Pervasive environmental monitoring by means of self-powered Particulate Matter LoRaWAN sensor nodes

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Abstract – **The aim of this paper is to propose the architecture of a self-powered sensor node, to be deployed on means of transport to pervasively collect measurements of Particulate Matter (PM) concentration in urban areas. The sensor node is based on the use of low cost PM sensors and exploits LoRaWAN connectivity to remotely transfer the collected data. It is also provided with GPS localization features that allow to associate the measured values with the geographical coordinates of the sampling site. The system is also provided with an innovative, small-scale, solar-based powering solution that allows its energy-self sufficiency and then its functioning without the need for a connection to the power grid.**

I. INTRODUCTION

The term "Particulate Matter" (PM) encompasses a wide range of solid, organic and inorganic particles and liquid droplets that are commonly found in air. In general, PM is composed of a wide range of different elements that change according to the different environmental features [1, 2], but include sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. PM is classified according to the dimensions of the single particles: we speak then of PM_{10} when the diameter of the particles is lower than 10 micron ($d_{PM10} \leq 10\,\mu m$) and of $PM_{2.5}$ when the diameter is lower than 2.5 micron ($d_{PM2.5} \leq 2.5\,\mu m$).

Both typologies of PM can be easily inhaled by human beings, and a chronic exposition to this kind of pollutants can bring to the emergence of cardiovascular and respiratory diseases. In particular [3], PM_{10} can penetrate inside lungs, while $PM_{2.5}$ can penetrate the lung barrier and enter the blood system, with even more harmful effects. For this reason, World Health Organization has defined two thresholds for each type of particulate, that can be seen in Table 1, that should not be overcome to safeguard the citizens' health.

PM levels are usually measured by public bodies which

Table 1. Particulate Matter Thresholds

	24-hour mean	annual mean
$PM_{2.5}$	$25\,\mu g/m^3$	$10\,\mu g/m^3$
PM_{10}	$50\,\mu g/m^3$	$20\,\mu g/m^3$

collect the data by means of fixed monitoring stations deployed in a limited number of spots: in general, only one or few monitoring stations are present in medium to large-sized cities. Moreover, data collected by these stations refer only to the area of the city where they are deployed, while they cannot provide a pervasive feedback on the PM levels in other parts of the city. This fact is mainly due to the high cost of this monitoring stations that prevents from deploying them in a large number across a large territory. Nevertheless, some low cost PM sensors are currently available on the market: while their accuracy level is not comparable with the fixed monitoring stations, they can still provide an interesting feedback on the level of PM, in particular for what concerns the overcoming of the daily and yearly thresholds. Moreover, these devices are characterized by small dimensions, and can be then integrated on portable data acquisition platforms that can be provided with the adequate connectivity to transfer the acquired data in real time to a remote data management centre. Deploying a large quantity of this kind of devices, a pervasive monitoring infrastructure can be then set up across a whole urban centre, thus perfectly fulfilling the paradigm of the Smart City [4, 5].

While several city-scale air quality wireless monitoring infrastructures can be found in literature [6, 7, 8], this paper focuses on the realization of a different typology of data acquisition architecture. Indeed, in the proposed solution, the sensor nodes are expected to be provided with localization features [9], and are then expected to be deployed on means of public transport. This approach is especially relevant since it allows to acquire data in a more

pervasive way, bringing the measurement instrumentation in almost every spot of a city. This approach is empowered by providing the sensor node with energy harvesting capabilities, thus ensuring the node energy self-sufficiency and then its full operativeness without the need to connect it to any power source.

II. SENSOR NODE STRUCTURE

The sensor node purpose is to periodically sample the amount of PM in the air and transmit this information over a LoRa radio channel. In addition, also the GPS position of the node has to be acquired every time a sample is collected. The sensor is powered by a battery that is recharged by means of a crystalline silicon solar cell. The structure of the system is shown in Fig.4.

