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A Low-Cost Air Quality Monitoring Internet of Things Platform

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Abstract**—**In the present paper, a low cost, compact and modular Internet of Things (IoT) platform for air quality monitoring in urban areas is presented. This platform comprises of dedicated low cost, low power hardware and the associated embedded software that enable measurement of particles (PM2.5 and PM10), NO, CO, CO_2 and O_3 concentration in the air, along with relative temperature and humidity. This integrated platform acts as part of a greater air pollution data collecting wireless network that is able to monitor the air quality in various regions and neighborhoods of an urban area, by providing sensor measurements at a high rate that reaches up to one sample per second. It is therefore suitable for Big Data analysis applications such as air quality forecasts, weather forecasts and traffic prediction. The first real world test for the developed platform took place in Thessaloniki, Greece, where 16 devices were installed in various buildings in the city. In the near future, many more of these devices are going to be installed in the greater Thessaloniki area, giving a detailed air quality map of the city.

Keywords**—**Distributed sensor system, environmental monitoring, Internet of Things, IoT, Smart Cities.

I. Introduction

POOR air quality remains a major environmental concern in many urban agglomerations worldwide. However, quantitative measurements of pollutant concentrations are usually only provided at a few locations. While central environmental monitoring stations, often governmentally operated, may provide accurate information regarding the air quality in a region, as a norm they are large monitoring stations of high complexity and cost (both for purchase and service). Based on the great advancement of sensor technology and IoT applications, a lot of low-cost devices have been introduced in the last decade, enabling a great shift to air quality monitoring approaches towards data collection through IoT-enabled sensor networks [1]. IoT-enabled environmental monitoring sensor networks are a promising technology in better representing the microclimate of an urban area or certain regions within it, improving our knowledge of emissions and identifying their source, increasing public awareness and lowering harmful exposure to pollutants. Complementary to measurements from central air quality monitoring networks, satellite monitoring and modelling simulations (e.g. weather, air pollution propagation), IoT environmental monitoring platforms can provide accurate and real-time information about the levels of air pollution to scientists and public authorities, for policy making purposes.

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While the majority of environmental sensor network-related projects is driven by the academia (i.e. government funding), there are also commercial and/or crowd-funded projects, that have been introduced to the public. The most profound of the projects that have been presented are the US EPA funded CAIRSENSE project, that focused on the performance evaluation of different sensors [2], the large scaled, multinational Citi-Sense project, that focused on ambient air quality, indoor environment at schools, and the quality of urban spaces [3] and the Village-Green project, that mainly focused on the power consumption of the wireless monitoring platform [4]. Other projects that have been widely used are the commercially funded AirVisual and Airpurple projects. Both projects are based on relatively low-cost platforms, monitoring the contamination by PM of different sizes and carbon dioxide (AirVisual). In total, during the course of these two projects, more than 10.000 monitoring devices have already been installed and provide data as a service upon request.

McKercher et al. [5] presented a state-of-the-art review of small, portable platforms that measure ambient gaseous outdoor pollutants. Their aim was to address broad trends during the past 5-10 years. In that work, the authors categorized the main environmental monitoring projects according to their sensor capabilities, battery life storage and approximate cost. Focusing mainly on portable platforms, the work gives a good overview of both trends and drawbacks of low cost - large scale projects. Going one step further, Morawska et al. [6] tried to provide some answers to two distinct matters: (1) the adequacy of these technologies for the desired purposes and (2) the ability of these technologies and their applications to provide answers and solutions. Based on literature review of both peer-reviewed papers and “grey literature”, the authors provide a concise overview of the current state of development of low-cost sensing technologies for air quality monitoring and exposure assessment. The most profound environmental monitoring platforms are being categorized based on cost, mobility, sensor technology, wearability, data communication protocol, cloud services, processing and dissemination. The authors agree with Snyder et al. [7] in that, while the application of low-cost devices has already changed the paradigm of air pollution monitoring, most of the existing platforms currently fulfil only the first two of the following four tasks: (1) supplementing routine ambient air monitoring networks, (2) expanding communication with communities, (3) enhancing source compliance monitoring and (4) monitoring of personal exposures.

