

Ambient Monitoring WSNs with Harvesting-aware Power Management

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Abstract – Capillary wireless sensor networks dedicated to air quality monitoring have provided essential information on hazardous air condition, generating early warnings to prevent danger situation for human health. The main challenge of capillary networks is the adoption of environmentally generated energy as primary and/or unique energy source instead of the replacement of hundreds or even thousands of batteries on a regular basis that leads to high costs and practical problems of devices management. We present in this paper a battery-less, autonomous, multi-parametric sensing platform for air quality monitoring, that is harvesting energy from the surrounding environment for perpetual operation. We present a complete system design and experimental results of the evaluation of the energy harvesting section and the budget allocation of the power consumption. Moreover, the paper shows the experimental results of the studies conducted on the sensors section. A tailored calibration process for the sensors' sensitivity and a standard portfolio of different energy sources around the power recovery section could effectively enable the system to trace air quality levels in indoor and outdoor application, in a sort of “set and forget” scenario.

Keywords – *Power harvesting; WSN; Environmental monitoring; Gas sensors;*

I. INTRODUCTION

The link between poor air quality and a number of health diseases has been confirmed in some recent studies [1-5]. The need to have satisfactory air pollutants monitoring systems that are able to improve reliability and data availability in places where traditional monitoring methods are difficult to establish, has led to the design of numerous autonomous systems able to check indoor and outdoor air quality. Focusing on the process of improvements of air quality (e.g., HVAC system, air sanitation, air cleaning) the paramount goal is to identify correctly the pollutants present in the air and

to define the polluted locations so as to provide proper remedies. The advances in low power electronics and the new affordable electrochemical sensors linked to low power wireless techniques have allowed the development of highly efficient, low cost and low power air quality monitoring systems (dedicated to specific target gases) and their deployment in real environments [6-12]. Advances in wireless networking technologies enabled to reduce installation difficulties and costs, and allowed rapid deployment and remote and easy reconfiguration of air quality monitoring systems. Low cost and autonomous monitoring systems that are able to operate in any kind of environment, especially in harsh and disruptive ones, are badly needed to monitor air quality while reducing the human intervention. The primary problem for the deployment of wireless sensing nodes is that they require high power-efficiency for autonomous, long and continuous operation. If nodes are battery-operated then the costs of battery replacement will make such systems too expensive to be deployed in wide area and harsh environment. The design of autonomous monitoring systems relies on “set and forget” scenarios, where minimal or no-human intervention is needed. This is, indeed, the system design we are proposing in this paper.

II. THE SYSTEM CONFIGURATION

The proposed system (named SERENO acronym of SENSor REceiver NOde), is portrayed in Fig. 1 (a), (b) and (c) in which the most important blocks are shown. The Fig. 1 (a) is related to the power harvesting sub-systems, in Fig. 1 (b) the blocks depicting the six gas sensors operating on the PCB board and in Fig. 1 (c), photographs of the realized prototypes. In the next paragraphs the description of each single section is given.

A. Air Quality Sensors

The main feature of the described system lies in having an array of gas sensors able to measure the most important pollutants present in the air. The investigation on products present on the market has led to select

electrochemical gas sensors, as reasonably good choice of technology and benefits.