The main blocks that compose the node are the Communication and Control Unit (CCU), the particle sensor, the GPS module, a battery and a step up DC-DC converter to manage the energy coming from the solar cells. The CCU has been developed ad-hoc (See Fig.2) and hosts a low power STM32L073 microcontroller (MCU) by STMicroelectronics, a LoRa transceiver (RFM95 by HopeRF) and a power management electronics to supply internal devices and charge a Li-Ion battery. The power from the solar cells is elevated and stabilized by a step-up DC-DC converter (LTC3105 on an evaluation board) that hosts a start-up controller (from 250 mV) and a Maximum Power Point Controller (MPPC) that enables operation directly from low voltage power sources such as photovoltaic cells. The MPPC set point can be selected depending on the solar cells used. If energy from solar cell is available, the battery charger (STC4054 by STMicroelectronics) will recharge the battery. The MCU and the radio module are supplied by a 2.5 V LDO regulator, the voltage level of the battery is controlled by an ADC channel on the MCU and a voltage divider. The Particle sensor (HPMA115S0 by Honeywell, shown in Fig.3) requires 5 V to operate: this power source has been generated by an other LTC3105 module directly from the battery. This latter can be powered off by a specific shut down line from the MCU. The GPS module (MTK3339 by Adafruit) requires a power voltage of 3.3 V that is available as an output of the particle sensor.

Since the sensor node is expected to operate continuously without the need of connection to the power grid, a power strategy based on a strict duty-cycling was adopted. In particular, the system is expected to perform data sampling and transmission, and then to be put in sleep mode according to an adaptive duty-cycling policy that will be described in detail in section iii..

III. POWER MANAGEMENT AND ENERGY HARVESTING

We addressed the powering of the sensor node in its actual working environment from a theoretical perspective,
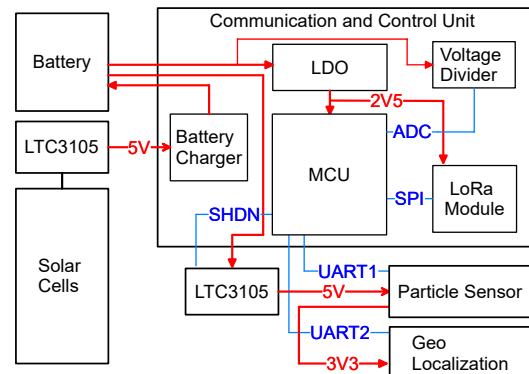

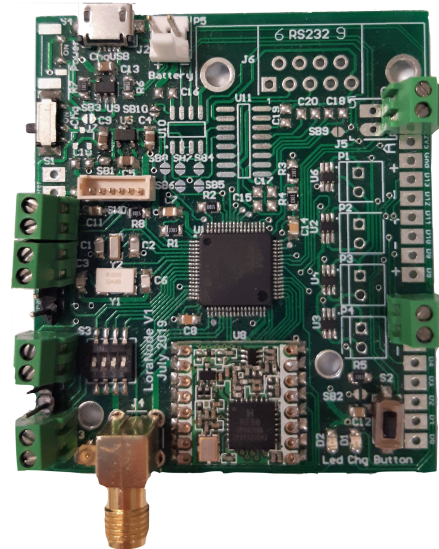Fig. 1. Sensor Node internal structure.

Fig. 2. Communication and Control Unit

Fig. 3. Honeywell HPMA115S0 Particulate Matter sensor.

evaluating a solar energy harvesting system charging a battery. The aim of the study presented in this section is mainly to foresee the maximum duty cycle of the operations depending on the provision of the solar harvester.

First, we estimated the power consumption of our module depending on the duty cycle. Let us indicate with t_0 the time (in seconds) necessary for a complete operating sequence, made up of the MCU acquisition, data transmission via LoRa and GPS localization. The maximum number of operating sessions in an hour is given by:

$$N = \left\lfloor \frac{3600}{t_0} \right\rfloor. \qquad (1)$$

In our case we have $t_0 = 10\ s$ and thus $N = 360$. Let n be the desired number of operating sessions in an hour. Then the duty cycle is plainly given by:

$$\delta = \frac{n}{N}. \qquad (2)$$

Now, let W_0 be the energy required for a single operating sequence. Considering the sensor and analog front-end powering, the microcontroller consumption in run mode, the LoRa module consumption in stand-by and transmission modes, and the GPS consumption, we obtained $W_0 \approx 0.29\ mWh$. Using equation (2), the daily energy consumption for a fixed duty cycle is given by:

$$W_\delta = 24 \cdot W_0 \cdot n = 24 \cdot W_0 \cdot \delta \cdot N. \qquad (3)$$

Equation (3) allows calculating the maximum feasible duty cycle for not draining the battery, given the daily available energy.

