Sensors and Materials, Vol. 27, No. 2 (2015) 177–189
MYU Tokyo

S & M 1057

Environmentally Powered Multiparametric Wireless Sensor Node for Air Quality Diagnostic

Farid Touati, Claudio Legena, Alessio Galli,
Damiano Crescini[1,*], Paolo Crescini[1] and Adel Ben Mnaouer[2]

Qatar University, College of Engineering, Electrical Engineering Department
POB 2713, Al Tarfa 68, Doha, Qatar
[1]University of Brescia, Faculty of Engineering, Branze Rd. n°38, Brescia, Italy
[2]Canadian University of Dubai, School of Engineering,
P.O.Box 117781, Sheikh Zayed Rd., Dubai, UAE

(Received July 21, 2014; accepted December 17, 2014)

Key words: power harvesting, environmental monitoring, sensor networks, electrochemical sensors, piezoelectric harvesting

Sensor networks dedicated to environmental monitoring have helped in the analysis of primal processes and have also provided vital hazard early warnings. At the same time, environmental energy is now becoming a popular workable energy source dedicated to embedded and wireless computing systems where manual recharging and/or replacement of hundreds or even thousands of batteries on a regular basis is not practical. In this paper, we present a sensor node (SENNO), a multiparametric sensor node that intelligently manages energy transfer for perpetual operation without human intervention during air quality monitoring. The overall system design and experimental results are presented together with energy budget allocation. Preliminary results demonstrate that, after a tailored calibration process, the presented platform could effectively report and trace air quality levels in a type of "set and forget" scenario.

1. Introduction

In recent years, the design and fabrication of satisfactory air monitoring systems have been emphasized in reports of health diseases linked to poor atmospheric quality levels.(1–3) Identifying pollutants in the air, defining polluted locations and adopting air monitoring systems are paramount to the preliminary process of standard air-quality improvement techniques (*e.g.*, improved ventilation, air cleaning and air sanitation). Advances in micro-electromechanical systems (MEMS), electrochemical gas transducers and wireless sensor networks technologies have permitted the development of highly efficient, low-cost (and low-power) air quality monitoring systems (dedicated to pollutant detection and analysis) and their deployment in real environments.(4–12) Moreover, the combination of an air monitoring system with wireless sensor network technology is expected to

---

[*] Corresponding author: e-mail: damiano.crescini@ing.unibs.it

reduce installation cost and enable rapid and simple reshaping of data acquisition/control arrangements. Moreover, networked monitoring systems dedicated to air pollutants ensure low-cost and continuous observation. However, remote monitoring needs rugged and reliable sensor nodes to be integrated in potentially wide, disruptive and distributed environments. The crucial issue for the deployment of these wireless nodes is that they require high levels of power efficiency for autonomous, long and continuous operation. This is partly due to the battery replacement cost that may get too prohibitive in the case of long operation time in wide deployment scenarios. This approach calls to envision a "set and forget" scenario. At first glance, batteries seem to guarantee an optimum source of energy for wireless sensor systems when commercial battery technologies are adopted, thus giving an aggregated, powerful energy capacity in nearly small form factors. Today, the main trend in battery technology is towards the improvement in energy density. This approach has obvious advantages for portable devices in which increasing the time between charges and the high miniaturization of system size are paramount. In any case, energy density is not, unquestionably, the critical issue for the choice of battery technology for a wireless sensor node in a "set and forget" use. On the basis of this scenario, battery characteristics, such as self-discharge and lifetime, are reasonably more important than energy density or capacity and size. The adoption of a "set and forget" approach in this wireless sensor platform definitely results in the energy accessible to the system being bounded by the starting energy capacity of the battery together with the unforeseeable lifetime characteristics of the battery. The above-mentioned effort has driven the development of methods to maximize the lifetime of wireless sensor systems by minimizing energy consumption. This is achieved by adopting ultralow-power electronics (i.e., ultralow-power microcontroller with a sleep current of around 100 nA). The use of virtually no-power-consumption sensors (*e.g.*, electrochemical sensors connected to signal conditioning electronics with a supply current of around 1 μA) coupled with a wireless communication system that uses duty cycling based on long sleep times (i.e., the device remains in the low-power "SLEEP" mode for more than 95% of the time) helps also to realize the above goal of maximizing the lifetime of sensors. Hence, the sensorized node will be operative only for the time needed to achieve the operations of sensor warm-up, sampling, data processing and wireless data transmission or communication. In this paper, some of the key issues related to the delivery of autonomous power for wireless sensor systems are discussed with the aim of developing a multiparametric smart sensor node (SENNO) dedicated to air quality monitoring systems.