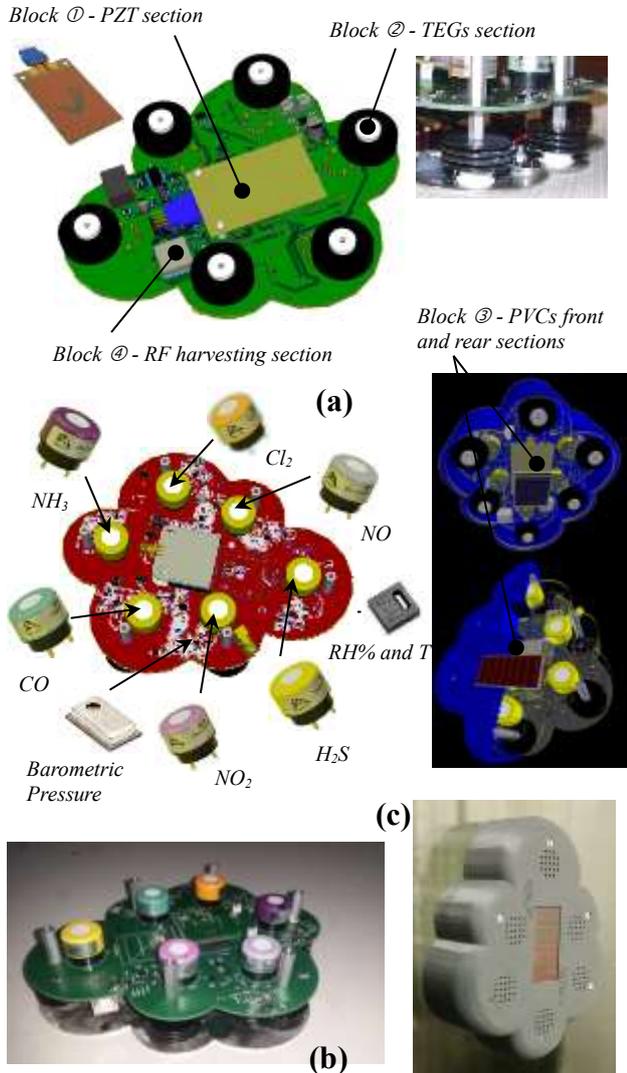


Fig. 1. (a) Power harvesting and sensing blocks (b) Example of SERENO prototype (c) SERENO sensing node applied on a window

They exhibit low power consumption, small package size and fast response to the target gas. Others parameters such as low temperature drift and good cross-sensitivity to others gas elements have been considered. Many manufacturers have wide electrochemical gas sensors portfolio, the main differentiation factors among them consist in the cost, the target gases (cross-sensitivity behaviour) and the resolution of each sensor in terms of parts per billion (ppb) of gas concentration, matching the EPA requirements. These kinds of sensors don't require any kind of power source, making them well-suited in self-powered wireless nodes. For our platform, we have adopted the following electrochemical sensors: NE4-CO Carbon monoxide, NE4-NO₂ Nitrogen dioxide, NE4-NO Nitrogen monoxide, NE4-H₂S Hydrogen Sulphide, NE4-

Cl₂ Chlorine and NE4-NH₃ Ammonia sensors from NEMOTO. The Sensirion SHT21 temperature and humidity sensors were also adopted due to the fact that the sensed data of the gas transducer are susceptible to ambient temperature and humidity so that we have developed a particular algorithm in order to cancel the value drift during the measurement process.

B. Power-Harvesting Sections

The designed single board consists of 6 gas sensors, the temperature and humidity sensors and the wireless transmission module with a μ C on board. With regards to the type of applications targeted, whether using a conventional lithium battery or using a solid state battery, it is important to define the energy consumption and management models employed so as to ensure either extended battery power longevity or autonomous energy source ("set and forget" scenario). In the present paper, we are focusing on the following energy sources, possibly activated together depending on deployment conditions:

1) Vibration energy harvester (see Fig. 1 (a) block ①) dedicated to the conversion of otherwise wasted energy from mechanical vibrations into usable electric energy. The mechanical resonator has been mounted in a tailored configuration tuning the natural frequency of the harvester to match the vibration sources. The mechanical resonator is based on a piezoelectric (PZT) material.

2) Six high-performance TEGs generators (see Fig. 1 (a) block ②) with highly-efficient thermoelectric effect and 17 N&P stack for each one. An example of peak power generated with a temperature gradient of 15°C is 0.562 mW

3) One thin-film amorphous silicon solar cell (see Fig. 1 (a) block ③ PVC front) as energy source for INDOOR artificial light energy harvesting with power density of 0.042 μ W/mm² @ 200 Lux (reference number AM-1801 from Sanyo semiconductor). The current/voltage ratio under this illumination level is 18.5 μ A @ 3.0 Vdc.

