Low cost sensor implementation and evaluation for measuring NO_2 and O_3 pollutants

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Abstract **– Air pollution affects life quality and already has measurable impact on the human health and ecosystem change. It is widely accepted that in order invert the continually growing pollution, citizen awareness policies must be adopted and encouraged. Under this concept large data sets are collected using new measuring systems adopting low cost technologies. This tactic led to the need of evaluating low cost sensing systems in order to be able to collect valid measurements and been able to use them and provide as accurate information as possible. Many research teams are working on this topic studying various factors that affect measured quantities like the temperature and humidity are and propose new low-cost monitoring systems, aiming to developing a network over large geographic areas. This work presents a low cost, low energy consumption and high processing power monitoring station. The monitoring station incorporates Alphasense electrochemical sensors of measuring NO2 and O3 as well as NO2-B43F and OX-B431. In order to be able to design proper calibration and correction formulas temperature, humidity and barometric pressure are also measured and in this work the results of the above process are described. Results collected from two monitoring stations that were installed next to official measuring point of the National Observatory of Athens are presented herein for the NO2 and O3 quantities.**

Keywords— Ozone measurements, NOx measurements, EMISSION project, Air quality IoT, Low-cost sensing systems.

I. Introduction

Nowadays, the air quality in urban areas is bad due to urbanization and industrialization [1],[2], thus worth to be studied in order to find ways of improving life quality. According to the World Health Organization, there are 4.6 million death tolls each year due to air pollution generated factors [3].Vehicles are one of the major sources of external air pollution in cities [4],[1],[2]. Y. Wang et al. [5] reported on the experience of collecting air quality data on the road for the 2008 Olympic Games in Beijing. In another work, [6] measurements of atmospheric pollutant levels in an urban area near highways in a wide area of traffic and meteorological conditions were carried out using a mobile monitoring platform.

There is an increasing trend worldwide in the collection of data on air quality using non official monitoring stations. There is still no legislation on how to use this data [1]. Low-cost electrochemical sensor systems can provide reliable measurements of air pollution under real world ambient concentrations according to the ARISense system [7]. The comparative results of low-cost sensors indicate that a similar solution can be adopted to increase the density of existing air quality monitoring stations for urban quality of life [8].

The Mosaic project [9], is a low cost mobile sensing system designed for urban air quality monitoring. The aim was to deploy air quality sensors to the moving city buses in order to increase the system coverage.

The CAIRSENSE project [10] uses electrochemical sensors for five different gas type and PM sensor. The topology based on WSN (one base station and four nodes) uses Xbee protocol.

The design and implementation of low-cost monitoring systems, using easily accessible monitoring results, can be a potential solution designed to assist existing inadequate methods. The reliability of low cost sensors has attracted the scientific interest and significant research is conducted under this topic. R. Laref et al., [11] present, the evaluation of electrochemical sensors, in a laboratory environment and in the field. N. Afshar-Mohajer et al., [12] observed the high linearity of gas concentration measured from sensor output voltage in relation to reference environmental instruments.

In another work [13] important details regarding selection of sensors and system architecture are explained analytically. During the European project hackAIR a centralized air quality data hub was developed enabling European citizens to contribute to air quality monitoring. During this project the air pollution is estimated from combining sky-depicting photos and data from low-cost sensing devices [8], [14], [15].

This work presents the implementation of an innovative design of a low cost air gas measuring station [8] and the evaluation of electrochemical sensors for ozone (O_3) and nitrogen dioxide (NO_2). Technology enables the design and implementation of reliable low cost systems that respond to low power consumption and high processing speed like the ST microprocessor ensures. These systems offer excellent local data analysis and data transfer flexibility using wireless technologies like WiFi and GPRS. During this work two monitoring stations were installed (Figure 1) at the National Observatory in Athens next to commercial measurement systems,(for NOx: HORIBA APNA-360 and ECOTECH Serinus 40, for O3: THERMO model 49i).

This paper is organized as follows: In section II the measuring station is described and in section III the sensor temperature calibration and the data evaluation procedure are presented.

