Chapter 2
CH_4 Monitoring with Ultra-Low Power Wireless Sensor Network

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Abstract We propose a novel method to reveal and measure natural gas presence in air, using commercial off-the-self available MOX gas sensors in wireless sensor network applications. This technique reduces the power consumed by the catalytic sensors of a factor 10×, by an analysis on a reduced sampled period and thus extending the autonomy of battery operated systems. The information about the gas concentration is extracted from the sensor transient response through a discrete cosine transform (DCT) analysis and permits to immediately discriminate between clean-air and hazardous situations. The characterization of the sensing device has been conducted using a wide range of humidity and environmental conditions to demonstrate the effectiveness of the approach and a detailed comparison with the standard usage has been performed. Finally, the technique has been implemented in a Wireless Sensor Network designed specifically to measure air-quality in a large area and to share information over the internet.

2.1 Introduction

The detection of volatile chemicals is an essential to assess the air quality and the safety of indoor environments, because together with surveillance techniques [1], it guarantees to keep the environment safe and secure. Catalytic gas sensors are widely used in environmental monitoring applications because of their low cost, and are available for many kind of chemicals. Moreover, they are more robust with very low maintenance, they exhibit long life time with respect to electrochemical sensors

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and have fast response time. However the low selectivity and the big energy consumption are challenging problems if the energy availability onboard is constrained. Indeed, nowadays, many environmental monitoring projects are moving toward the use of wireless sensor networks, where any mW of power counts. Usually WSN are designed with low power sensors (e.g. temperature, light, pressure, acceleration…); thus catalytic gas sensors would impact with the highest power consumption with respect to any other component on the sensor node, including radio transceivers. Sensors of this kind are commonly used with continuous power supply leaving it always powered (e.g. in smoke detectors), or, at least, for a time interval sufficient to ensure a reliable response. Furthermore, the influence of air humidity variations has been never investigated in the sensor behavior. In this work, both the energy reduction and the humidity influence are taken into consideration to describe the effectiveness of the proposed method.

Analyzing features of the transient response such as the DCT, it is possible to determine gas concentration and its dependence on environmental conditions (in particular humidity). The outcome is an estimation of the gas concentration, which is, of course, less accurate than the traditional method, but still reliable and capable to discriminate between clean air and hazardous concentration, saving more than one order of magnitude in terms of energy absorbed by the sensing device. The goal is to outperform the state-of-art gas sensors in terms of energetic efficiency, providing, at the same time, a new method to integrate the traditional time-based characterization [2] for catalytic sensors. A Wireless Sensor Network (WSN) has been developed to characterize the autonomy of the systems when the sensor are used on battery operated boards. To pave the way to future developments, the coordinator mote has been USB-connected with a smartphone to add internet connectivity. With this configuration, the system can upload the data about air quality to the cloud and make them available everywhere. The power budget needed to maintain the network is also mitigated by compressive sampling techniques such as [3].

2.1.1 Related Works

Chemoresistive sensors are usually targeted at natural gas and combustibles detection, with a focus on performance in terms of ppm/ppb rather than consumption [4, 5]. A great variety of reliable sensors exists, but no one designed to low power applications as it is mandatory for WSNs. However, recently, electrochemical sensors and new catalytic sensors have been presented [6], with low consumption and developed to achieve good performance in environmental monitoring applications.

Unfortunately, an exhaustive characterization of these innovative sensors is not reported, and generally electrochemical devices exhibits a limited lifetime, due to the consumption of the electrochemical reactive elements. Thus, smart and not destructive power management, is still fundamental to achieve ultra-low power consumption with traditional and more robust technology. Some researchers focused their attention on the strategy used to sense the environment. Articles [7–10] propose efficient