2. Related Work: Air Pollutant Monitoring Systems and Power Supply Issues

Different preceding research works have attempted to focus on networked air quality monitoring systems dedicated to diagnosis. In ref. 4, Barrenetxea *et al.* describe case histories of massive wireless environmental monitoring systems utilized in real-world deployment. The test took place on a rock glacier in Switzerland, while in ref. 5, CitySense, an example of large-scale wireless environmental monitoring systems, is discussed. In CitySense, the development and evaluation of wireless systems are reported and discussed, where an entire city has been covered by over 90 Wi-Fi-enabled Linux-based PCs embedded throughout offices and neon lights along the street. The system proposed by Barrenetxea *et al.* makes use of solar energy with a recharging battery only. Additional power sources are not taken into account and/or studied. Moreover, serious power limits are found during extensive radio duty cycling operation. Differently, CitySense uses a wired power supply. Other methods have also been proposed on energy-intensive platforms. As another example, indicated in ref. 6 (UC Berkeley), Honicky *et al.* proposed N/SMARTS, a global positioning system (GPS)-enabled cell-phone-based environmental data acquisition platform. The main transducer module consists of CO, CO_2, a three-axis accelerometer, and temperature sensors. A sample mobile air quality monitoring system is the SensorMap based on sensors that can detect ozone and nitrogen dioxide together with CO or a volatile organic compound (VOC).(7) The design focused on sensor signal acquisition and presentation, but it does not take into account various issues, such as metrological parameters of the gas sensors (*e.g.*, long-term stability, thermal effects on gas sensor sensitivity, cross-sensitivity and response time) and energy management. An approach using laser spectroscopic trace-gas sensors has been discussed in ref. 8. The use of integrated laser technology led to reductions in both the size and full cost of the platform while a wide range of gases are still detectable. As a primary drawback, the power consumption is very high. Finally, in ref. 9, Postolache *et al.* present a network for out-door air quality monitoring. Each node is deployed in a tailored scenario and incorporates SnO_2 sensor arrays linked to an acquisition system. Looking at the system morphology, in most cases, the nodes are hardwired to a central unit. With the aim to augment the gas measurement accuracy and prevent inappropriate early warnings and alarms, gas transducer influence parameters, i.e., air humidity and temperature, are also measured. Major drawbacks of this platform are the gas sensors used (*e.g.*, TGS 203 carbon monoxide and TGS800-general air contaminant sensor-AC; both sensors are based on a metal oxide semiconductor with an on-board electrical heater), where power dissipation across the electrodes (i.e., 300 mW) made it impossible to be applied in an environmentally powered network in indoor applications. As reported in antecedent works, detailed considerations pertinent to arguments, such as energy harvesting and storing (together with energy consumption), sensor choice, and perpetual operation without a battery, are not completely discussed as in refs. 10 and 11. The aim of the present study is to discuss in more detail the design, practical implementation, and operation of an indoor air quality monitoring system based on environmentally powered approaches in a “set and forget” scenario.

3. System Configuration

The complete designed and manufactured system named SENNO is depicted in Figs. 1–3, where the main blocks are indicated and well distinguishable (in Fig. 1, green blocks are related to power harvesting; in Fig. 2, red blocks are related to the 9 sensors operating on the printed circuit board (PCB); you can see in Fig. 3, black blocks are related to functional parts of the system). In the following paragraphs, the different sections are briefly described.

