Environment 4.0: An IoT-Based Pollution Monitoring Model

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Abstract. While professional pollution monitoring stations are used worldwide to measure levels of pollution, they are usually costly and sparsely deployed across cities, hence leading to a visibility gap in pollution maps that need to be filled through alternative solutions. This paper proposes a pollution monitoring model designed within the "Environment 4.0" project to showcase how fourth industrial revolution technologies such as the Internet-of-Things (IoT) can fill such visibility gap using low cost off-the-shelf devices. The validation of our approach was done by developing two prototypes of a pollution monitoring system. These include a system built upon a Raspberry Pi and an android based IOIO micro-controller. Using a testbed experimentation approach, the two systems were validated through a number of scenarios, where both air and noise pollution levels were measured in certain locations of the city of Lubumbashi in the Democratic Republic of Congo. The relative values obtained from the two IoT devices validate the designed systems as they revealed that i) heavy traffic locations experienced higher air pollution ii) the average level of PM2.5 outside buildings over one day of observation was lower in less densely occupied suburbs compared to the city center and iii) high noise levels were observed in locations referred to in our experiments as "red light districts" which were expected to be more noisy because of the type of activities carried in such locations. The experimental results revealed that the designed system will indeed make it possible to address the visibility gap problem in the near future at an affordable cost.

Keywords: Environment monitoring · Air pollution · Noise pollution · Internet-of-things · Fourth industrial revolution

1 Introduction

Pollution (noise, air and water) [1] is one of the greatest health risks that targets the lungs, heart, brain, etc. [4] and also one of the greatest scourges of our

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time that is causing significant increase in the rate of morbidity and mortality in developing countries [2,3]. To address the issue of air pollution, many countries worldwide have developed strategies to measure levels of pollutants, analyse the collected measures, inform both the administration and the population about the state of the environment, and propose remediation strategies to be applied [5]. To measure pollutant levels, some countries have deployed pollution networks using professional monitoring stations located at pre-established locations in cities. However, these professional devices are installed in limited numbers and at certain locations of a city, therefore do not cover the entire city [6]; hence a visibility gap that is generally found in air pollution maps around the world. Numerical simulation techniques are often used to track pollutant concentrations in space and time, however, these techniques cannot provide satisfactory pollution results [5]. In South Africa for example, the air quality monitoring system, called the South African Air Quality Information System (SAAQIS), provides information on air quality based on air pollution stations located in only 20 of the 54 municipalities of the western cape, leading to only 37% visibility [7]. While many researchers have been working on the design and development of environmental monitoring systems based on the Internet-of-Things (IoT), each solution differs by the type of IoT devices used, the protocol used to enable communication between these IoT devices, the data processing method, the cost of the developed end products/devices, the energy consumption of the end devices/products, etc. [8].

Regarding air quality monitoring, the authors of [8] reviewed the state of the art, discussed the different aspects that differentiate the different environmental monitoring solutions and considered seven aspects of difference between the solutions. These include the size and type of experiment, the number of environmental sensors, the communication protocol between the sensor nodes, the mode of data transmission to the web server, the energy consumption, cost per node, platform. They also presented the challenges of existing WSN environmental monitoring systems; as well as a number of requirements that must be taken into consideration before designing and implementing a Wireless Sensor Network (WSN) environmental monitoring system. These include low cost of deployment, scalability, positioning of sensor nodes, remote access, etc. Bagula et al. in [6] used XBee series 1 and the Zigbee standard as a communication protocol to monitor 10 pollutants in the city of Cape Town, while Chen in [7] developed a gas pollution monitoring device based on the Raspberry pi, Arduino and specific gas sensors. Their solution was able to perform dynamic network selection, to choose between Bluetooth, Wi-Fi, GSM or LoRa to transmit gathered data. The main objective of the work proposed by Mandava et al. in [9] was to analyze the environmental data collected at specific locations in Cape Town to determine if the examined area is polluted or not using machine learning algorithms, and to further compare the performance metrics these various algorithms adopted. The key challenge addressed by all these studies was to set up a participatory surveillance system using alternative technologies, complementary systems and strategies to bridge the visibility gap left by professional pollution stations deployed in cities.

