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Application of Low-Cost Sensors in Stationary and Mobile Nodes for Urban Air Quality Index Monitoring †

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Abstract: The air quality in the modern cities and urban areas is strongly affected by chemical pollutants such as toxic gases, volatile organic compounds and particulate matter. They are monitored by governmental agencies using regulatory monitoring stations which are highly accurate, but also very expensive, bulky, and maintenance demanding. There is a compulsory need to monitor air quality at high spatial-temporal resolution in smart cities for public health protection and environmental sustainability. The low-cost and low-accuracy sensors, properly calibrated, are usually deployed in stationary and mobile nodes for urban air quality monitoring. A simple indicator of the current status of urban air pollution is the Air Quality Index (AQI) used to communicate the pollution level under time-changing trend of a specific pollutant. In this study, continuous measurements have been performed in the city of Bari (Southern Italy) by electrochemical gas sensors (NO_2, O_3, CO), optical particle counter (OPC) for particulate matter (PM_{10}), NDIR infrared sensor (CO_2), including microsensors for temperature and relative humidity. The sensors have been installed in stationary nodes located in urban sites and in a mobile node mounted on a public bus moving in the urban routes. AQI data gathered by the low-cost sensors have been compared with reference instrumentations as a case-study of citizen science.

Keywords: low-cost air quality sensors; portable devices; air quality index; air quality monitoring

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1. Introduction

Urban air quality is a major issue for public health, especially in cities and metropolises. Many worldwide cities do not meet the requirements for cleaner air as reported in UN Environment Program Report 2016 [1]. For now, air pollution remains to be the number one environmental cause of premature deaths in the European Union as reported by European Environment Agency (EEA) Report 2023 [2]. Besides this, millions of Europeans suffer from respiratory and cardiovascular diseases caused by air pollution: NO_2, O_3, SO_2 and Particulate Matter (PM) are identified as key species affecting quality of life and mortality rates, as reported by World Health Organization (WHO) Report 2006 [3]. The economic costs of air pollution in the European Union are well over €20 billion a year. To mitigate these negative effects of air pollution on human health, environment and ecosystems, the European Commission adopted an Ambient Air Quality Directive (2008/50/EC) [4] that fixed stringent thresholds for any pollutant.

Climate change monitoring is crucial to implement abatement strategies of greenhouse gases and CO_2 emissions for a low-carbon footprint in the sustainable cities. In the recent years, low-cost sensor-systems and sensor networks [5-8] for air quality monitoring have been demonstrated in real-world for performance assessment, environmental awareness, personal exposure, compliance, legislative purposes, and decision support.

Air Quality Index (AQI) is an essential measure of air pollution evaluation, which describes the air pollution degree and its impact on health, so the accurate measurement and prediction of AQI is significant [9-10].

This study addresses to assess the sensors network performance in terms of AQI for urban air quality monitoring in the Bari city (Southern Italy) by 30-month long-term measurements (1 July 2015 - 31 December 2017). The sensor data have been compared to the reference environmental public data to evaluate the accuracy and data quality objective of the European Air Quality Directive (2008/50/EC) for *Indicative Measurements*.

2. Materials and Methods

2.1. Air sensors used and electronics

The sensor nodes AIRBOX, shown in Figure 1, were designed to be small size (23 cm width x 30 cm height x 10 cm depth), thermoplastic weatherproof (IP 65/66), able to operate stand-alone, and connected to power. Each node includes a suite of low-cost sensors: 3 electrochemical gas sensors: NO_2, O_3, CO; 1 Near Dispersive Infra-Red (NDIR) sensor: CO_2; 1 Particulate Matter sensor: PM_{10}; 1 temperature (T) sensor and 1 relative humidity (RH) sensor. The components are listed in Table 1. These sensors were selected due to their low-power consumption (< 10 mW for electrochemical sensor, and < 60 mW for NDIR sensor) and their low-voltage operation (3.3 - 5.0 Vcc), including good sensitivity and low limit of detection at ppb or $\mu g/m^3$ level of environmental interest.

Figure 1. Sensor-node AIRBOX, developed by ENEA, deployed for air quality monitoring.

The sensor node incorporates a Raspberry-Pi based computer (Model B+) with 4 USB ports, 1 Ethernet port and 512 Mb RAM using the open-source operating system Linux for data acquisition management by a SD-card (2 Gb) for on-board data logging. The remote node uses a GPRS modem (Key HSPA Huawei E303) with SIM card, operated by a public provider, to transmit data to a central server (Dell, Model PowerEdge R320, 6 core-Intel Xeon, 16 Gb RAM, 6 disks by 500 Gb in raid5 configured) with a pack sampling rate to be configured properly. Additionally, a Wi-Fi key (Edimax USB 2.0, 802.11, 2.4 GHz, 150 Mbit/s) is installed for city-operation covered by digital network. Finally, a Global Positioning System (GPS) receiver (Garmin, Model GPS 18x USB) was used for convenient deployment, mainly for mobile sensing purposes.