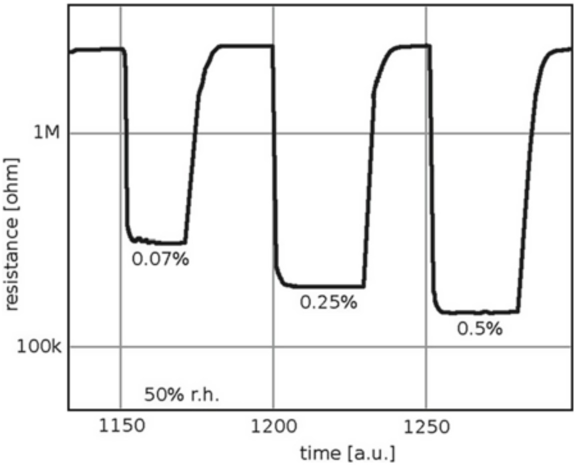

Fig. 2.1 AS-MLK standard response for continuous monitoring

duty-cycle activity of the node, and achieve an extension of the life of a node by 2× or 3×, still using the sensor as indicated by the manufacturer. Other kind of optimization were introduced in the hardware of nodes [11, 12], achieving significant reduction of wasted power when the device is in idle or sleeping state.

2.2 Gas Measurement Characterization

To validate our approach, we used the AS-MLK natural gas sensor, from the Applied Sensor. [1] This is intended for mass market application which key requirements are long lifetime, low cross sensitivity and long term stability. The AS-MLK is targeted at real-time monitoring applications, this means that it must be always switched on to have a prompt response, as shown in Fig. 2.1, where the characteristic provided by the manufacturer is depicted, and the output resistance (versus time) changes quickly to varying concentrations. This device is able to detect gas level in air in the order of hundreds part per million, well below the explosive threshold (5 %), and temperature and humidity slightly influence the measure. Generally, catalytic gas sensors need a constant voltage supply for a reliable measure because the reversible chemical reaction is triggered by heat. The energy consumption are then closely related with the time a sensor needs to reach stability, however, to save power, this time has to be shorten. In environmental monitoring applications, a high frequency of measurement is enough to detect abrupt changes, especially when a dangerous situation is unlikely to happen.

A duty-cycle strategy, in which a measure lasts for less than 6 s and are repeated with intervals of 2 min are shown in Figs. 2.3 and 2.4. The first one was collected with

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[1] AS-MLK Datasheet, http://www.appliedsensor.com.