"Environment 4.0" is a research project led by the ISAT group at the University of the Western Cape. The project aims to use tools and technologies of the fourth industrial revolution (4IR) such as IoT, Artificial and computational Intelligence, Big Data technologies, Robotics and Immersive technologies in the design of environment monitoring systems, with the expectation of reducing the impact of the negative effects of environmental pollutants on public health and the environment itself. This paper proposes a pollution monitoring model designed within the "Environment 4.0" project to showcase how 4IR can fill such visibility gap using low cost off-the-shelf devices. The contributions made by this paper include the following:

- Expand the work done on pollution monitoring by previous authors to include noise pollution.
- Expand the work done by previous authors to include crowd sourcing.
- Design and implement the environmental trends visualization platform.

The expanded crowd sourcing option will enable general public participation in environmental monitoring based on an android-based IOIO-OTG device connected to a mobile phone via Bluetooth. This will allow users to register to participate in social community-based pollution monitoring while the visualization platform was built around the"Openstreet map" to provide different types of visualization for both air and noise pollution in different locations of a city. The remainder of this paper is organized as follows: Sect. 2; Sect. 3 discuss the evaluation of system performance using various scenarios; and finally, this article is concluded with and an overview of future research directions in the Sect. 4.

2 The Pollution Based Environment 4.0 Model

The main feature of the Environment 4.0 Model (E4M) is the use a variety of data collection sources for environmental pollution monitoring. With the combination of static sensors installed at certain places in cities and mobile sensors on board automobiles, the entire system can detect the distribution of air pollution and noise pollution in real time, thus fill the identified gaps in visibility. We will describe in detail the architecture of the E4M in the following points.

2.1 System Architecture

The entire system design is adopted from the four-layer IoT architecture and is shown in Fig. 1. Each of the layers are described as follows:

- **Sensing Layer:** The system consists of two categories of sensors - static sensors, which are deployed in fixed locations around the cities and send data to a centralized server at set intervals, and mobile sensors, which are carried around or attached to vehicles. These mobile sensors, enable coverage of previously uncovered zones. Figure 2 depicts the general logical design of

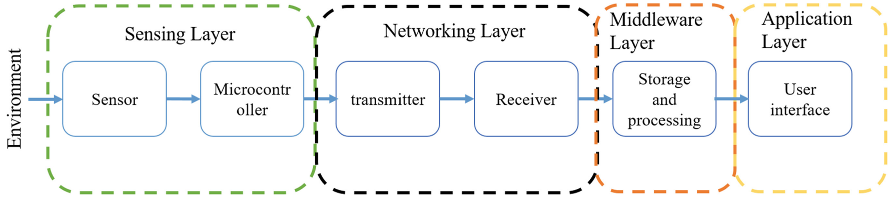


Fig. 1. Hardware system architecture

the system. For the mobile sensors, data capture devices are based on the IOIO-OTG and Raspberry Pi, similarly to that proposed in [7], but with the Arduino board replaced with an IOIO-OTG board. The IOIO-OTG board was chosen because it incorporates a Bluetooth radio, which enables easy communication with smartphones and also runs a variant of Android, hence fully controllable from an Android app using a simple and intuitive Java API [10]. Figure 3 shows an overview of the IOIO-OTG - Smartphone connection. Since the sensor unit is designed to mobile, we built it into a Mobile Detection Box (MDB), which contains the IOIO micro controller and numerous sensors including gas (CO2, NO2, O3, PM) and a sound (microphone). The MDB can then be powered from a USB power bank or the vehicle's battery. Figure 4 shows the physical appearance of the MDB.

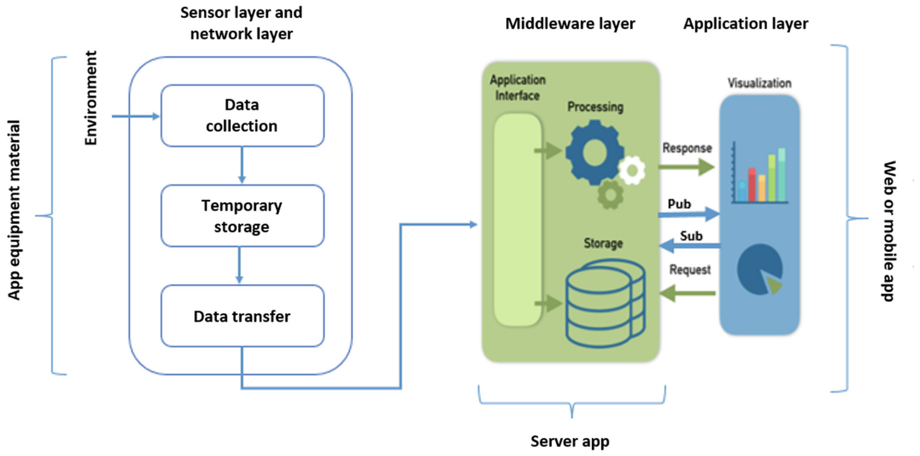


Fig. 2. Software system architecture

- **Network & Middleware Layer:** Many deployed IoT networks use a mesh architecture. In a mesh network, end nodes transmit information from other nodes to increase the communication range [11]. Although this increases the range, it adds complexity, reduces network capacity and battery life, as nodes