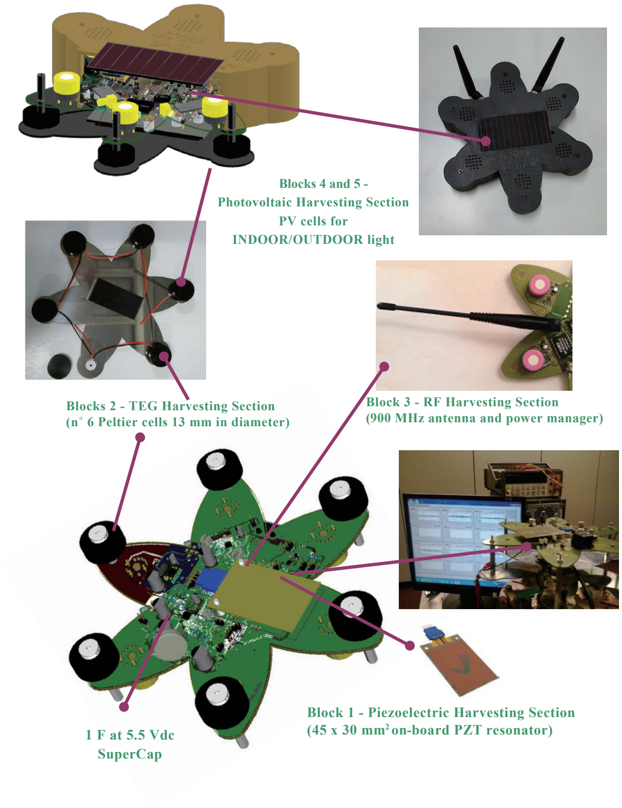

Fig. 1. (Color online) 3D view of SENNO (PCB top view) and photos of the prototype where the five harvesting blocks are illustrated in green together with the SuperCapacitor.

3.1 *Air quality sensors*

The primary target of our system is to build an air quality monitoring tool that measures pollutants with inexpensive compact sensors. Several types of off-the-shelf chemical gas transducers can be found in the market. Each gas transducer has different operation principle size, accuracy and power consumption, which vary with the sensor type. With the use of electrochemical technology, this type of sensor features both a small size and a short response time. Moreover, electrochemical sensors offer several advantages for systems that detect or measure the concentrations of different toxic gases. All the sensing elements are gas-tailored and show resolutions of around one part per million (ppm) of gas concentration matching the US Environmental Protection Agency (EPA) requirements.(13,14) They operate with a very small amount of current, making them well-suited in self-powered wireless nodes. In our project, we have adopted the following electrochemical sensors: NE4-CO carbon monoxide, NE4-NO_2 nitrogen dioxide, NE4-NO nitrogen monoxide, NE4-H_2S hydrogen sulphide NE4-CL_2 chlorine and NE4-NH_3 ammonia sensors from NEMOTO (examples of the sensors integrated in

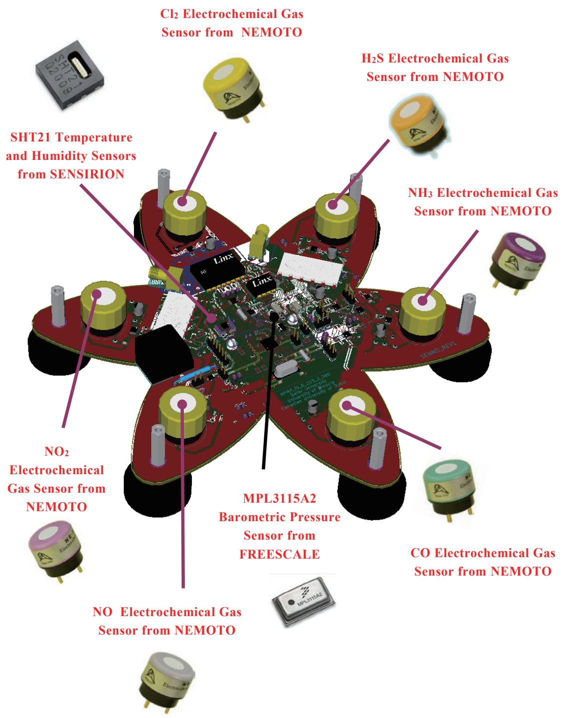

Fig. 2. (Color online) 3D view of SENNO (PCB bottom view) where the 9 sensors are illustrated in red.

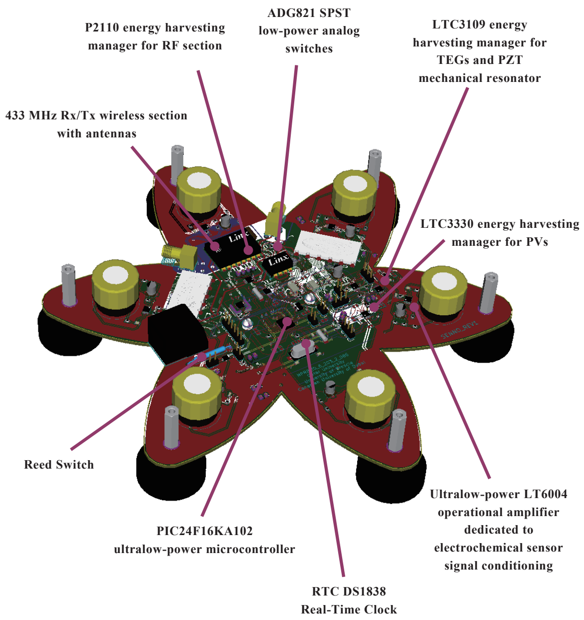

Fig. 3. (Color online) 3D view of SENNO (PCB bottom view) where functional blocks are illustrated.