In order to address the above challenges, this work presents a low-cost, adjustable, wireless sensor platform for air pollution monitoring in urban areas. The platform is capable of real-time measuring of the concentration of Nitric Oxide (NO), Nitrogen Dioxide (NO_2), Ozone (O_3), Carbon Monoxide (CO), as well as concentration of PM2.5 and PM10 sized particles in the air [8]-[11]. Throughout this paper, it is shown that the platform presented in this work can be adjusted to connect to up to four different sensors, according to the requirements of each application. The platform operates as part of a grid of distributed measuring stations, collecting data for air pollution monitoring applications. This study is implemented as part of the ongoing funded project "Sympnia- Air quality monitoring and forecasting using satellite and low-cost sensors deriving data", during the course of which a detailed local air quality map is being developed [12].

The rest of the paper is structured as follows: In Section II, we initially briefly present the basic architecture of the Sympnia IoT Platform. We then introduce and describe both the hardware and the embedded software developed for the Sympnia Smart Collector, which constitutes the basic module of the Sympnia IoT Platform. In Section III, the laboratory testing methodology of the IoT platform is presented. Test results and general outcome of the tests performed are also discussed. In Section IV we discuss the key results of the study. Finally, in Section V we present the next steps of the project that are currently ongoing.

II. System Description

A. System Architecture

For the development of the Sympnia IoT Platform we relied on the PrismaSense™ system [13], which was redesigned to measure the concentration of 6 atmospheric pollutants: PM10, PM2.5, NO_2, NO, O_3 and CO. Data from low-cost sensors are collected from a node device, the Smart Collector. The Smart Collector consists of a microcontroller and the appropriate interfaces to connect to the sensors and performs data pre-processing and calculation of several parameters. The sampling rate, as well as the rate of the parameters calculations, can be set from 1 s up to 30 minutes.

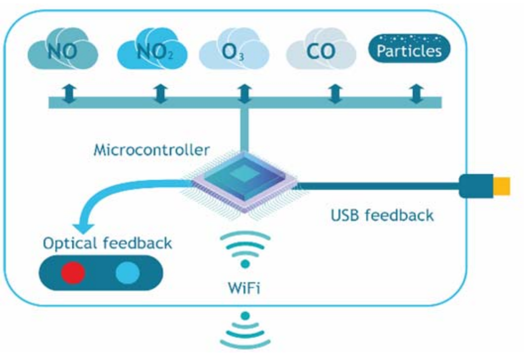


Fig. 1 Sympnia IoT platform architecture

The Smart Collector initially sets up a wireless secure network in order to be configured, it then connects to a wireless network that is set up either inside a building or in an open area and transmits the pre-processed data to a local router and, from there, to a central Server where an existing air quality platform is operating. Data are being transmitted in real time and on an hourly base. A custom-made communication protocol has been adopted in order to transmit both measurement values and corresponding meta-data (e.g. time, location, ID, log data) through a JSON file.

B. Smart Collector Design

The main technical specifications of the Sympnia Smart Collector are summarized in Table I.

TABLE I
Technical Specifications of the IoT Platform

No.	Category	Type
1	Processor	Xtensa® 32-bit L106/80MHz
2	Memory (RAM)	512 KB
3	Primary Wireless Communication	Wi-Fi 802.11 b/g/n
4	Sensor communication	3x UART, 1x I2C
5	Power	5V DC (micro-USB)/battery
6	Max Current	1.5 A

The main processing module found on the latest version of the board is an ESP8266 [14], manufactured by Espessif. The module is an ultra-low power, mixed signal microcontroller with a dual core 32-bit RISC CPU running at 80MHz, incorporating 512KB of RAM. The unit is easily programmable through either an in-house development environment (IDF) or any third party IDEs and incorporates advanced calibration circuitries for dynamic removal of imperfections inserted from external conditions. The main processing module is responsible for controlling the sensors, processing the collected data and preparing the data for transmission over Wi-Fi.