Figure 1. Photo of two stations installed on NOA

II. SYSTEM OVERVIEW

The parts: Each measurement station (Figure 2) consists of a microprocessor, a set of sensors, and other power and communication peripherals. The main controller CPU is the STM32 Nucleo F091RC. This processor covers the needs for communication (8xUART, 2xI2C) with the peripherals and I/O ports, also present high data processing speed (ARM Cortex-M0 clock rate of 48 MHz) and low power consumption. The barometric sensor Bosch BME280 exhibits measuring resolution of <0.1% with minimum error deviation ± 3 % in relation to DHT22 [8], and power consumption of the order of μA. For gas sensors Alphasense ozone and nitrogen dioxide sensors were used. The sensors are connected with the main CPU board using I2C protocol. To record the station location and accurate data timestamp a Ublox Neo 6 GPS device was used since it is relatively fast and has a low power consumption of 45mA approximately. The GPS communicates with the CPU unit using serial protocol. In case of long power interruption the station continues recording and sending data for 4 hours, using a mini UPS comprising a PCB battery charger and a battery of 3,6V/3400mA. The same circuit provides capabilities of measuring voltage drop and enables central system to estimate the remaining station availability on a case of power failure. Regarding communication two implementations were conducted for data transfer; one over wireless network (WiFi) using ESP8266, and one over mobile network (GPRS) using sim808. The total power consumption of a measuring station is 1.5W approximately. The Alphasense OX-B431 Ozone sensor (Table 1) and Alphasense NO2-B43F Nitrogen dioxide sensor (Table 2), are electrochemical sensors consisting of 4 electrodes, supported by Individual Sensor board (ISB), providing the output measurement in mV, obtaining high precision and repeatability as can be seen in Figs 3 and 4 [16]. The total cost of each station is 500 € approximately.

Sensitivity	nA/ppm at 1ppm O3	-225 to -650
Response time	t90 (s) from zero to 1ppm O3	< 60
Zero current	nA in zero air at 20°C	-80 to 80
Noise	±2 standard deviations (ppb eq.)	15
Range	ppm O3 limit of perf. warranty	20
Linearity	ppm error at full scale, linear at zero and 20ppm O3	< ±0.5
Overgas limit	maximum ppm for stable resp.	50

Table 1. Specifications O_3 sensor

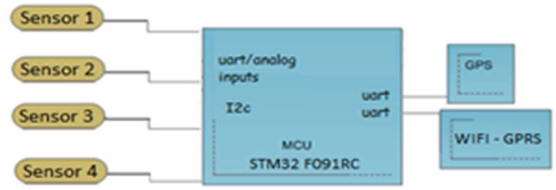

Figure 2. System architecture diagram.

Sensitivity	nA/ppm at 2ppm NO_2	-220 to -650
Response time	t90 (s) from zero to 2ppm NO_2	<80
Zero current	nA in zero air at 20°C	-80 to 80
Noise	±2 standard deviations (ppb eq.)	15
Range	Ppm NO_2 limit of perf. warranty	20
Linearity	ppm error at full scale, linear at zero and 20ppm NO_2	< ±0.5
Overgas limit	maximum ppm for stable resp.	50

Table 2. Specifications NO_2 sensor

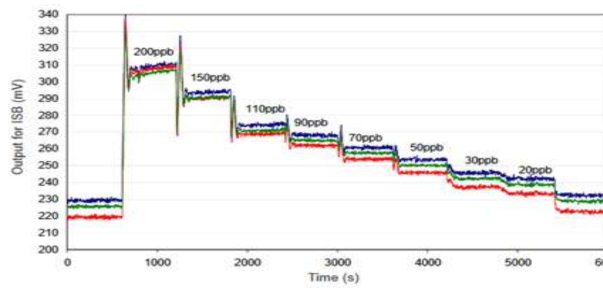

Figure 3. O_3 response from 200 ppb to 0 ppb, each color (red, green, blue) represents an individual sensor. (Figure 4 from [16])

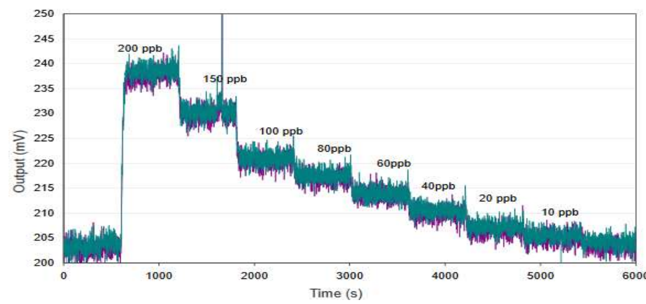

Figure 4. NO_2 Response from 200 ppb to 0 ppb, each color (cyan, purple) represents an individual sensor. (Figure 4 from [16])

Implementation details: To build a station, hardware and software parts are required. The hardware comprised interface boards and modules ensuring that the size of the station would be small enough. Additionally, all EMC precautions (coaxial cables, metal shielding components) were taken under consideration in order to avoid external or internal noise affecting the measurements or near modules. The software controls the parameters of measurements (i.e. sampling rate, self-tests, Over the Air updates) as well as manages sensors, measurement reading and preliminary functions. For the described stations a measurement is conducted every ten seconds and the five minutes average values are transferred over the cloud to the central station. Data is formatted as json-string. The main (O_3m) and auxiliary (O_3a) outputs of an O_3 sensor are presented in mV in figure 5.