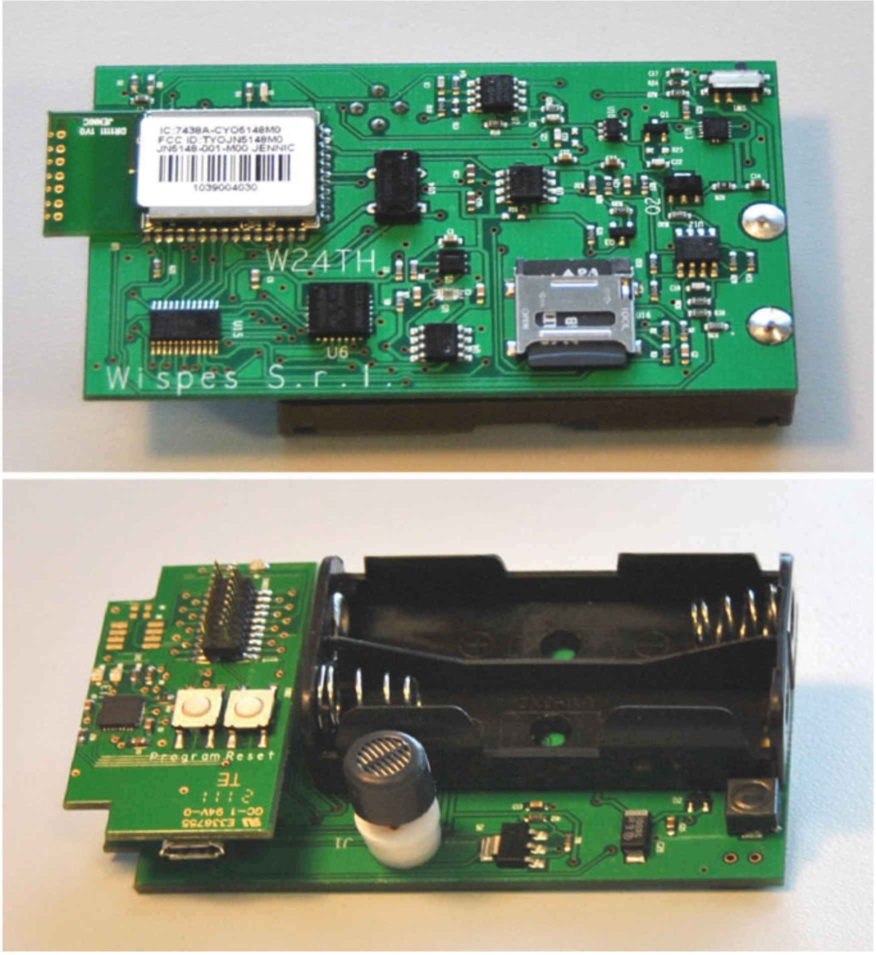

Fig. 2.2 W24TH mote used in our testbed with MOX sensor onboard

30 % of relative humidity in the fluxed mixture (technical air + natural gas), while the latter with 50 %. In both the cases the sensor reaches the stability in the response and it is easy to distinguish the gas level, which traces out the values extracted from the characteristic curve in the datasheet (Fig. 2.1). Unfortunately this approach does not achieve the expected performance, because of the transient response is too long and requires too much power.

2.2.1 Ultra-Low Power Strategy

The transient responses presented in this paper are illustrated in Figs. 2.3 and 2.4, and are detailed in Figs. 2.5 and 2.6. Generally, the larger the humidity, the slower