the PCBs are shown in Fig. 2).(15) Temperature/humidity and barometric pressure sensors (Sensirion SHT21 and Freescale MPL3115A2 shown in Fig. 2) were also adopted in the sensor board. This is due to the fact that the sensed data of the gas transducer are susceptible to ambient temperature and humidity, while barometric pressure is an import parameter to be correlated with the data of air pollutants.

3.2 *Power management and energy harvesting methods*

The integration of numerous sensors (i.e., gas, barometric pressure, humidity and temperature sensors) and the wireless data transmission into a single sensor board led to practical problems, especially in terms of energy consumption and energy management. To provide an autonomous source of energy for the wireless sensor system SENNO, one can take into account scavenging energy from the environment with the aim to increase the battery energy storage capacity (if the battery is intended to be used in a rechargeable configuration) or indeed completely replace it. The sources of energy that have been identified (*e.g.*, working together in concurrent energy recovering functionalities) are as follows:

- A vibration energy harvester (see Fig. 1, Block 1) dedicated to the conversion of otherwise waste energy from mechanical vibrations into useable electric energy. With the aim to best accomplish this, 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 PZT materials (reference number V25W Volture series from Midè Inc.). Examples of the power generated for different combinations of resonance frequencies/seismic masses/accelerations are given below.
  - Frequency tuned to 75 Hz with acceleration = 0.5 g and 16 g seismic mass: Power extracted = 2.3 mW
  - Frequency tuned to 130 Hz with acceleration = 0.5 g and 2.5 g seismic mass: Power extracted = 0.8 mW
  - Frequency tuned to 180 Hz with acceleration = 0.5 g and 0 g seismic mass: Power extracted = 0.6 mW
- Six high-performance thermoelectric generators (TEGs) (see Fig. 1, Block 2) with highly efficient thermoelectric effect (reference number TG12-2.5-01L from Marlow Industries Inc.). The current/voltage ratios under different temperature gradients are reported below.

  5 °C: I_{CC}= 47 mA at 75 mV (power transferred to SENNO, due to impedance mismatching = 0.5 mW)

  15 °C: I_{CC}= 127 mA at 200 mV (power transferred to SENNO, due to impedance mismatching = 3.8 mW)
- One RF power source at 900 MHz (see Fig. 1, Block 3) based on the Powercast P2110 harvester receiver that converts RF to DC. This module features high efficiency and ultralow power consumption.
- One indoor thin-film amorphous silicon solar cell (see Fig. 1, Block 4) as energy power source with power density of 0.035 μW/mm^2 at 200 lux (reference number 12/096/048 from Solems S. A. France). The current/voltage ratios under different

illumination levels are
– 200 lux (artificial light): 33 μA at 4.8 V DC,
– 1000 lux (artificial light): 165 μA at 5.4 V DC.

- One outdoor (through window) thin-film amorphous silicon solar cell (see Fig. 1, Block 5) as energy power source with power density of 6 μW/mm^2 at 200 W/m^2 (reference number 12/096/072 from Solems S. A. France). The current/voltage ratios under different illumination levels are
  – 200 W/m^2 (natural light): 7 mA at 6 V DC,
  – 1000 W/m^2 (natural light): 33 mA at 6.5 V DC.