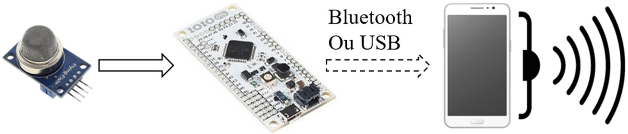
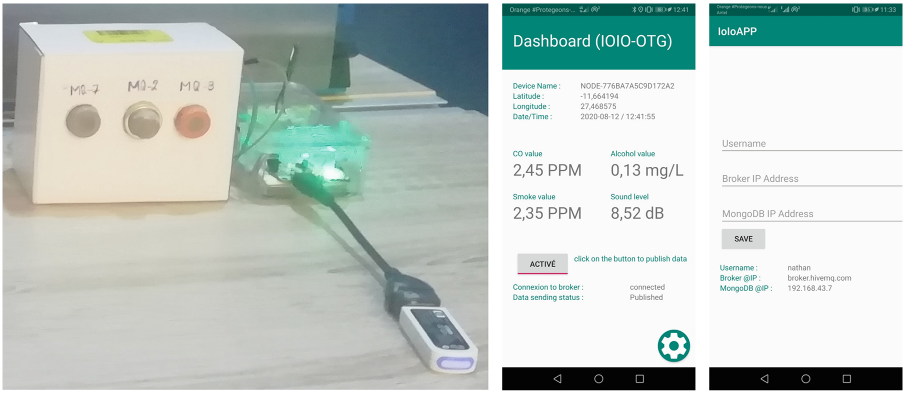


Fig. 3. Overview of the mobile sensing device



Dashboard (IOIO-OTG)

Device Name : NODE-776BA7A5C9D172A2
Latitude : -11,664194
Longitude : 27,468575
Date/Time : 2020-08-12 / 12:41:55

CO value 2,45 PPM
Alcohol value 0,13 mg/L
Smoke value 2,35 PPM
Sound level 8,52 dB

click on the button to publish data

Connexion to broker : connected
Data sending status : Published

IoloAPP

Username
Broker IP Address
MongoDB IP Address

Username : nathan
Broker @IP : broker.hivemq.com
MongoDB @IP : 192.168.43.7

(a) Physical appearance of the device (b) Main interface (c) Settings

Fig. 4. Physical appearance of the device (a) and Android application (b)-(c)

have to act as information transceiver from other nodes. The star network architecture has been shown to preserve battery life the most while achieving long-range connectivity [12].

Low-power wide-area network (LPWAN) are long-range wireless networks operating in the license-free frequency bands. They are characterized by low power consumption and low speed transmission, and are well suited for non-demanding applications in equipment limited in resources and for which the battery life must be extended in the order of several decades [12]. For this work, we chose the LoRaWAN for our network layer, which is a type of LPWAN. The main elements of this network are shown in Fig. 5. There are 3 communication stages, which are: (1) "end-devices" (sensors) communication with gateway(s), using LoRa this communication across a single sensor-gateway [14]. (2) communication between the LoRa gateway and the Edge server. This can be through either wired Ethernet connections or wireless (with WiFi or 3G/4G). These heterogeneous links represent the Internet connection. The Edge server pre-processes data received from the sensors and relays it to the gateway. Here, the LoRa gateway must have at least 2 communication interfaces; a LoRa radio and an Ethernet, WiFi or 3G/4G interface. (3) Finally, the Edge-server data is made accessible to users via the Internet. One of the peculiarities of the LoRaWAN network is that a device does not communicate exclusively through a concentrator [13]. All hubs covering the

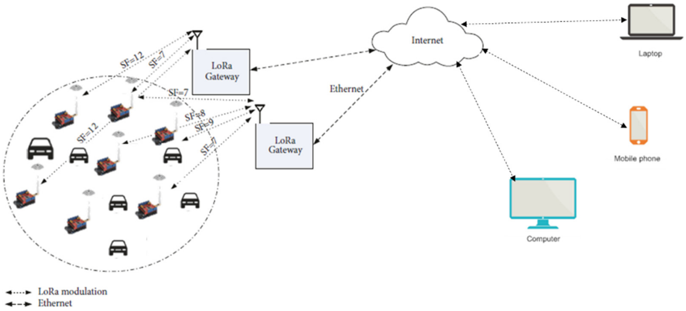


Fig. 5. Sample LoRaWAN communication architecture [1]

equipment can receive the data transmitted by it [11]. This greatly facilitates communication with mobile devices by relieving the network of hand-over mechanisms (switching from one concentrator to another) which would have the effect of complicating its management and very probably reducing its performance.