A sensor network based on 11 AIRBOX nodes (10 stationary and 1 mobile mounted on public bus) has been deployed for urban air quality monitoring in the city of Bari (Southern Italy). The sensor nodes were distributed in urban sites (offices, buildings, streets) near to Air Quality Monitoring Stations (AQMS) by ARPA-Puglia, the regional agency for environmental monitoring. A Virtual Private Network (VPN) has been implemented to communicate by secure digital certificate with each remote node using TCP/IP protocol. Also, a Global Information System (GIS) has been designed and realized to manage the visualization of air sensor network data. Moreover, in-field calibration by co-location of sensors and related reference equipment has been realized to convert sensor output voltage into concentration and assess the error of the deployed sensors.

Table 1. List of air quality and environmental sensors installed in each AirBox sensor-node.

Pollutant	Sensor Type	Manufacturer	Characteristics	Principle of Operation
CO	CO-B4	Alphasense, UK	0–20 ppm	Electrochemical
NO_2	NO2-B4	Alphasense, UK	0–2 ppm	Electrochemical
O_3	O3-B4	Alphasense, UK	0–2 ppm	Electrochemical
CO_2	CO2-IRC-A1	Alphasense, UK	0–5000 ppm	NDIR
PM_{10}	PPD20V	Shinyei, Japan	0–100 µg/m^3	Light Scattering
Temperature	TC1047A	Microchip	−40–+125°C	Thermo-converter
Relative Humidity	HIH5031	Honeywell	0–90%	Capacitive

2.2. Definition of Air Quality Index (AQI) and Classification Rate

The *Air Quality Index* (AQI) is an indicator for reporting daily air quality using simple and effective figure of merit. It tells you how clean or unhealthy your air is, and what associated health effects might be a concern. The standardization of information is a challenge: different international organizations (e.g., US EPA, EEA, etc.) and national environmental agencies use a proper standard for air quality index. In order to benchmark data, we adopt the AQI standard defined by US EPA [9]. For each pollutant, an air quality index is defined as follows:

$$AQI(\%) = \frac{CurrentPollutionLevel}{PollutionStandardLevel} * 100 \quad (1)$$

The air pollution thresholds, regulated by EU Air Quality Directive, used in the mentioned AQI formula are reported in Table 2.

Table 2. Thresholds of the air pollution for some significant pollutants, regulated by EU Air Ambient Directive (2008/50/EC), as used in the AQI formula.

Pollutant	Limit Standard Level
NO_x	First alarm: 100 ppb (200 µg/m^3) Second alarm: 200 ppb (400 µg/m^3)
CO	8 ppm (10 mg/m^3)
SO_2	First alarm: 130 ppb (350 µg/m^3) Second alarm: 190 ppb (500 µg/m^3)
O_3	90 ppb (180 µg/m^3)
PM_{10}	50 µg/m^3
$PM_{2.5}$	25 µg/m^3
BTEX ([1])	5 µg/m^3

[1] BTEX = Benzene, Toluene, Ethylbenzene, Xylene.

The AQI in the US EPA standard is divided in five classes from 0 (*clean air*) to higher than 150 (*heavy pollution*): each class is associated to a risk for health and a color for visualization. When AQI exceeds the value of 100, the threshold has been overpassed to indicate a worse situation of alarm. The US EPA AQIs classification is reported in Table 3.

Table 3. Air Quality Index (AQI): categories and risk for health by US EPA classification [9].

AQI Values	Level of Health Concern	Colors
When AQI is in this range:	***Air quality conditions are:***	***As symbolized by this color:***
0 to 33	Very clean air - *Excellent*	Blue
34 to 66	Clean air - *Good*	Green
67 to 99	Light pollution - *Moderate*	Yellow
100 to 150	Significant pollution - *Bad*	Red
> 150	HEAVY POLLUTION - *Worse*	PURPLE

Furthermore, the *Classification Rate* (C), expressed as percentage of the right assignments of the health risk class (symbolized by a color) divided by the total monthly cases, has been measured individually for each air-pollutant and for each sensor node. Generally, the Classification Rate indicates the number of right assignments in the risk class, by comparison of the AQI measured by both sensor and reference analyzer. The higher C, the better the performance of the sensor to classify the air pollutant in the specific site. For each compound, the Classification Rate, C (%), is defined as follows:

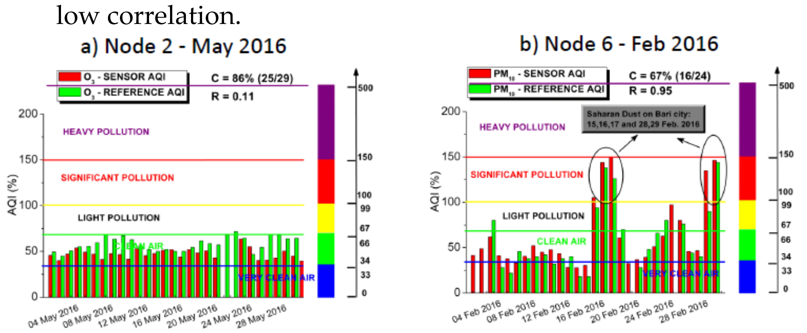
$$C(\%) = \frac{N.of Right Assignments of Risk Class}{N.of Total Monthly Cases} * 100 \quad (2)$$

3. Results and Discussion

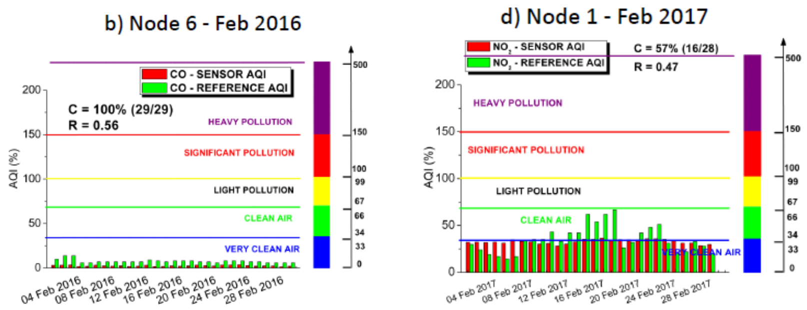
3.1. Air Quality Index by stationary sensor nodes

Figure 2 shows the AQI monthly trend of the PM_{10}, O_3, NO_2 and CO, respectively for some selected nodes during specific months of the experimental campaign in the Bari city. The daily AQI, measured by a node sensor, has been compared to the official AQI, referenced by the closest Air Quality Monitoring Station (AQMS) with available monitor of the local environmental agency (ARPA-Puglia). The results of the sensor-versus-analyzer assessment are reported in the Table 4. The Correlation Coefficient (R) and the Classification Rate (C), expressed as percentage of the right assignment of the health risk class (symbolized by a color shown in Table 3) divided by the total monthly cases, have been measured individually for each air-pollutant. The higher R and C, the better the performance of the sensor to measure the air quality index.

Generally, the PM_{10} AQI exhibits the highest R values ranging from 0.80 (Node 6 - AIRPORT, May 2017) to 0.95 (Node 6 - AIRPORT, Feb 2016), and high C values ranging from 17% (Node 2 - ENEA, May 2017) to 70% (Node 6 - AIRPORT, May 2017). This means that PM_{10} AQI is properly classified with high correlation. In the contrast, the O_3 and NO_2 AQI exhibit lower R values ranging from 0.11 (O_3, Node 1 - ENEL, Feb 2017; and O_3, Node 2 - ENEA, May 2016) to 0.47 (NO_2, Node 1 - ENEL, Feb 2017) and high C values ranging from 33% (NO_2, Node 2 - ENEA, May 2016) to 86% (O_3, Node 2 - ENEA, May 2016). The C (61% and 86%) of the O_3 AQI is usually higher than C (33% and 57%) of the NO_2 AQI. This demonstrates higher performance of the O_3 sensor compared to NO_2 sensor in the individual AQI measure. Finally, the CO AQI exhibits low R values ranging from 0.14 (Node 2 - ENEA, Feb 2016) to 0.56 (Node 6 - AIRPORT, Feb 2016) and the highest C values as 100% for all four cases under test. This means that CO AQI is properly classified with low correlation.



(**a**) (**b**)



(c) (d)

Figure 2. AQI for PM_{10}, NO_2, O_3 and CO, as measured by the sensor-node AIRBOX installed on specific sites in the Bari city during indicated months of the campaign, as compared to AQI measured by ARPA-Puglia reference analyzers.

Table 4. Comparison of the monthly AQI for individual pollutant (PM_{10}, O_3, NO_2, CO) as measured by a single sensor and compared to AQI measured by the closest air quality station of the ARPA-Puglia monitoring network, operated in Bari during campaign in the 2016 and 2017.