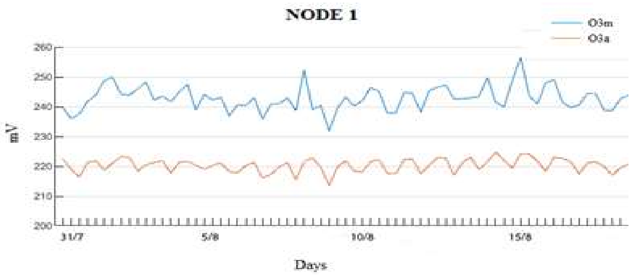

Figure 5. O_3 **output sensor WE, AE in mV**

Alphasense [16] proposes formula (1) to extract the corrected working electrode (WE_c) value using the measured working electrode reading (WE_u), auxiliary electrode reading (AE_u) and temperature parameter n_T according to the application note AAN 803-05. To complete the correction, for each individual sensor and ISB Alphasense provides a set of background electrode noise values corresponding to working electrode electronic zero (WE_e) and auxiliary electrode electronic zero (AE_e) that also participate to formula (1) [16]:

$$WE_c = (WE_u - WE_e) - n_T * (AE_u - AE_e) \quad (1)$$

Normalization values According to the manufacturer instructions [16] a vague methodology must be designed and followed in order to go beyond correcting measurements due to temperature, aging etc. In this case after various tests the best fit algorithm for calibration in relation with official values from instrumentation installed nearby, was found to be the following:

$$GASx_c = GASx_m / C1 + C2 \quad (2)$$

When the $GASx_c$ is the calibrated value of x gas, the $GASx_m$ is the corrected value of x gas and the C1 and C2 are constants when applying in algorithm to calibrate the station to provide accurate mV values. Using the previous function, the values in ppb may be extracted by dividing by the sensor sensitivity. Regarding electrochemical sensors O_3 sensors are also activated from NO_2. (see specs Alphasense OX-B431). Under the above concept equation (3), must be applied on the measurements in order to get the O_3 and NO_2 concentrations.

$$O_3ppb = O_{3ALL} - NO_2ppb \quad (3)$$

Where NO_2ppb stands for the NO_2 concentration measured from the NO_2 sensor and O_{3ALL} stands for the concentration measured from the O_3 sensor.

III. VERIFICATION PROCEDURE

For the experimental setup two measuring stations were installed in the National Observatory of Athens, next to the official instruments. The data analysis implementation has been done under MATLAB environment. Figures (6, 7) present the coefficient of correlation (R^2) between the two stations and specifically for each sensor NO_2 and O_3 including temperature parameter n_T. Applying the correction formula (2) the coefficient of correlation (R^2) between the two stations, as present in figures 8 and 9 is significantly improved. It has to be noticed that comparable values of R^2 may be found in other published works [7]. Figures 10 and 11 present the data of O_3 and NO_2, after coefficients correction and the normalization, between two stations for 21 days in July 2019 correspondingly. It should be noted that the results for the same time period from station 2 corresponded to station 1 with a slight deviation of 7%.