- **Application Layer:** The application layer consists of three aspects which are so described. The sensors and communication hardware run a software (firmware) responsible for collecting and transmitting data. Server-based software belonging to the middleware layer and is responsible for receiving and analyzing data. Finally, Web or mobile software of the application layer is responsible for displaying information to the end users.
  The traditional web infrastructure is not suitable for the majority of IoT applications. Some connected objects are limited in terms of memory and energy, while constraints on IoT networks are due to high packet error rates and low throughput (a few tens of kbit/s) [17]. Therefore, to overcome these constraints less verbose protocols are needed with a limited number of messages and small sizes. We used MQTT because it has the peculiarity of being a lightweight protocol, the number of messages is small and have small sizes [18]. This protocol starts from the observation that the polling of an increasing number of connected devices leads to a waste of bandwidth by conveying irrelevant information. It is a messaging protocol based on the publish/subscribe architecture using the TCP/IP protocol at the transport layer [18]. Figure 6 shows an overview of the application layer architecture.

3 Performance Evaluation

The validation of our approach was done by developing two prototypes of the system and using some scenarios to test the E4M in monitoring the air quality and the noise level in certain places of the city of Lubumbashi, Democratic Republic of Congo. The experiments were carried out indoors and outdoors, with the goal of detecting the level of pollutants inside and outside buildings respectively.

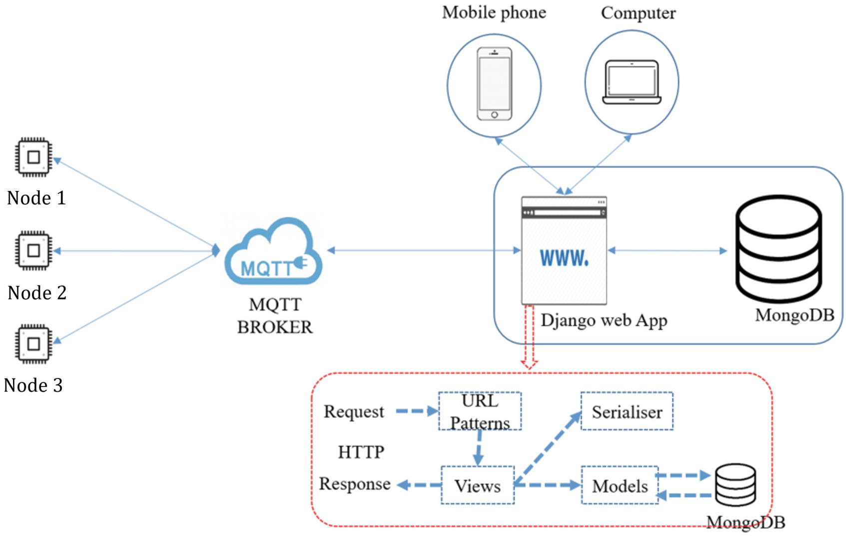


Fig. 6. Software architecture.

3.1 Data from Static Collectors

For this device we carried out the experiments at 4 locations across Lubumbashi - Golf Lido, Kamalondo, Bel Air Kaleja and Kampemba Tunnel. Table 1 shows the respective coordinates of these locations.

Table 1. Geographical coordinates of the places targeted for the experiments

Location	Latitude	Longitude
Golf Lido	−11.6641938	27.4685747
Kamalondo	−11.6826254	27.4866533
Bel Air Kaleja	−11.672574	27.5036688
Kampemba Tunnel	−11.662097	27.467992

For each location, we tested the level of CO2 (in ppm) and noise levels (dB) over a 24 h duration. Table 2, summarized the mean value of readings taken at some of the locations. Figure 7 shows the MDB in action.