The highly integrated LTC3109 together with the LTC3330 converters ideal for harvesting surplus energy from extremely low input voltage sources have been used for the mechanical resonator and TEG section.(16) In particular, the module LTC3109 is designed to use two small external step-up transformers (adopted ratio is 1:100) to create an ultralow-input-voltage step-up DC/DC converter and a power manager that can operate from an input voltage of either polarity. This capability enables energy harvesting from TEGs in applications where the temperature differential across the TEG may be of either (or unknown) polarity. This function covers automatically SENNO stacked to a window in the case where differences between external ambient temperatures and indoor room temperature, at which thermal polarity changes for example with seasons, can serve as a source of energy harvesting. The energy converter manages the charging and regulation of multiple outputs in a system in which the average power draw is very low, but where periodic pulses of higher load current may be required. This approach is crucial where the quiescent power draw is extremely low most of the time, except for wireless data transmit pulses when circuitry is powered up to perform measurements and transmit data. In the design of SENNO nodes, we have also focused our attention on an RF energy harvester, which can produce only a small amount of energy; however, it is more stable than solar, piezo-magnetic and thermoelectric power. The target frequencies of the ambient RF energy harvester are 500 MHz, 900 MHz, and 2.45 GHz. For example, as indicated in ref. 17, Parks *et al.* successfully performed a sensor node operation using RF energy harvesting from a 500 MHz digital TV broadcasting radio wave. The frequency of 2.45 GHz is widely used for communication systems, such as Wi-Fi and Bluetooth. Olgun *et al.* developed a technique to continuously drive a temperature and humidity sensor with a liquid crystal display (LCD) using a Wi-Fi RF energy harvester. In the present research, we focus on the use of a RF harvester module operating in the 902–928 MHz ISM band using the Powercast P2110's module that provides a variable output voltage, in our case set to 5.25 V (as a maximum value), in order to charge the SuperCapacitor in logical OR with the other energy sources. The P2110 converts RF energy to DC and stores it in a capacitor (on the V_{cap} pin). When a charge threshold (1.25 V) on the capacitor is achieved, the P2110 boosts the voltage to the set output voltage level and produces the voltage output. When the charge on the capacitor declines to the low voltage threshold (1.02 V), the voltage output is turned off. Smaller capacitors will charge more quickly, but will result in shorter operation cycles. Larger capacitors will charge more slowly, but will result in longer operation cycles. During experimental tests, we have adopted a 330 mF capacitor. The value of the capacitor will determine the amount of energy available from the V_{OUT} pin. To determine the amount of energy recovered from this source, the tests were carried out in an anechoic chamber using the transmitter coded TX91501 with a transmitting power of 3 W effective isotropic radiated power (EIRP). In Fig. 3, a graph that shows the trend of the energy recovered as a function of transmission distance is shown. Figure 4 shows that the law of the recovered energy (in μW) from 3 W EIRP power at 915 MHz follows the law expressed by the exponential function P_{OUT} [μW] = $1196.49 \cdot d^{-2.50}$, where d (in m) represents the distance between the transmitter and the receiver. As an example,

- at 2.0 m with RF 3 W EIRP (915 MHz) transmitted power, we recover a power of 194 μW;
- at 5 m with RF 3 W EIRP (915 MHz) transmitted power, we recover a power of 21 μW.

On the basis of the experimental results shown in Fig. 3 and taking into account the Friis transmission equation for free space, we need an approximately 30 W EIRP at 915 MHz transmitting power to cover a 100 m^2 open area. Measurements were also conducted to define the charging time of the 330 mF SuperCapacitor. In the worst case, the charging time was around 10 h (considering the distance between SENNO and the transmitting module of about 3 m with an RF transmitting power of 3W EIRP power at 915 MHz or 10 m with an RF transmitting power of 30 W EIRP power at 915 MHz).

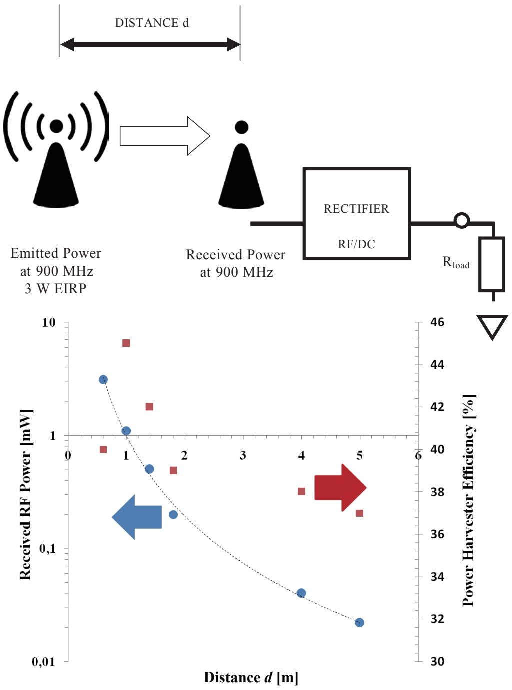

Fig. 4. (Color online) Received RF power vs distance d and power harvester efficiency.