Wireless communication is handled by a 2.4 GHz receiver and transmitter. The transmitter includes a high-powered Complementary Metal Oxide Semiconductor (CMOS) power amplifier delivering up to +20.5 dBm of power for an 802.11b transmission and +18 dBm for an 802.11n transmission. The 2.4 GHz radio infrastructure enables wireless communication via WiFi and Bluetooth. The Sympnia IoT platform communication channel relies on Wi-Fi Radio and Baseband supporting the following features: (a) 802.11b/g/n, (b) 802.11n MCS0-7 in both 20 MHz and 40 MHz, with bandwidth up to 150 Mbps of data rate or up to 20.5 dBm of adjustable transmitting power. Selection of communication protocols was based on the comparative study of different communication protocols presented by Tsantilas et al. [15].

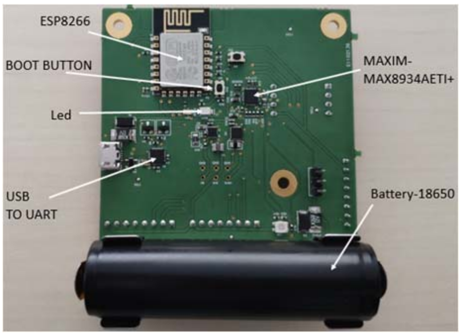
The Sympnia Smart Collector is compatible with all 5V and 3.3V sensors that use UART, I2C, SPI and GPIO protocols. For the purpose of the "Sympnia" project, five different sensor platforms were used as shown in Table II.

Provided that the sensor manufacturers are limited and that for low-cost sensors the primary issue is the calibration of the sensors [5], the selection among the low-cost air quality sensors was based on three criteria: (a) calibration sheets provision from the manufacturer, (b) provision of detailed description of acquisition and transmission procedures, (c) impact of sensors on literature. The Sympnia platform provides normalization of the measured data with respect to the temperature and humidity of the device's surrounding environment.

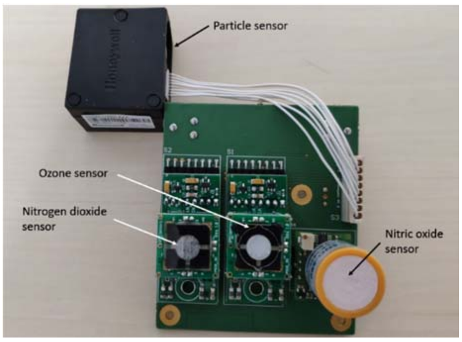
TABLE II
TECHNICAL SPECIFICATIONS OF THE SENSORS

No.	Type	Com. Protocol	Measurement/Unit
1	Honeywell HPM 32322550	UART	PM2.5 and PM10 (μg/m^3)
2	Euro Gas 4-NO-250	I2C	NO (ppm)
3	SPEC DGS-CO 968-042	UART	CO (ppm), temperature (°C), relative humidity
4	SPEC DGS-NO2 968-043	UART	CO_2 (ppm), temperature (°C), relative humidity
5	SPEC DGS-O3 968-042	UART	O_3 (ppm), temperature (°C), relative humidity

The platform is programmable via USB, can be adjusted to operate up to 4 sensors at a time, can operate for up to five days on a 18650 battery on a single charge (full operation) and can easily be charged via micro-USB. Fig. 2 provides a detailed description of the Sympnia Smart Collector from each side of the PCB. Indicative sensors have been mounted on the board for illustrative reasons.