This available energy is the energy produced by the solar harvester and stored in the battery. We chose to focus on crystalline silicon, as it exhibits excellent performances being a well-standardized and steady technology. As an example, we estimated the performances of the 25.7 % efficiency cell presented in [10], during different periods of the year. For this purpose, we reckoned the solar spectra (with the software PV Lighthouse) throughout the 15th of every month at different hours of the day in Siena, Italy. On the other hand, we kept the cell External Quantum Efficiency (EQE) from [10]. Using these pieces of information, it was possible to obtain the short circuit current corresponding to each spectrum applying the following equation [11]:

$$J_{sc} = \int_{300nm}^{1200nm} \frac{q}{hc} \cdot P_{in,\lambda} \cdot EQE_\lambda \cdot \lambda d\lambda \qquad (4)$$

where λ is the wavelength, $P_{in,\lambda}$ is the incoming power at wavelength λ, q is the elementary charge, h is the Planck constant and c is the speed of light in vacuum. Afterwards, we calculated the open circuit voltage using the equation [12]:

$$V_{oc} = V_T \ln\left(\frac{J_{sc}}{J_0} + 1\right) \qquad (5)$$

where V_T is the thermal voltage and J_0 is the reverse saturation current. Finally, we calculated the maximum power

production achievable, for each short circuit current and open circuit voltage, using the equation:

$$P_m = FF \cdot J_{sc} \cdot V_{oc} \qquad (6)$$

where FF is the fill factor of the cell. We took 83.3% as a reference value for the fill factor from [10] and assumed it to be constant through variations of lighting conditions. Summing the contributions for every hour of a day we obtained an appreciation of the total energy produced by the solar cell during that day. The results are summarized in the plot in Fig. 4. The minimum energy
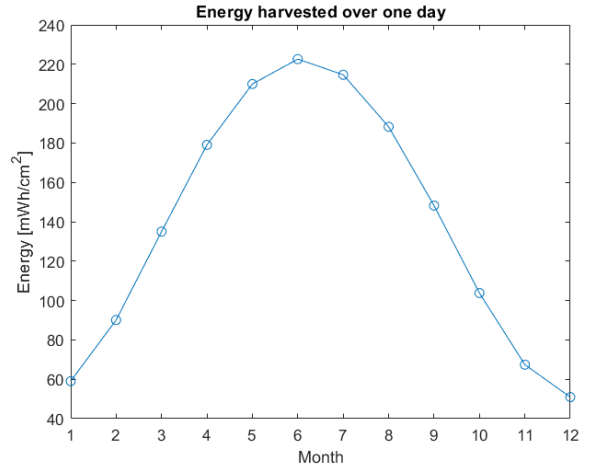

Fig. 4. Energy produced by the selected crystalline solar cell in different days of the year.

($50.95\ mWh/cm^2$) is produced in December, while the maximum is achieved in June ($222.63\ mWh/cm^2$). Using equation (3) it was possible to estimate the maximum duty cycle in the various circumstances. For example, considering a single $5\ cm^2$ solar module, for December and June we obtained $\delta_{max} = 10\ \%$ and $\delta_{max} = 44\ \%$ respectively. This assessment suggests that a possible strategy to extend the autonomous lifetime of our module would be to adjust the operation duty cycle basing on the period of the year.

Note that the presented reasoning is a best-case assessment, being founded on three assumptions:

1. The system is able to fully exploit the harvested energy.

2. The incidence of bad meteorologic conditions is not taken into account. In case of cloudy weather, the energy production of the solar cell worsens dramatically. Therefore, in such periods the system would rely only on the battery. Monitoring the battery charge level can be useful to establish whether the system should reduce the duty cycle or even enter in sleep-mode.