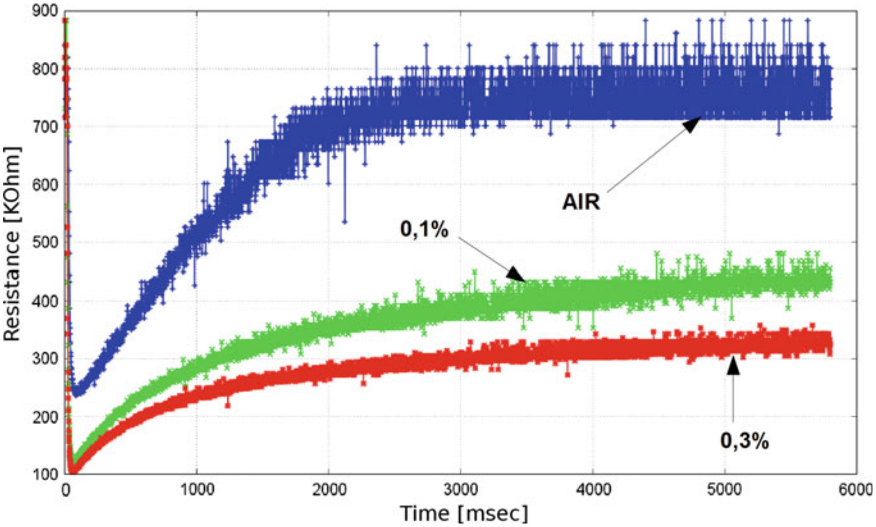

Fig. 2.3 Standard output response 20 °C with 30 % RH, 5 % duty-cycle

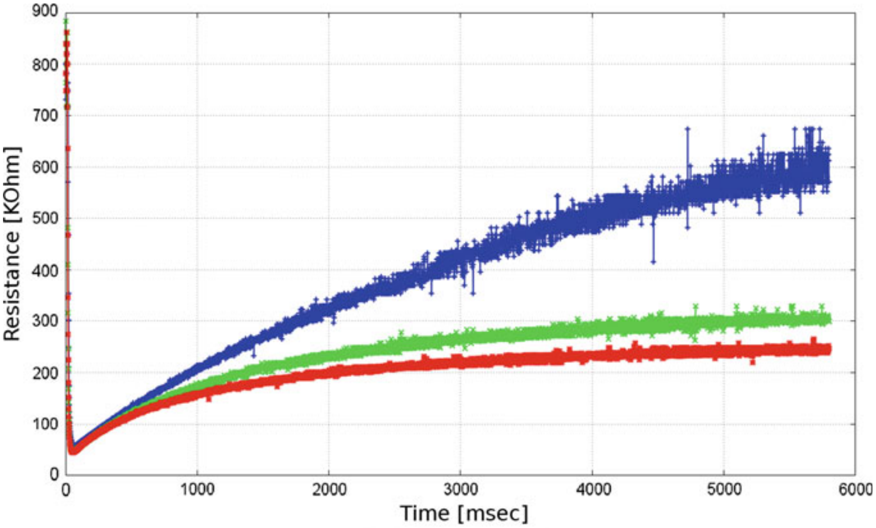

Fig. 2.4 Standard output response 20 °C with 50 % RH, 5 % duty-cycle

the response time. Thus to achieve a good trade-off between energy saving and reliability, reducing the duty-cycle by decreasing the power-on time is not sufficient, because in some environmental conditions it is not possible to discriminate the gas concentration from few samples.

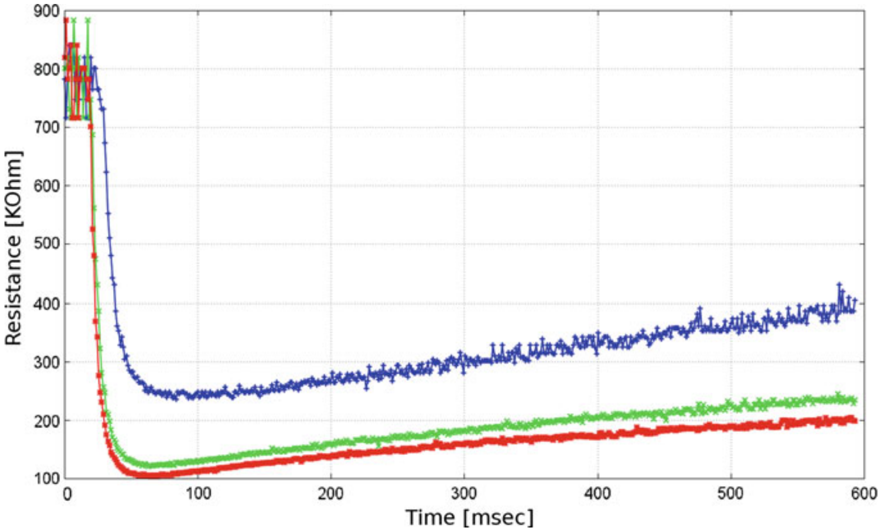

Fig. 2.5 Detail on first 512 samples 20 °C with 30 % RH, 5 % duty-cycle

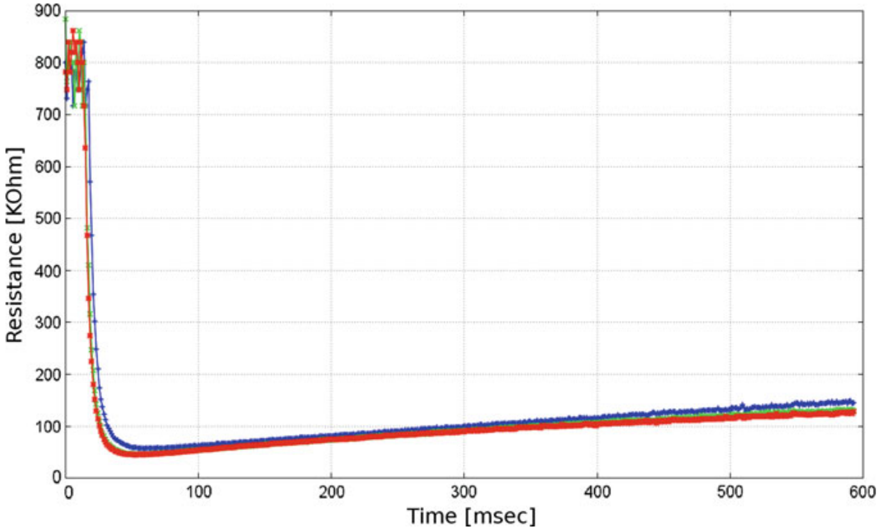

Fig. 2.6 Detail on first 512 samples 20 °C with 50 % RH, 5 % duty-cycle

The output resistance of the catalytic sensor is an aperiodic signal and can be interpolated to extract a continuous spectrum through the Discrete Fourier Transform. From the analysis of the normalized amplitude spectrum, it has been observed that the components around 20 Hz, are pretty proportional to the gas concentration, despite the parameters listed before (i.e. time and humidity). This property has

