card.

A comprehensive comparison with other commercial IoT systems implemented on a PCB shows that the proposed platform represents a sensible advance of the state of the art thanks to its very high flexibility, low standby power consumption and small volume.

Fig. 13. Performance comparison with commercial devices on PCB reported in [35] a) RF receiver sensitivity; b) number of devices embedding each type of sensor.
APPENDIX - EVALUATION OF THE ENERGY BUDGET AND SUSTAINABILITY

The energy storage devices of the WSN node and its worst-case power consumption have been tailored by specifying acquisition and data transmission rates to reach the energy balance, also on the basis of the system architecture described in Sec. II, of the available energy source, and of the “office” case study selected in Sec. III.

Energy Source. Each PV module provides a maximum output power of about 46 μW under a radiation of 300 lux. Since the PV panel is made up of 2 strings of 3 series-connected modules (Fig. 3), the total power from the PV panel, $P_{\text{panel}}$, is 276 μW. Moreover, SPV1050 has a power conversion efficiency of 77% and an efficiency of 96% related to the Maximum Power Point Tracker (MPPT) algorithm, thus the available output power is: $P_{\text{avail}} = P_{\text{panel}} \cdot 0.96 - 0.77 = 204$ μW. Assuming a nominal battery voltage of 3.9 V, and 8 h of light per working day, the WPN node can store a charge of: 204 μW h / 3.9 V = 51.8 μAh.

Storage. The EFL700A39 rechargeable solid-state lithium thin-film battery has a capacity of 700 μAh. Its operating voltage ranges from 3.6 V to 4.2 V. It can also provide maximum a continuous discharge current of 5 mA and a maximum pulsed discharge current of 10 mA.

Current consumption. Current consumption of each component has been evaluated in the three different operating modes (sleep, run and peak) by taking into account the electrical characteristics included in the datasheets and summarized in Table III. These data take into account consumption of external RTC, ambient sensor, power management, microcontroller and RF module.

Energy Sustainability. The best trade-off between energy sustainability and expected performance was met by selecting a suitable number of acquisition and transmission cycles within the different scenarios WD, WN and WE. The energy sustainability of the WSN node can be hence ascertained. Table II shows the amount of charge and duration in the envisaged operating scenarios. Combining consumption and energy production data together, the battery charge and, consequently, the system energy balance was evaluated. Figure 14 shows the battery state of charge during the four weeks, assuming that the battery is fully charged when the system is switched on. In the worst case (i.e., at the end of the weekend) the battery charge is still above 20% ensuring an adequate lifetime. Moreover, along the week the system is able to fully recharge the battery. In particular, it is fully recharged at the beginning of every WE, confirming a positive energy balance. In case of a prolonged absence of light, the power manager will disconnect the battery to preserve its lifetime and to avoid a condition of over discharge. Later, when the energy source will be available again, the platform is able to restart its functionality, without the user intervention, reconnecting the battery and requesting a new operating configuration from the central node, as showed in the flow diagram in Fig. 9. Finally, the base station can adapt the acquisition and transmission rate depending on the residual charge level of the battery.

### Table II

| Contributions of the Main Components to the Energy Balance of the System |
|-----------------------------|----------------|-------------|-------------|
| Device          | Sleep (μA) | Run (μA) | Peak (μA) |
| Microcontroller   | 1.3        | 1.55      | 1100       |
| Sensors          | 1.5        | 38.1      | -          |
| Radio            | 0.85       | 400       | 4400       |
| Power manager    | 0.1-1.3    | 3         | -          |

### Table III

<table>
<thead>
<tr>
<th>Summary of Predicted Energy Consumption</th>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>WD</td>
</tr>
<tr>
<td>Acquisition + Sleep</td>
</tr>
<tr>
<td>Charge per cycle (μAh)</td>
</tr>
<tr>
<td>Cycles</td>
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<td>Charge (μAh)</td>
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<td>Average current (μA)</td>
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### References


Crispino S. Abella graduated in Electronic Engineering at the University of Palermo (Sicily) in 1990 and joined STMicroelectronics, Catania site, in the same year. He was involved as a characterization Engineer for High Speed Bipolar Technologies (collaborations with the Design Center of Montgomeryville, PA, and the Department of Electric Engineering of the University of Palermo, Italy).