3. The analysis does not include the deterioration of the solar cell behaviour due to rising temperature [12].

These issues could be addressed in a future work, with the support of direct measurement data of solar cell performances exposed to real working conditions.

IV. TESTS AND MEASUREMENTS

The performances of the system were tested in a real environment: in particular, the sensor node was placed for 1 week on the facade of the Department of Information Engineering and Mathematics of the University of Siena, Italy (See Fig.6), acquiring PM_{10} and $PM_{2.5}$ values each 15 minutes. During each sampling, 10 values were acquired and then their mean value was transmitted by means of LoRaWAN protocol to a LoRaWAN Gateway positioned inside the building.

In order to verify the operation of the system, the sampled values were compared with the ones available on the website of the Regional Environmental Protection Agency of Tuscany Region (ARPAT), which owns a set of fixed monitoring stations deployed across the whole territory of Tuscany. In particular, daily average values are available on ARPAT website: for this reason, for the acquired values the daily mean value was calculated. The values were compared with the ones acquired by the fixed staton positioned in Viale Bracci, Siena, Italy, which is the closest one to the University building, at a distance of 2.5 km. A deployment close to this fixed station was not possible due to security reasons.

Fig.5 shows the daily mean values of PM_{10} concentrations measured at the fixed station by ARPAT and by the system described in this work, positioned on the University building. While the two values are notably different, this is due to the deployment site: while the ARPAT fixed station is positioned close to the very busy road that leads to the Siena hospital, the University building is positioned in a limited traffic area located in a peripheral part of the Historic Centre of Siena. Nevertheless, the effectiveness of the system can be noticed, since the trend of the two values all week long are almost similar: in particular, the values measured by the system are always almost half of the ones provided by ARPAT.

An important comment has to be done: a low cost sensor has been used in the realization of the system, and its accuracy level cannot be compared with the professional, and then very expensive, measurement platforms used by ARPAT. Nevertheless, looking at the values measured by the system, it is evident that the proposed solution can still be useful to collect data about PM in a more pervasive way, even if with a lower level of accuracy level. In this sense, the proposed solution is not expected to replace the existing fixed measurement station but mainly as system to enrich the knowledge about the different levels of PM that may be recorded in correspondence of different environmental conditions.
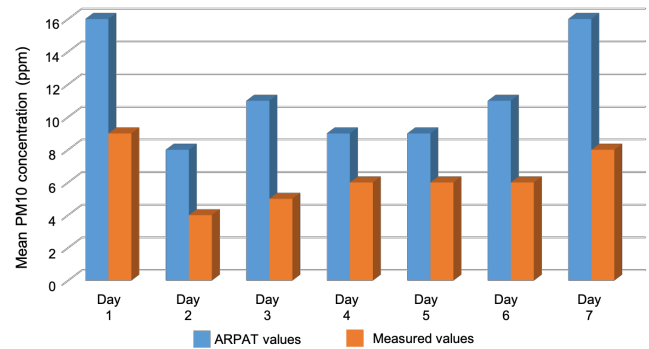

Fig. 5. Comparison between daily mean PM_{10} concentrations provided by ARPAT and measured by the system.

Fig. 6. Sensor node testing setup.

V. CONCLUSION

The aim of this paper was to propose the architecture of a self-powered LoRaWAN sensor node for the pervasive measurement of PM concentrations in urban areas. According to the results presented in this paper, the system is able to operate autonomously exploiting an energy harvesting system based on the use of solar cells. At the same time, the system can sample the PM concentrations by means of a low cost sensor, transmitting them to a LoRaWAN Gateway together with the geographic coordinates of the sampling location. By positioning the measurement system on means of public transport and combining these two data, PM levels may be measured across a large area and the level differences related to different areas of an urban centre may be identified.

A prototype of the system has been already tested, and the acquired values have been compared with the certified ones, provided by a public body. The next step of the work will be the replication of the sensor node and the positioning of a set of devices on a group of vehicles, in order to demonstrate the effectiveness of the solution in its real deployment scenario.

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