3.3 *Sensor board*

The sensor board was basically powered by using a 1 F SuperCapacitor charged from the harvesting section at 5 V DC, while all sensor signal conditioning electronics, the microcontroller and the 433 MHz transceiver are powered at 2.5 V DC. The main controller is built around a 16-bit Microchip PIC24 featuring nanowatt extremely low power consumption (XLP) with a 500 nA SLEEP mode supply current. The microcontroller has nine dedicated analog channels with internal 10-bit analog-to-digital counter (ADC) conversion (SAR). The gas sensor signal conditioning section has been developed using Linear LT6004 operational amplifiers. The LT6004 presents an ultralow supply current (1 μA at 2.5 V DC) and a low operating voltage combined with excellent amplifier specifications such as an input offset voltage of 500 μV maximum with a typical drift of only 2 μV/°C, an input bias current of 60 pA maximum, and an open loop gain of 100000 that makes it ideal when excellent performance is required in environmentally powered batteryless applications. The 433 MHz receiver and transmitter are modules of Linx Technology that are able to work at 2.5 V DC with 5 mA current consumption in transmission and receiving modes.

The ADG918, with only 1 μA current consumption, of analog devices is used to switch the antenna signal from the receiver and transmitter modules; thus, only one external antenna is used for bidirectional communication.

3.4 *Data transmission protocol*

Communication is an essential, but power-hungry, aspect of SENNO. Energy-efficient operation requires careful management, such as scheduling operations of the system, and applies energy to a transmitter module only when data is ready. It is also important to develop a robust save-energy protocol transmission system that guarantees low energy consumption and at same time data integrity in a noisy environment. At SENNO, a transmission protocol has been applied to the Manchester encoding technique to obtain a robust data transmission system. In this type of encoding, logic level “1” is defined as a mid-point transition from a low pulse to a high pulse, and logic level “0” is defined as a mid-point transition from a high pulse to a low pulse. Each pulse width has a time of 1 ms; thus, every logic level has a time duration of 2 ms. Precision width pulses are obtained using the internal timers of the PIC24, the main features of which are repeatability and a stable quartz source reference. The data packet transmitted is composed of a synchronization signal with a 10 ms high level pulse, another synchronization signal with a 10 ms low level pulse, 24 transitions “1” to “0” (1 ms for each pulse), the data obtained by the sensors and a final signal that ends the transmission with “1” logic level encoded pulses. The data sent by the first SENNO prototype (where NO_2 and CO sensors have been installed) contains in order the SENNO ID (10 bits), which identifies the node, the ADC that induces the conversion of the analogic sensor CO (10 bits), the ADC that induces the conversion of the analogic sensor NO_2 (10 bits), temperature (16 bits), relative humidity (RH) (16 bits), barometric pressure (18 bits) and the cyclic redundancy check (CRC) (16 bits) calculated using the previous data with a specific algorithm. The entire transmission cycle has a total time duration of around 600 ms, which leads to, with 16 mW power requirement during operation, an energy consumption of about 10 mJ.

4. Preliminary Experimental Results

Preliminary experiments have been conducted to obtain and understand the basic characteristics of the environmentally powered sensor node SENNO in two prototypes. Each of the two complete SENNOs has been equipped with the harvesting section (thermoelectric, photovoltaic and RF, all loaded at the same time into 1 F SuperCapacitor at 5.5 V DC) together with a five-sensor array based on two gas sensors (CO and NO_2), one temperature sensor, one humidity sensor (RH%) and one barometric pressure transducer. The prototypes have been tested for 5 months in three dedicated studies, both in Italy and Doha (Qatar) under different conditions (light emission, vibration level, temperature gradient and RF radiation power). We carried out three basic studies. The first study was one week long and focused on how the five-sensor array installed on the PCB board responded to temperature variations in a thermal range from +5 to +50 °C in a controlled environment. The electrochemical sensors NEMOTO NE-CO (output current of 65 nA per 1 ppm of carbon monoxide) and NEMOTO NE-NO_2 (output current of 690 nA per 1 ppm of nitrogen dioxide), together with the PCB board and the other sensors, were placed in the PERANI UC150/70 climatic chamber (fixed location), and the atmosphere was controlled so that no substance could cause pollution. Figures 5(a)