4) One (through window) thin-film amorphous silicon solar cell (see Fig. 1 (a) block ③ PVC rear) as energy source for OUTDOOR solar harvesting with power density of 1 μ W/mm² @ 50 kLux (reference number AM-5904 from SANYO semiconductor). The current/voltage ratio under this illumination level is 4.5mA @ 5.0 Vdc.

5) One RF power source at 915 MHz (see Fig. 1 block ④) based on the Powercast P2110 harvester receiver and RF to DC converter. This module features high efficiency and ultra-low power consumption

C. The Sensor Board

As stated above, the aim of the present study is battery-less operations. Therefore, a 1 mAh solid state battery, being charged from the energy section at 4.1 Vdc, has been used as energy storage. The conditioning circuit of the gas sensors, the digital sensors of temperature and humidity, with the microcontroller and the RF module are powered at 3.3 Vdc. The on board 10-bit A/D converter (SAR) allows accurate measurements of the electrochemical sensors. A conditioning circuit for the sensors gases must be used, the signals from sensors are in current, and it is necessary to convert it into voltage for the ADC of the microcontroller. Following the datasheet guidelines of the sensors, the conditioning circuit has been built using the ST TSU102 operational amplifiers. The main feature that makes this component suitable for the designed system is the low power consumption. Supply current is around 600 nA at 3.3 Vdc per channel, and the input bias current of 1 pA maximum is an excellent feature for to use with the electrochemical sensors. The input offset voltage of 100 μ V maximum with a typical drift of 5 μ V/ $^{\circ}$ C only, doesn't affect the response of the sensors gas read by microcontroller at different temperatures. A frequency of 2.4 GHz is used by the wireless transmission system, allowing more flexibility of transmission protocol and enabling low power consumption in sleep mode. The very low power TSSA3166 single-pole single-throw (SPST) analog switch with 0.5 μ A current consumption from Texas Instrument is used to power only the analogic section necessary for the warm-up sensors phase.

D. Data Transmission Protocol

Wireless communication over 2.4 GHz is essential to send data to the main controller that will gather the data from the sensors. This is the most power-hungry operation of SERENO tasks. The design of a system able to perform energy efficient, scheduled operations required that energy is applied to transmission module only when it's necessary. Moreover it's necessary to have a robust and power-saving transmission protocol, which will help achieve low energy consumption and will ensure data integrity in noisy environment. To this end, the RF module works with the IEEE 802.15.4 standard that uses the spread spectrum coding technique, that is known for its good performance in noisy channels. The IEEE 802.15.4 standard was proposed to support low-cost, low-power devices, and supports scalable mesh topology and lower power consumption.

III. METHODS AND RESULTS

Four hardware prototypes of SERENO have been mounted and tested in real condition, to evaluate their

functionality in real application deployment. Each SERENO board has been equipped with a harvesting section able to recover energy from the photovoltaic indoor/outdoor solar cell panel harvesting, six thermoelectric modules, a piezoelectric module and a radio frequency harvester at 915 MHz. All the sources load at the same time a 1 mAh organic solid state battery that for each test begins with an energy level equal to zero. An array of sensors have been used that includes six gas sensors (CO, NO₂, NO, NH₃, Cl₂, H₂S), in addition to temperature, humidity and barometric pressure sensors. Tests have been conducted on the prototypes to define the features of the energy harvesting section and the sensors responses. Some tests took place in Italy and in Doha (Qatar) in several times. Different conditions of light emission, vibration levels, temperature gradients and RF radiation power have been experimented. At first, experiments were conducted on every sensor mounted on the board to define how the sensor responds to different gases concentration @ 25 $^{\circ}$ C in order to verify the reliability measure and the cross-sensitivity. Fig. 2 (a) and (b), instead, show the devices under test using gas cylinders with accurate gas concentrations to check the output voltage coming from the analogic section for each sensor.