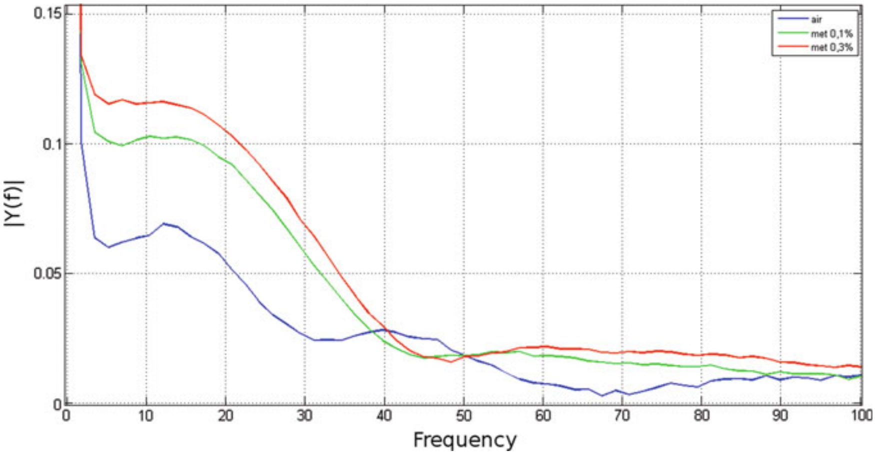

Fig. 2.7 DFT on interpolated standard response 20 °C with 30 % RH, 5 % duty-cycle

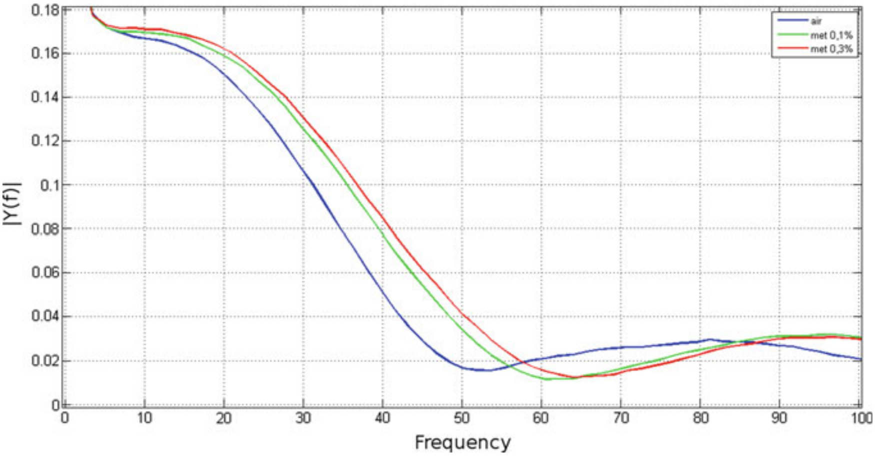

Fig. 2.8 DFT on interpolated standard response 20 °C with 50 % RH, 5 % duty-cycle

been fully characterized and then used as feature to assess the gas concentration, while reducing the energy need by the device. Figures 2.7 and 2.8 show the normalized amplitude spectrum of the first 512 samples extracted from the experiments of Figs. 2.3 and 2.4. A Normalized Discrete Cosine Transform (DCT) has been implemented to concentrate on only one component at a time (20 Hz), as the definition shown in Eq. 2.1.

$$\hat{X}_k = \frac{\sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi \frac{k}{N} n}}{\sum_{n=0}^{N-1} x_n} \tag{2.1}$$