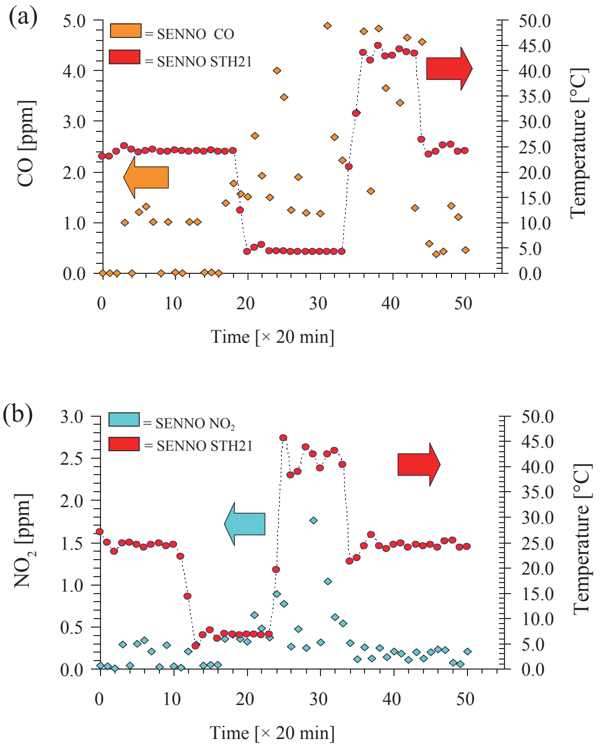

Fig. 5. (Color online) Zero drifts of (a) SENNO CO and (b) SENNO NO_2 gas sensors due to temperature effect.

and 5(b) show that zero drift lower than 5 ppm was obtained for the NEMOTO NE-CO, while the NEMOTO NE-NO_2 demonstrated a drift as low as 1 ppm.

The results of the second study, which involved the characterization of CO and NO_2 sensors, are summarized in Figs. 6(a) and 6(b). Each of the studied gas sensors is separately deployed in a tailored test chamber as part of the Laboratory of Sensors at the University of Brescia (Italy). The gas concentrations in ppm are fixed using a mass flow controller connected to gas bottles with a standard concentration (*e.g.*, 10 ppm NO_2). Important parameters, such as temperature and humidity, are measured using the temperature and relative humidity sensors installed on-board the SENNOs. The temperature and relative humidity are fixed at around 25 °C (±5 °C) and 50 ± 10%, respectively. The voltages obtained from the channels of SENNO sensors are received via a 433 MHz wireless line in a receiving node and stored in the main processing and control unit (desk PC) that performs data processing and data logging. The data have also been published through a LabVIEW web server that stores the history of the evolution of air quality in the monitored gas chamber areas and evaluates air quality trends.

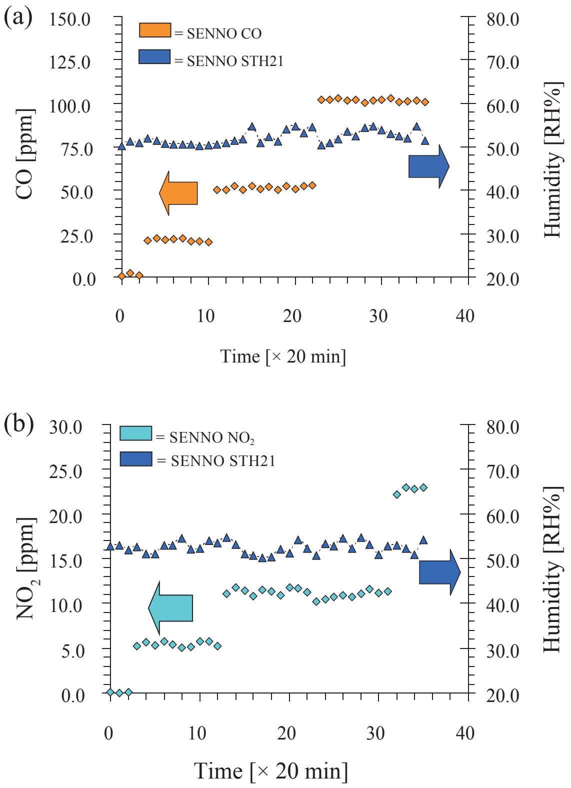

Fig. 6. (Color online) Responses of (a) SENNO CO and (b) SENNO NO_2 gas sensors.

Table 1
Energy allocation per day under different conditions.