Pollutant	Node	Month/Year	Closest Air Quality Monitoring Station	Correlation Coefficient (R)	Classification Rate, C (%)
PM_{10}	Node 2 - ENEA	Feb. 2016	Via Caldarola	0.84	69
	Node 6 - AIRPORT	Feb. 2016	Modugno EN2	0.95	67
	Node 2 - ENEA	May 2017	Via Caldarola	0.93	17
	Node 6 - AIRPORT	May 2017	Modugno EN2	0.80	70
O_3	Node 1 - ENEL	Feb. 2017	Viale Kennedy	0.11	61
	Node 2 - ENEA	May 2016	Viale Kennedy	0.11	86
NO_2	Node 2 - ENEA	May 2016	Via Caldarola	0.14	33
	Node 1 - ENEL	Feb. 2017	Viale Kennedy	0.47	57
CO	Node 2 - ENEA	Feb. 2016	Via Caldarola	0.14	100
	Node 6 - AIRPORT	Feb 2016	Modugno EN2	0.56	100
	Node 2 - ENEA	May 2017	Via Caldarola	0.22	100
	Node 6 - AIRPORT	May 2017	Modugno EN2	0.20	100

3.2. Air Quality Index by mobile sensor node

A mobile sensor-system AIRBOX based on low-cost sensors has been mounted on a public bus (AMTAB) running in Bari (Italy) for urban air quality monitoring. By exploiting this cost-effective sensor-system, it is possible to use a mobile node on public bus to achieve fine-grained monitoring, because when a public bus is moving, it could conduct environmental measurements at different locations in an urban micro-climate monitoring scenario to enhance environmental awareness of the citizens by mobile sensor-nodes at high spatial and temporal resolution. Figure 3 shows typical CO, NO_2, O_3, PM_{10} and CO_2 AQI trend measured on 9 November 2015 by a mobile sensor-node installed on a public bus circulating in the Bari city. The colors (blue, green, yellow, red, purple) of the marked positions are correlated to the risk classification of the air pollution for human health, as agreed in the EPA AQI standard for each pollutant (see Table 3). The mobile AQI has been compared to the AQI measured by air quality monitoring stations (AQMS) installed in the Bari city. The AQI measured by mobile sensor for CO, NO_2 and O_3 indicates clean air and very clean air mainly with colors as blue and green, while the AQI for PM_{10} exhibits a mix of risk categories (colors) properly overlapping the stationary stations AQI. Finally, the mobile AQI for CO_2 shows a significant level (red color) but no comparison with a reference analyzer is available.

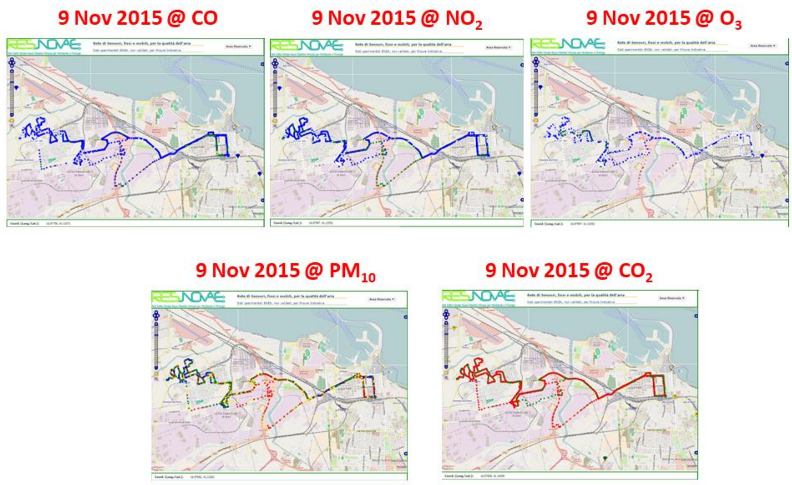


Figure 3. Typical CO, NO_2, O_3, PM_{10} and CO_2 air quality index (AQI) trend (1 min average on 9 November 2015) of the mobile sensor-node installed on the roof of a public bus (AMTAB) circulating in Bari (Southern Italy).

4. Conclusions

In this study, we demonstrate the feasibility of a sensor network based on 11 nodes (10 stationary and 1 mobile operated on board of a public bus), distributed in the Bari city (Southern Italy) in a city area as 24 km^2, for urban air quality monitoring during a 30-month long-term campaign of continuous measurements.

The Air Quality Index (AQI) of the PM_{10}, NO_2, O_3 and CO has been compared by sensor and reference analyzer of the closest AQMS of the local environmental agency. The results show high correlation coefficient (R = 0.80 - 0.95) with excellent performance for PM_{10}. On the contrary, lower performance has been measured for O_3 ($R < 0.2$), NO_2 ($R < 0.5$) and CO ($R < 0.6$). However, high Classification Rate for the AQI has been measured for CO (C= 100%), PM_{10} ($C < 70\%$), O_3 ($C < 86\%$), NO_2 ($C < 60\%$) exhibiting a right classification of the health risk class associated to a proper color, as categorized by the US EPA standard. Moreover, the AQI is an easy tool to show the air quality in the mobile sensing such as a proved sensor-node mounted on public bus circulating in the city to map locally the air pollution level in near real-time at high spatial-temporal resolution.

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