(a)



(b)

Fig. 2 The Sympnia Smart Collector: The top (a) and bottom (b) layer of the PCB are depicted

For the housing of the platform a 3D case, shown in Fig. 3, was developed. The housing has been designed so as to enable proper airflow and protection of the sensors as well as to enable safe and secure operation of the platform in open space. The IoT platform's dimensions are 8x8 cm making it suitable for low profile, in-city applications that require installation of the Smart Collector on balconies, train stations, bus stations, airports, etc.

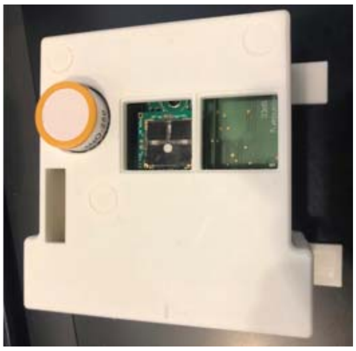


Fig. 3 Sympnia IoT platform's housing

C. Embedded Software Design

The embedded software for the Sympnia IoT Platform has been developed around four main groups of functions: (a) initialization of the platform, (b) measurement activities and visual indication, (c) preparation of data for transmission, (d) transmission of the data. Each one of the groups provides distinct functionalities to the system, as described below.

Initialization group: Within this group of functions, the Platform Initialization and initial configuration of the device take place. The functions are called once on startup or after a reset occurs. Initialization includes configuration of the device's LEDs, the sensors selected, as well as the USB debugging and WiFi modules.

Mainloop group. Within this group of functions, the platform checks every 1 ms if the device is connected to a WiFi network and whether the time is set. Furthermore, the device checks every minute if the remote server is connected. The measurements from the sensors are transmitted every 1 minute for a period of 5 minutes and then every 1 hour. The device prints status messages in a serial communication port and changes the LED displays to manifest the state of the device accordingly.

A different library for each sensor has been written in order to secure proper communication with the different protocols used and to enable specialized data acquisition and management for each one of the sensors. As an example, Figs. 4 and 5 present the data acquired by two sensors (NO and NO_2 respectively). The raw data (blue lines) vary even within the limit of short timeframes. The moving average (red lines) of these measurements is calculated based on sensor response and accuracy testing.

Post function: This is the function used to send all measurements inside a HTTP POST method in a JSON packet according to arguments. The JSON body consists of an access key, a metric, a measurements array and a timestamp. Each measurement cell includes a metric (e.g. NO_2), a spec (for metric TEMP and HUM only, it indicates whether it is from the NO_2, CO or O_3 sensor) and a value. The function returns the code of the http response.

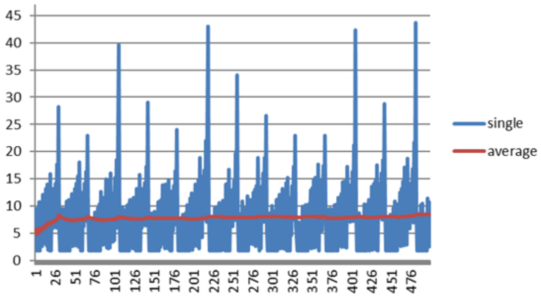


Fig. 4 Euro N Gas NO raw measurements (blue) and moving average values (red)

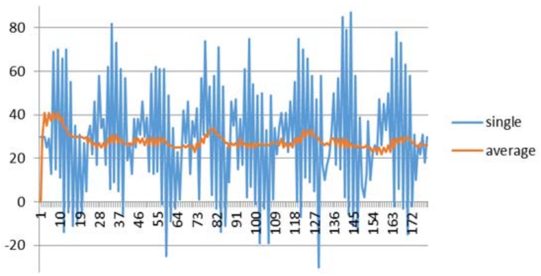


Fig. 5 SPEC NO_2 raw measurements (blue) and moving average values (orange)

Send function: This function sends the measurements via a JSON packet to the defined server. If the sending operation is successful, the function returns a True value; otherwise, it returns a False value. In case no connection is achieved, the system restarts.