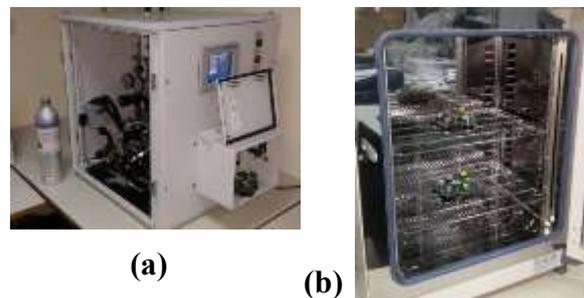


Fig. 2.(a) Chamber for gas sensors characterizations (b) Chamber for thermal test

Cylinders have been provided with certificates of composition and uncertainty value for each gas concentration. The boards mounting the six sensors array have been placed inside the chamber; the controlled atmosphere allows that no contaminants affected the measurements. The electrochemical sensors were tested on each of four boards mounted. In Fig.3, cross sensitivity values measured during the testing campaign are reported. These data have been compared with data provided on NEMOTO sensor's datasheets. Good accordance have been found. A temperature drift compensation, hardware by NTC resistor and software using a fourth order polynomial function according to NEMOTO gas sensor's datasheets, has been applied, and the measurement value is stable at different temperatures (Fig. 4). The zero temperature drift for each sensor has been tested using a climatic chamber (see Fig. 2 (b)) and the values after the compensation were found stable at

different temperatures. Finally, Fig. 5 shows an example

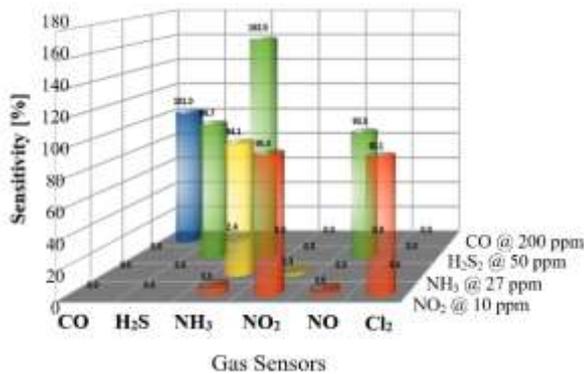


Fig. 3. Cross-sensitivity gas sensors characterization

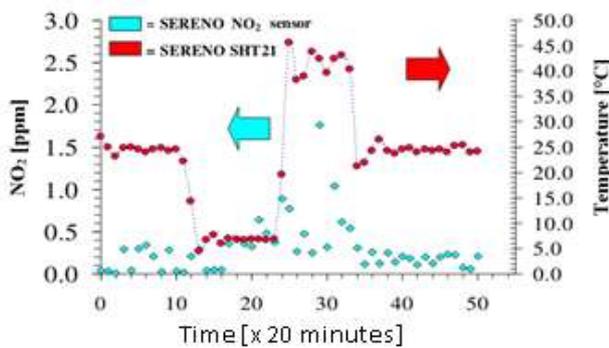


Fig. 4. Example of gas sensors (here NO₂) thermal drift analysis from 0°C to 45°C

of a measurement campaign taken in Doha (Qatar) with a device mounted on a car dashboard, conducted in a day of normal city traffic, in the middle of the traffic jam.

IV. CONCLUSION

In this work, we have proposed a multi-parametric sensing platform called SERENO (SEnsor REceiver NOde) totally powered from the environment and which presents a new approach to air quality monitoring. SERENO is able to manage intelligently energy transfer for perpetual operation without human intervention, allowing its deployment in indoor and outdoor applications. A system design with a novel power supply approach, avoiding use of conventional battery, has been presented. The experiments that have been conducted demonstrated that the described platform was able to operate as an air quality monitor in a “set and forget” scenario using a mesh network topology for wide area coverage. The system could be able to send data to a central platform, creating an “air quality pollution map” that users might consult, in order to let people decide if they should spend time outdoor or indoor. Moreover, no-maintenance capability (“set and forget”), makes the system scalable and expandable, without any further costs.

V. ACKNOWLEDGMENT

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