A compact, modular and low-cost Internet of Things (IoT) platform for air quality monitoring in urban areas

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Abstract. The recent emergence of low-cost sensor technologies, measuring various air pollutants, enables the real-time collection of air pollution data, with high spatio-temporal resolution. In our recent study, we developed and deployed low-cost air quality monitoring sensors and distributed them to citizens of Thessaloniki, Greece. The aim of this study was to provide near real-time air pollution measurements that will allow the better representation of the air pollution levels in the greater area of Thessaloniki. In the current work, we present the low-cost adjustable wireless sensor platform that has been developed for air pollution monitoring in urban areas. The platform can take sensor measurements down to one sample per second and is suitable for Big Data analysis applications such as air quality forecasts, weather forecasts and traffic prediction. The paper aims to contribute to the area of low-cost, distributed sensor networks for Environmental Intelligence applications.

1. 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 Internet of Things (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]. 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, multi-national Citi-Sense project, that focused on ambient air quality, indoor environment at schools, and the quality of urban spaces [3] as well as 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. McKercher et al. [5] presented a state-of-the-art review of small, portable platforms that measure ambient gaseous outdoor pollutants.
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 (NO2), Ozone (O3), Carbon Monoxide (CO), as well as concentration of PM2.5 and PM10 sized particles in the air [6]–[9]. 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 [10].

2. System description

2.1. Hardware design

The development of the Sympnia IoT Platform (Figure 1) was based on the PrismaSense™ system [11], which was redesigned to measure the concentration of 6 atmospheric pollutants: PM10, PM2.5, NO2, NO, O3 and CO. Data from low-cost sensors are collected via a node device, the Smart Collector, which 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, and the rate of the parameters calculations, can be set from 1s up to 30 minutes. The Smart Collector measures atmospheric pollutants locally (sensing coverage area of up to 2m²) and sets up a secure wireless network in order to be configured. It then connects to a Wi-Fi network that is set up either inside a building or in an open area; it transmits the pre-processed data to a local router and, from there, to a server where an existing air quality platform is operating (star topology). 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) in a JSON file.

The main processing module found on the latest version of the board is an ESP8266 [12], manufactured by Espressif. 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 IDE 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. Selection of communication protocols was based on the comparative study of different communication protocols presented by Tsantilas et al. [13].

The Sympnia Smart Collector is compatible with all 5V and 3.3V sensors that use UART, I2C, SPI and GPIO protocols. For the “Sympnia” project, five (5) different sensor platforms were used: a) Honeywell HPM 32322550 (PM2.5 & PM10: 0-1000 μg/m³, 15% accuracy), Euro Gas 4-NO-250 (NO), SPEC DGS-CO 968-042 (CO: 0-1000 ppm, 15% accuracy), SPEC DGS-NO2 968-043 (NO2: 0-5 ppm, 15% accuracy), SPEC DGS-O3 968-042 (O3: 0-5 ppm, 15% accuracy). 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. The platform is programmable via USB, can be adjusted to operate up to 3 sensors at a time, can operate for up to five days on a 18650 battery on a single charge in full operation or 3 months in limited operation (low sampling rate and daily transfer of data) and can easily be charged via micro USB.
For the housing of the platform a 3D case 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 8x8cm making it suitable for low profile, in-city applications that require installation of the Smart Collector on balconies, train stations, bus stations, airports, etc.

2.2. 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 takes 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 Wi-Fi modules.

Mainloop group. Within this group of functions, the platform checks every 1 ms if the device is connected to a Wi-Fi 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 on one hand and to enable specialized data acquisition and management for each one of the sensors on the other. As an example, Figure 2 presents the data acquired by two sensors (NO and NO2). 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. NO2), a spec (for metrics TEMP and HUM only, it indicates whether it refers to the NO2, CO or O3 sensor) and a value. The function returns the code of the http response.

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.
Figure 2. Raw measurements of air pollutants depicted in blue and moving average values depicted in red.

(a) NO measurements
(b) NO2 measurements

3. Laboratory testing

For verification and validation of Symnia Collectors’ operational capacity, a series of laboratory tests were performed ranging from System Tests (operation according to the specifications) to efficiency (operation similar to test bench) and to data integrity (uninterrupted operation). This section presents a summary of the results of sensitivity laboratory tests performed on the hardware components, prior to their installation in the field, following standard testing approaches [14]. 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.

The measured data for 24 hours were captured from each individual Smart Collector and the mean values from all devices were 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. Each sub-figure of Figure 3 (a, c, e) depicts the normalized data series of measurements from three different sensors and three different devices along with the average value. The average normalized value is depicted with a solid black line. Visual inspection of these diagrams provides confidence regarding the good sensitivity of the platform. In order to quantify this result, the values for each sensor compared to the others were plotted (Figure 3, b, d, f) and the R-squared values 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 and high level of platform sensitivity.
Figure 3. Normalised to the average values from the CO, O₃ and NO₂ sensors of three devices (a, c, e) and correlation of the sensors’ measurements along with the corresponding R-squared values (b,d,f).
4. Conclusions

In the present manuscript, a new and sustainable air quality sensor monitoring platform has been presented. The platform is able to operate with any combination of three 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 measurements and verification results.

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 [10]. The pilot testing period is currently ongoing and the outcomes will be included in our next work.

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