D. Software Application

An Application Programming Interface (API) was developed on the air quality platform for receiving datasets from the sensors, storing them in a database and sending them to a web and mobile application. Sympnia is built upon an existing commercial system of DRAXIS, Envi4All [16], that provides services of air quality monitoring and forecasting. It also offers targeted information on both current levels of air pollution and predicted levels of it to citizens by collecting and analyzing data from a number of different sources, such as official, ground-based air quality monitoring stations, the Copernicus Atmosphere Monitoring Service (CAMS) and low-cost sensors of Sympnia Smart Collectors.

The data collected are displayed in near real time in high spatiotemporal resolution. At the same time, citizens are informed about the deviation of simplified air quality indices and are provided with personalized recommendations on how to protect their health from air pollution. It is expected that air pollution trends that may lead to policy changes and, eventually, to behavioral change are going to be spotted by using data collected and analyzed by the software.

III. Laboratory Testing

This section presents a summary of the results of laboratory tests performed on the hardware components (HD), prior to their installation in the field, following standard testing approaches [17]. The integrity and robustness of the measurements was assured by performing each series of measurements at least 3 times, according to the standard laboratory test practice.

A. System Testing

This test involves evaluation of the Sympnia IoT platform operation according to its specifications. The operation includes testing of the system in both normal and non-normal conditions, so that the platform's operation and outputs can be tested during its normal operating conditions as well as in case of malfunction. When needed, simulated signal where used as a system input. A brief description of testing scenarios and the outcome of each one is provided in Table III. As shown in this table, the platform is able to correctly measure and send data, as well as blink, sleep and wake-up. In addition, auto connect provision fires up properly and behaves as expected upon connection loss, malfunctioning sensor, timeserver fault and Sympnia server unavailability.

TABLE III
IoT Platform System Tests

No.	Sympnia IoT Platform Test Cases		
	Test Case	Test Description	Result
1	Normal Operation	Normal operation, connects, measures, sends, sleeps and repeats. Normal use of LED indications	Pass
2	Initial connection to internet	Connects to network at device startup	Pass
3	Connection Loss	Connects at first, but cannot achieve Wi-Fi connectivity at a next wake-up cycle	Pass
4	Problematic Sensor	Sensor is not operating properly	Pass
5	Time server fault	After connection cannot access time server	Pass
6	Server not available	After connection cannot access Sympnia server	Pass

B. Sensitivity Testing

In order to test the sensitivity of the platform three different platforms with the same sensor configuration were installed in the same location and as close as possible to each other, as shown in Fig. 6. The measured data for 24 hours were captured from each individual Smart Collector and the mean value from all devices was extracted for each time stamp. This test involved comparison of each device's collected data series with the average value of data series from all devices and calculation of the relevant dispersion. This kind of testing involved signals that change over time. It has to be noted that only the system's steady state response and not its transient response was evaluated due to laboratory restrictions.

Figs. 7-9 depict the normalized data series of measurements from three different sensors and three different devices compared to each other and the R-squared values that were calculated in order to represent the proportion of the variance between them. In most cases, the R-squared values have been measured very close to unity; that is proof of good linearity

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and high level of platform sensitivity.

Fig. 6 Three different IoT platforms have been installed in the same location in order to proceed with sensitivity testing

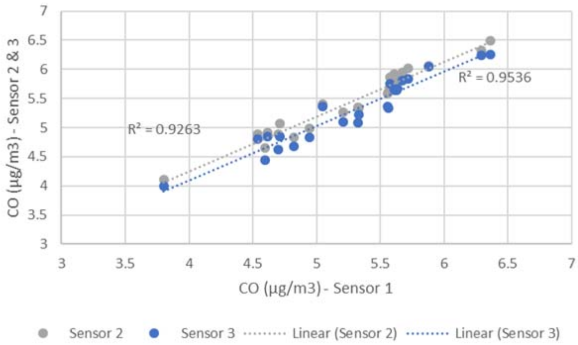

Fig. 7 Correlation of three CO sensors' measurements along with the corresponding R-squared values