Operation	Energy per day (J)
Sensor warm-up (60 s every 20 min)	0.4
Sensor measurement (2 s every 20 min)	1.15
Data processing and storage (1.0 s every 20 min)	0.01
Data transmission (0.6 s every 20 min)	0.69
Sleep mode (19 min every 20 min)	0.5
Total system energy budget required by SENNO prototype per day	**≈ 2.75**
Total energy recovered per day under the following conditions:	**≈ 137.3**
1. Energy from external low sunlight (average: 4 h 100 W/m^2, 3 h 50 W/m^2, 10 h night 0 W/m^2)	125
2. Energy from internal artificial light (office average: 8 h 200 lux)	4.3
3. Energy from temperature difference through the window: 10 h with 5 °C and 14 h with 0 °C (nonoperative)	6.2
4. RF energy at 900 MHz: 3 W EIRP (transmitted) with SENNO positioned at 5 m (24 h operative)	1.8
5. Energy from vibrations: none	0

The third study was dedicated to the first evaluation of the SENNO power consumption vs perpetual functionality in an indoor application where the harvesting sections were fixed to a window, as shown in Table 1; in this case, no vibrations are taken into account owing to the fixed window. The total energy harvested from the environment exceeded the total energy required by SENNO by almost a factor of four when we considered the internal artificial light, RF and thermoelectric effect (the factor increased to 50 when external light was considered); thus, we envision a perpetual operation without human intervention for battery replacement. A system operating one measurement and transmission cycle every 20 min is considered.

In the case where no energy is available, and with the condition of SuperCapacitor fully charged, the system could work for up to 24 h ensuring the correctness of the data.

5. Conclusions

In this paper, we have presented SENNO, a multiparametric sensor node that intelligently manages energy transfer for perpetual operation without human intervention during air quality monitoring in indoor applications. We have also presented the overall system and first experimental results together with energy budget allocation. Preliminary results demonstrate that, after a tailored calibration process, the presented platform could effectively reveal and monitor the air quality in a “set and forget” scenario.

Acknowledgements

This publication was made possible by NPRP grant #6-203-2-086 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

References

1 B. Argrow, D. Lawrence and E. Rasmussen: Proc. 43rd AIAA Aerospace Sciences Meeting and Exhibit, 2005, paper AIAA-2005-1237.
2 G. Bernhard, C. R. Booth and J. C. Ehramjian: SPIE **5156** (2005) 167.
3 R. Shepherd, S. Beirne, K. T. Lau, B. Corcoran and D. Diamond: Sens. Actuators, B **121** (2007) 142.
4 G. Barrenetxea, F. Ingelrest, G. Schaefer, M. Vetterli, O. Couach and M. Parlange: Proc. 7th Int. Conf. Information Processing in Sensor Networks, 2008, p. 332.
5 R. N. Murty, G. Mainland, I. Rose, A. R. Chowdhury, A. Gosain, J. Bers and M. Welsh: Proc. 8th IEEE Conf. Technologies for Homeland Security, 2008, p. 583.
6 R. Honicky, E.A. Brewer, E. Paulos and R. White: Proc. 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions, 2008, 25.
7 P. Volgyesi, A.Nadas, X. Koutsoukos and A. Ledeczi: Proc. 7th Int. Conf. Information Processing in Sensor Networks, 2008, p. 529.
8 S. So, F. Koushanfar, A. Kosterev and F. Tittel: Proc. 6th Int. Conf. Information Processing in Sensor Networks, 2007, p. 226.
9 O. Postolache, J.M. Pereira, P. Silva Girão and A. Almeida Monteiro: Electr. Eng. **146** (2012) 81.
10 D. Crescini and E. Viganò: Italy Patent EP2366950 (2011).
11 F. Fei, S. Zhou, J. D. Mai and W. J. Li: Energies **7** (2014) 2985.
12 F. Fei, J. D. Mai and W. J. Li: Sens. Actuators, A **173** (2012) 163.
13 U.S. Environmental Protection Agency: Air Pollution Monitoring, http://www.epa.gov/oar/oaqps/monitoring.html (accessed on September 28, 2009).
14 Synergist Buyer’s Guide, Indoor Air Quality, http://www.aiha.org/thesynergist/html/bg/iaq.htm (accessed on September 28, 2009).
15 Nemoto Chemical Sensors Catalogue, Nemoto & Co., Tokyo, Japan, http://www.nemoto.co.jp/product.
16 Linear Technology Catalogue, www.linear.com.
17 A. Parks, A. Sample, Y. Zhao and J. R. Smith: IEEE Topical Meeting on Wireless Sensors and Sensor Networks (WiSNET), 2013, p. 127.