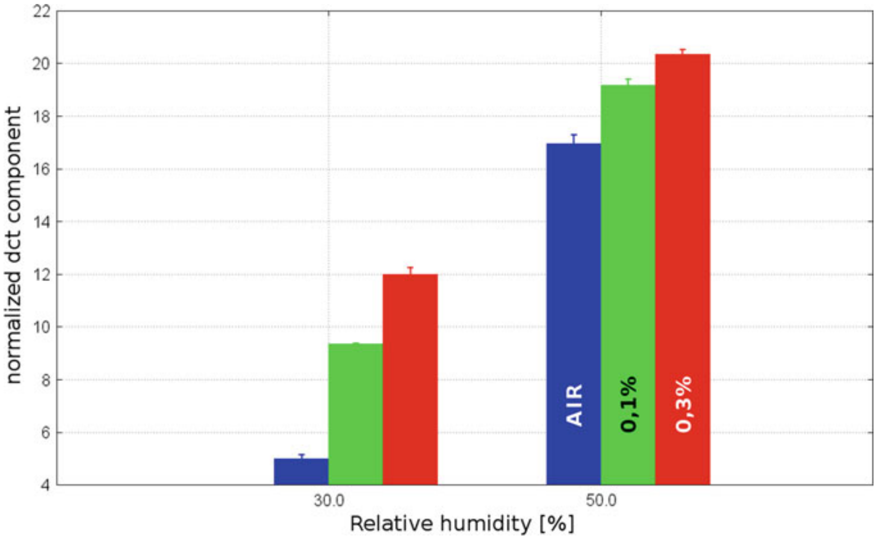

Fig. 2.9 Characteristic response with DCT analysis 20 °C versus RH, 0.5 % duty-cycle

The main advantage of the DCT is the lack of complex computation, thus reducing the arithmetical operations and the amount of memory required, finally resulting in a fast execution of the task. Thus, the smart characterization of the sensor consists in the analysis of the spectrum obtained by the normalized DCT transform of 512 samples taken every 1 μs, but it is strongly related with the strategy employed (i.e. repetition interval between measurements).

2.2.2 Characterization

Natural gas is a dangerous volatile substance, thus it is important to guarantee a frequent measurements in the environment, and to assess the features of the proposed technique, we compared it with others implementation characterized by longer repetition interval, namely 2 min: 0.5 % duty-cycle, and 15 min: 0.07 % duty-cycle.

In both the characterization, showed in Figs. 2.9 and 2.10, the results are promising, despite the reduced range of relative humidity condition presented, due to the limits of the gas bench used. The first consideration is related to the very small standard deviation in the measures (the thick lines on top of each bin) which suggests the possibility to reach a smooth characterization and a quantitative determination of this chemical. The other is the behavior of the sensor, strongly related with the sleep time. For short interval, higher the concentration, higher the normalized measure, the opposite in the other case. This underline the importance of defining the sleep interval before each measurements and a careful characterization of the sensor response.

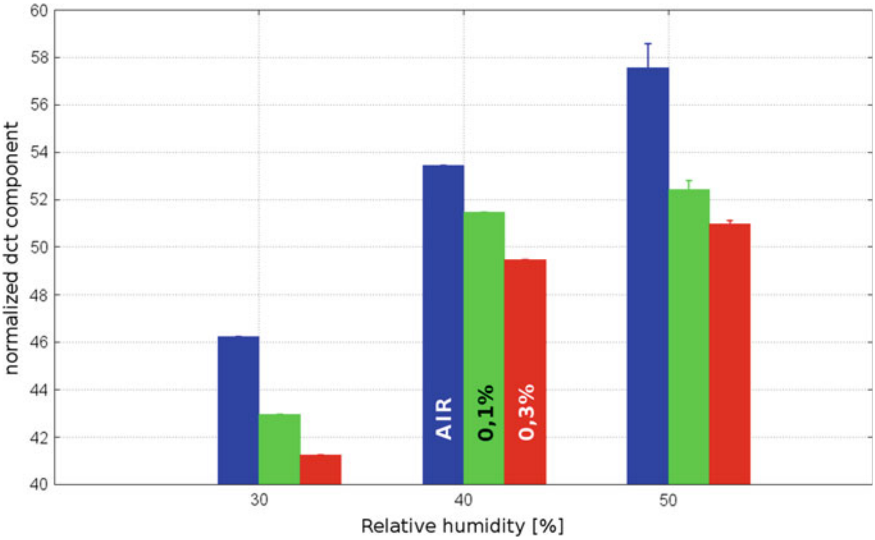

Fig. 2.10 Characteristic response with DCT analysis 20 °C versus RH, 0.07 % duty-cycle