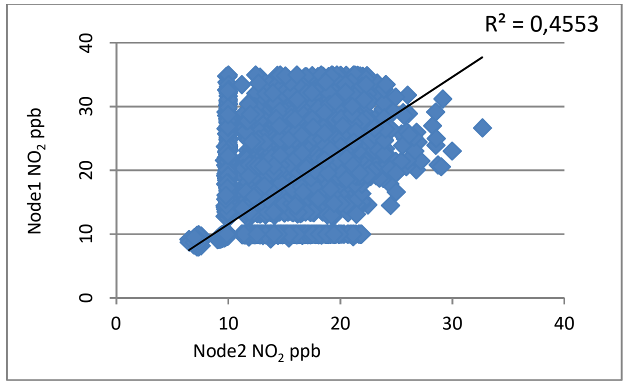

Figure 6. Correlation for NO_2 **sensors**

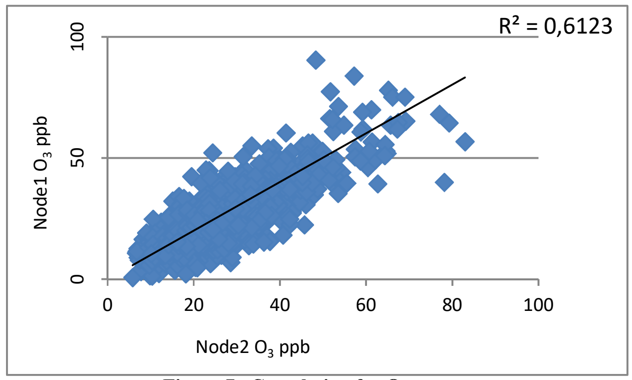

Figure 7. Correlation for O_3 **sensors**

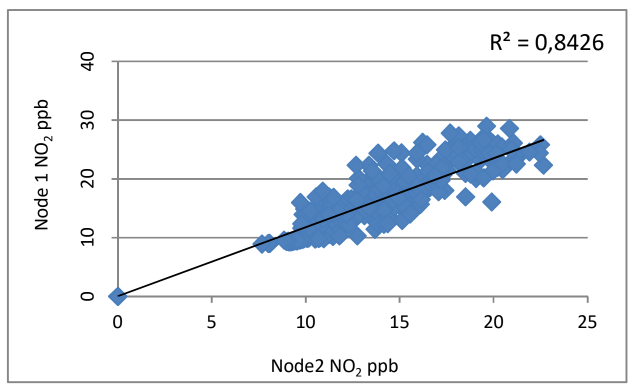

Figure 8. Final correlation for NO_2 **sensors**

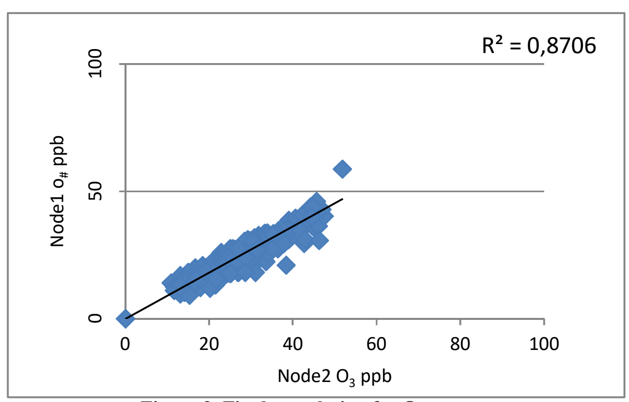

Figure 9. Final correlation for O_3 **sensors**

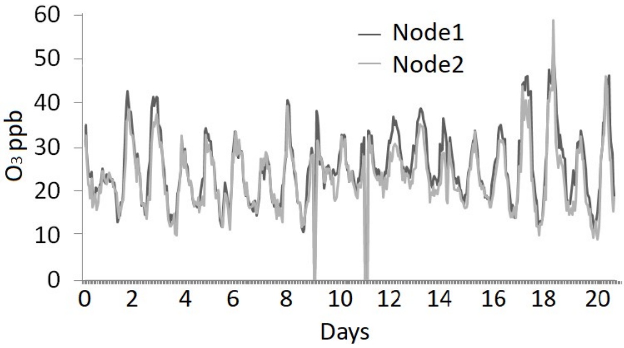

Figure 10. Ozone O_3 ppb from two nodes for July 2019.

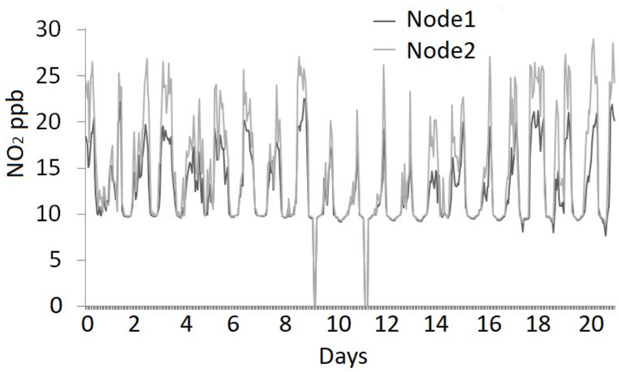

Figure 11. Nitrogen Dioxide NO_2 ppb from two nodes for July 2019

IV. Conclusions

Air pollution is a major threat to health in large cities, and the quality of life of citizens is dependent on it. This work describes the implementation of low cost air quality stations, with low energy consumption, high processing power and different modes of data transmission. The measured values are barometric pressure, ozone and nitrogen dioxide. Two stations were installed and data were collected in the period of June to August 2019 at the National Observatory in Athens.

This work mainly focuses on the evaluation and the correlation between two low cost sensor, for O_3 and NO_2. Correction formulas were evaluated and the impact of the temperature on the O_3 and NO_2 measurements was found in order to correct the collected data. Furthermore, a calibration function, for each individual station, was build and data evaluation shows significant improvement of the accuracy of the stations as can be seen by the corresponding correlation factors. It is concluded that after conducting data correction and station calibration process both stations provide correlation regarding O_3 (R^2=0.87) and NO_2 (R^2=0.84).

V. Acknowledgment

This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH CREATE INNOVATE (project code: T1EDK-00242-EMISSION)

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