In 1995 he was involved in the design of devices of the Logic Families CMOS400B, HSCMOS, AC/ACT, LCX, LVQ and of the Standard Interfaces for RS422 communication.

In 1999 he was Section Manager of the Space Design Center of STMicroelectronics, aimed at developing projects for satellite applications.

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Salvo Bonina was born in Catania, Italy, in 1980. He graduated in Computer Sciences at the University of Catania, Italy, 2001. On January 2001 he joined STMicroelectronics, Catania, initially as a contractor and then on September 2002 as an employee, first in the ICT Department working on Office Automation platforms and Networking infrastructures and then in 2008 he joined the System Lab Department, where he worked as an Application Engineer for embedded applications in the following areas: IoT, wireless and wired connectivity, wearable sensors, mobile devices, energy harvesting and management. Besides that, he has provided customer support for Europe and Asia regions.
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Gioia S. Mauro received the degree in Telecommunication Engineering (summa cum laude) at the University of Catania, Italy, in 2012. From 2013 to 2015 he worked as RF engineer at NTT New Terra Technology for R&D of microwave components (antennas, waveguides, etc) operating in RF and THz frequency ranges to be used for mail control and security. During the same years he worked, within a joint collaboration with STMicroelectronics and the Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, University of Catania, for the study, RF simulation and characterization of innovative compact printed antennas. From 2016 he works as RF engineer at INFN for the RF design, simulation and tuning of metallic and dielectric accelerating structures such as drift tube linac and woodpile waveguides. In 2016 he began the doctorate in Information Engineering at “Mediterranea” University of Reggio Calabria, Italy. His current research interests include the study and characterization of metallic particle accelerators, the RF design of innovative electromagnetic band gap (EBG) based on dielectric structures for particle acceleration and the development of planar antennas and ultra-wideband compact antennas.
Giuseppe A.M. Nastasi was born in Catania, Italy, in 1976. He graduated in Electronics Engineering at the University of Catania, Italy, in 2003. In the same year, he joined STMicroelectronics, Catania, as an Application Engineer in the R&D and systems development groups. Over the years he has worked on highly innovative applications and reference projects based on ST products within the field of energy management, 8 bit and 32 bit microcontrollers, IoT, embedded systems and electronics on flexible substrates. He cooperated with Italian and European industrial partners as well as research centers in several research projects alternating the role of ST technical team member and technical coordinator. He is author of several scientific papers and holds many EU and US industrial patents.

Gaetano Palumbo (F’07) was born in Catania, Italy, in 1964. He received the Laurea degree in Electrical Engineering in 1988 and the Ph.D. degree in 1993 from the University of Catania. In 1994 he joined the University of Catania, where he is now full professor. His primary research interests are in analog and digital circuit design. He is co-author of four books by Kluwer Academic Publishers and Springer, in 1999, 2001, 2005, 2014 respectively, and a textbook on electronic devices in 2005. He is the author of more than 400 scientific papers on referred international journals (170+) and in conferences. Moreover, he has co-authored several patents. He served as an Associated Editor of the IEEE Transactions on Circuits and Systems Part I in 1999-2001, 2004-2005 and 2008-2011, and of the IEEE Transactions on Circuits and Systems Part II in 2006-2007. From 2011 to 2013 he served as a member of the Board of Governors of the IEEE CAS Society. In 2005 he was one of the 12 panelists in the Italian Scientific-Disciplinary area 09 – “industrial and information engineering” of the CIVR (Committee for Italian Research Assessment). In 2003 he received the Darlington Award. In 2015 he has been a panelist of the Italian GEV (Group of Evaluation Experts) in the scientific area 09 - industrial and information engineering of the ANVUR, for the Assessment of Italian Research Quality in 2011-2014.

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