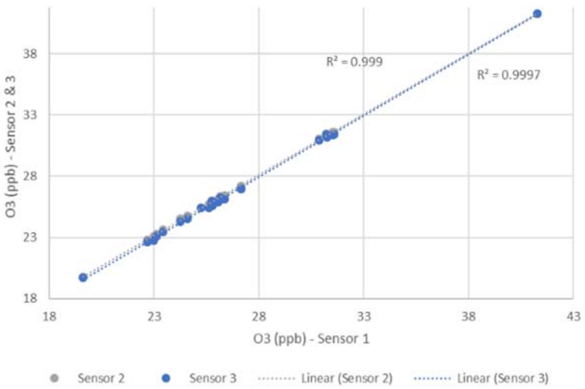

Fig. 8 Correlation of three O_3 sensors' measurements and the corresponding R-squared values

C. Data Integrity Testing

This test involved (a) Calculation of data packages loss and time shift, (b) Collection and transfer of data in periodic intervals between two servers. The evaluation of the results was based on comparison between transmission and collection of data. Three parameters were evaluated in all cases: (a) The number of values collected and stored in a database compared to the number of values that was expected (b) The rate of the reported values compared with the sampling rate and (c) The number of missing values.

Testing proved that all values were successfully transferred to the end destination without loss or duplication and on the correct sampling rate. Deviation from the precise sample timing intervals occurred. This deviation was of the order of 1 second and it is assumed to happen due to noise in the link budget.

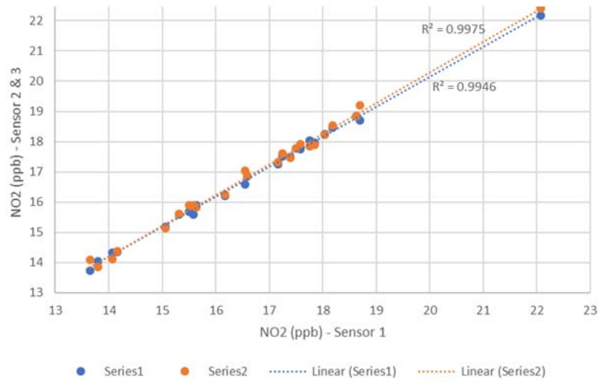

Fig. 9 Correlation of three NO_2 sensors' measurements along with the corresponding R-squared values

D. General Outcome of Laboratory Testing

The Sympnia IoT platform performs very well with a standard deviation of less than 0.1% in its measured data in steady state conditions. Furthermore, its transient state validation showed a deviation of less than 4% between the data measured from it and experimental data. This deviation is generally accepted and is mainly caused by sensor sensitivity.

Further testing that involves comparison of collected signals with those measured by a reference measuring device is crucial for the evaluation of the platform's measurement accuracy. Dedicated accuracy testing has been scheduled for the pilot testing period in the city of Thessaloniki, Greece and is part of the next testing steps, presented in Section IV.

IV. Pilot Testing

Pilot testing involves 70 low-cost air quality sensors embedded in 43 boards. The batch of the first 16 devices sent to Thessaloniki, Greece for the platform's pilot testing phase is presented in Fig. 10. Each board consists of 1, 2 or 3 air quality sensors, covering every pollutant factor monitoring combination in various areas. The sensors' spatial distribution was selected in such a way that, inter alia, a homogeneous distribution is achieved and areas with high expected levels of air pollution are covered. During this pilot testing phase, the Sympnia Smart Collectors stability is going to be tested, since a number of devices are going to operate on a daily basis in different parts of the city of Thessaloniki. Moreover, a large number of data is going to be collected from all the installed devices, providing an adequate amount of data via which the system's accuracy is going to be tested. During this testing phase, a first air quality map of the city of Thessaloniki is going to be created, providing the citizens with useful health-related data for their neighborhood and city.