However, these figures demonstrate that discriminating natural gas presence in air is possible, with a minimal energy. Moreover such techniques are compatible with renewable aware policies such as the scheduling proposed in [13].

2.3 Energy Saving in WSN Monitoring Applications

The ultra-low power approach, presented in this paper, permits to reduce of one order of magnitude the energy required to estimate the gas concentration in air, decreasing the response time from 6 s of continuous supply to almost 0, 6 s. The whole characterization of the devices and the final example presented in the results were conducted interfacing the sensor to battery operated and resource constraints platform such as a node of a Wireless Sensor Network. Specifications and performance of the nodes can be found in [11]; the most remarkable are the computational architecture (a 32bit microcontroller 32 MHz useful to perform on line processing), with integrated RF module, IEEE 802.15.4 compliant, and integrated antenna, sensors for temperature, relative humidity, light and dock for the catalytic sensors.

The analysis of the consumption is plotted in Fig. 2.11. The trace represents the profile of the power consumption and it is taken using 1 Ω shunt-resistor. It can be split in two parts: processing and transmission. From the data collected during the tests, we notice that the average duration of the measurement phase (collecting temperature, humidity, battery level, gas sampling, processing and log into SD-card) completes in 2.5 s with an average current consumption of 29 mA, while sleeping

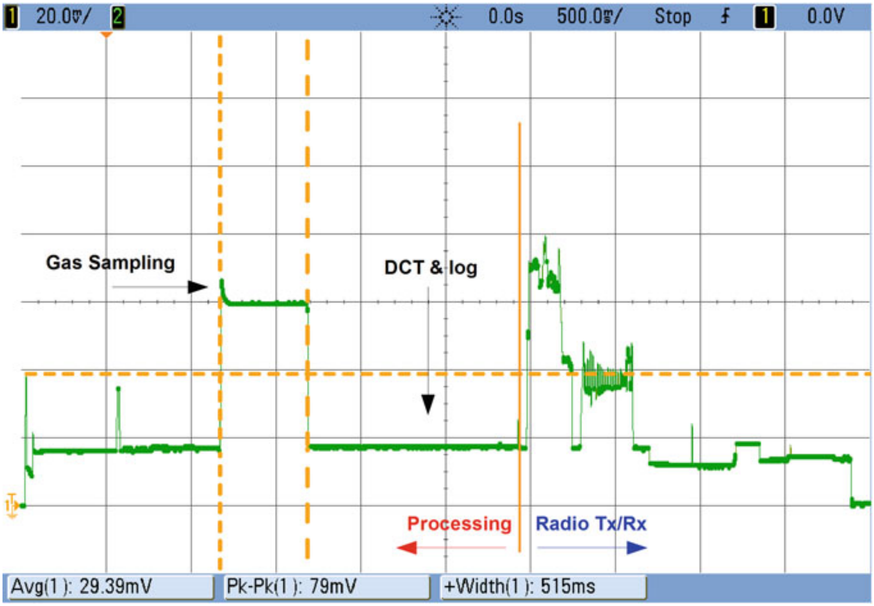

Fig. 2.11 Power consumption profile of the W24TH node

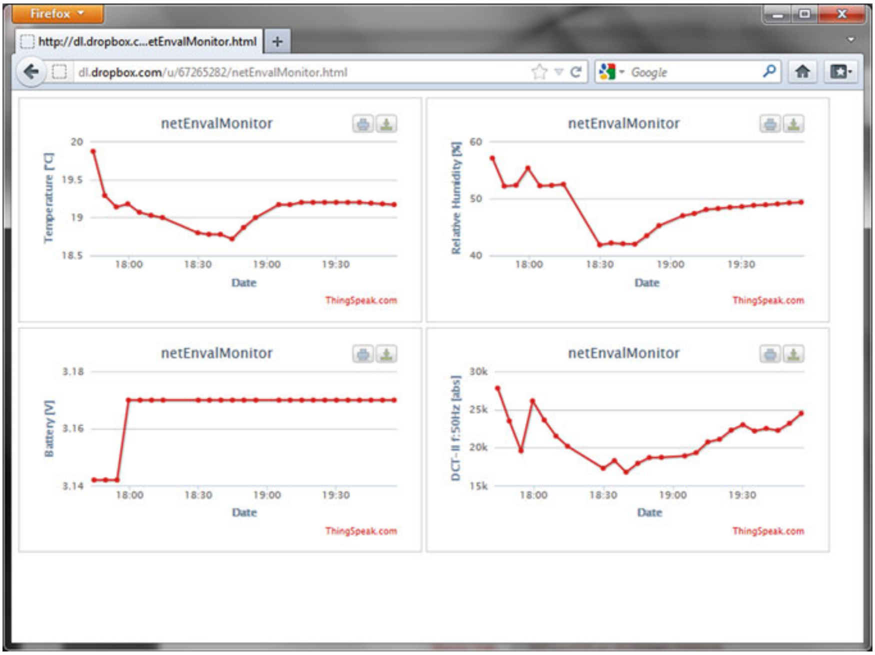

Fig. 2.12 Web based user interface to represent collected data