The pilot testing period is currently ongoing and the outcomes will be included in our next work. In what follows preliminary data regarding the air quality trends during the period of quarantine (start day: 11/3/20 end day: 4/5/20) due to COVID-19 in Greece are presented.

Fig. 10 First 16 devices sent to Thessaloniki, Greece for pilot testing

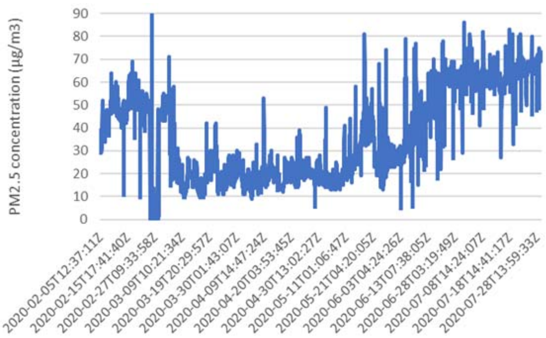

Fig. 11 PM2.5 concentration measured during the project's pilot testing in Thessaloniki, Greece

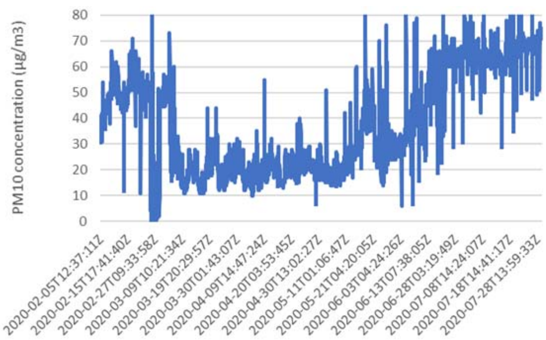

Fig. 12 PM10 concentration measured over an extended period of time in Thessaloniki, Greece

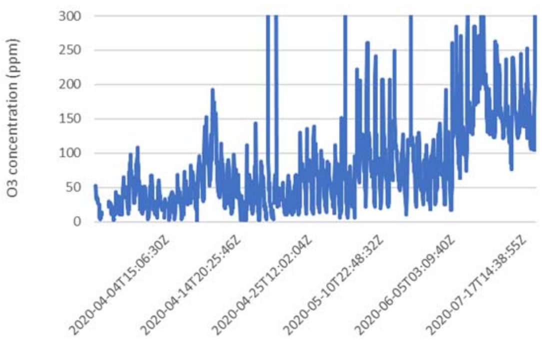

Fig. 13 Measurements of O_3 in Thessaloniki, Greece, during the project's pilot testing phase

In Figs. 11 and 12, concentrations of PM2.5 and PM10 are depicted for a specific location in Thessaloniki during this initial pilot testing phase of the project. Both figures depict a significant improvement of air quality during the reference period, while a hysteresis after the end of quarantine is also present, as expected. In addition, Fig. 13 graphically illustrates the O_3 levels in a specific region of Thessaloniki, Greece during the initial pilot testing of the project.

V. Conclusions

In the present manuscript, a sustainable air quality sensor monitoring platform has been presented. The platform is able to operate with any combination of four types of sensors incorporated in a single Smart Collector. The Smart Collector acquires atmospheric measurements once per hour and transmits the data in JSON format via Wi-Fi to a remote server for further analysis. The designed platform is compact and low cost. In addition to that, it is able to operate using an 18650 battery for five days and be charged using a USB 2.0 cable.

Throughout this work, it was shown that the platform is able to provide a feasible, low cost, yet reliable solution for environmental monitoring IoT applications. It is envisioned that the platform will expand in order to house a larger selection of sensors. Future work will include the installation of a grid of 80 Smart Collectors in the city of Thessaloniki, Greece, along with the corresponding measurement and verification results.

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