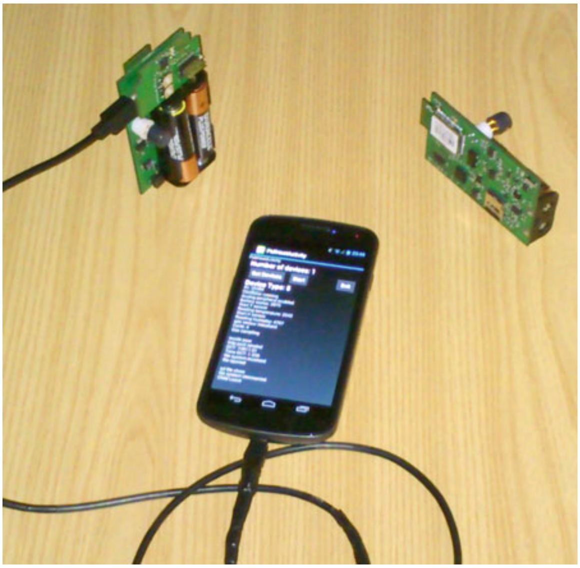

Fig. 2.13 Picture of the extended wireless sensor network setup

the motes drains 8 μA in average (oscillator on during sleep). Using two 2,500 mAh batteries, it is possible to reach nearly 168 weeks of autonomy in the case of 15 min interval, considering that gas sampling is not the only task to execute on the microcontroller. Of course, better autonomy performance can be achieved if the system is equipped with energy harvester devices [14–17] capable to extract and convert energy from the surroundings. Figure 2.13 shows the extended version of the environmental monitoring network, where the coordinator node has been connected to a smartphone, running Android Ice Cream Sandwich (ICS) OS. The data collected by the coordinator are then sent by USB to the smartphone, which uploads the information to the web. Figure 2.12 is a screenshot of the monitoring application's user interface.

2.4 Conclusion

To extend the lifetime and energy autonomy of air monitoring devices, a new strategy of sensing have been investigated for available commercial off-the-shelf gas sensors. The approach is cheaper and faster with respect to developing a new silicon sensor-device. The results presented are straightforward with a reduction of one order of magnitude in energy consumption that has been achieved using the AS-MLK catalytic sensor for natural gas detection, by reducing the sampled interval to $\approx$500 μs compared to the 5 s, at least, of the standard approach. In the near future we expect to make a more exhaustive testing and to reduce even more the sampling period of the aerosols, to achieve an aggressive power saving strategy useful for an environmental monitoring application.

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