At Golf Lido we considered two scenarios - within a building, with all windows and doors closed and outside the building. By comparing the two observations we find that the level of carbon monoxide is approximately the same, while the difference in noise levels was about 10dB. Kamalondo is a busy district, buzzing with commercial activities, including bars, nightclubs, hotels, which operate 24 h a day. For this location, we did not consider indoors, as sound levels would remain

Table 2. Mean readings from the MDB capture device

Location	Date	Type	CO2 (ppm)	Noise (dB)
Golf Lido	12/08/2020	Indoor	1.76	9
Golf Lido	12/08/2020	Outdoor	1.75	19
Kamalondo	12/08/2020	Outdoor	2.82	49
Bel Air Kaleja	12/08/2020	Outdoor	4.11	22.86
Kampemba Tunnel	14/08/2020	Outdoor	7.63	46.78

Fig. 7. Data collection with the MDB device

mostly unchanged. Being a commercial hub, noise levels were much higher (49 decibels) compared to the results obtained in Golf Lido. Interestingly, CO2 levels were lower than expected at just 2.82 PPM. By observing the results obtained in the Bel Air Kaleja district, a relatively low noise level is observed (with an average of 22.86 decibels) compared to the results obtained in the Kamalondo. CO2 levels are however are higher in Bel Air Kaleja than the previous locations, this is probably due to the high vehicular traffic. Finally, CO2 levels at Kampemba Tunnel were fairly high level at 7.63 PPM. This can also be attributed to car emissions. Most vehicles in the city are imported from Europe and are often without an exhaust catalyst converter to reduce carbon monoxide emissions. We also note a high noise level with an average of 46.78 decibels, this noise is produced by the honking of vehicles such in traffic jams.

3.2 Data from Mobile Collectors

Similar to the previous section, we conducted a different set of experiments by placing the MDB in a vehicle and slowly driving around a region of interest. 3 distinct locations around Lubumbashi were considered: Golf Lido, Kampemba Tunnel and POSTE place. Their respective coordinates are shown on Table 3. For this set of experiments we considered temperature, humidity, PM1, PM2.5 and PM10.

The Table 4 illustrates the averages of the observations made with the mobile capture device. The values observed validate the fact that places with heavy automobile traffic experience a sharp deterioration in air quality.

Table 3. Geographical coordinates of the locations targeted for the experiments

Location	latitude	longitude
Golf Lido	−11.6641938	27.4685747
Kampemba Tunnel	−11.662363	27.4875928
POSTE place	−11.665875	27.4846518

Table 4. Averages of observations with mobile MDB

Location	Type	Temperature	Humidity	PM1	PM2.5	PM10
Golf Lido	Outdoor	24.07	59.32	45.36	72.9	88.72
Kampemba Tunnel	Outdoor	25.13	42.71	111	208.46	241.92
POSTE place	Outdoor	26.59	44.19	88	137.91	163.36

The environmental situation around the Kampemba Tunnel is a source of concern during traffic jams, as readings show a higher average value compared to other observations. A relatively high level of particulate matter is observed, which is probably due to the gasses emitted by cars. In comparison, vehicular density is much lower in POSTE place than Kampemba. Slightly low particulate matter values are thus observed compared to Kampemba, but much higher than those of Golf Lido.

3.3 Simulation of the LoRaWAN-Lubumbashi Network

To simulate the deployment of a LoRaWAN for the city of Lubumbashi, we used Radio Mobile [21]. We considered 20 sensor nodes distributed across the city to measure pollution levels. The different locations chosen where: Terril Lubumbashi Company, CDM (Congo Dongfang International Mining), Somika (Katanga Mining Company); Ruashi Mining, Roundabout at Crossroads, Matshipisha at the GCM; and Kampemba tunnel (where at peak hours very high traffic is observed).

Radio Mobile is the software that allowed us to perform this implementation to highlight the balance sheet of the connections between the sensor nodes and the gateways. This simulation considers the communication portion between the LoRa modules on the sensor nodes and the gateways. This is as illustrated in Fig. 8. By inserting the characteristics of the peripherals in the simulator we obtain important parameters for the study of a radio link. These parameters are: the elevation and antennas orientation, losses by category, the signal level at reception (Rx level), the relative Rx level (the difference between the signal level at reception and the reception threshold), and the distance between the equipment. Figure 9 is a snapshot of the network simulation in Radio Mobile.

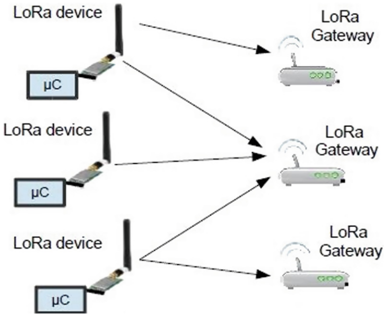


Fig. 8. Communication between sensor nodes and the gateway

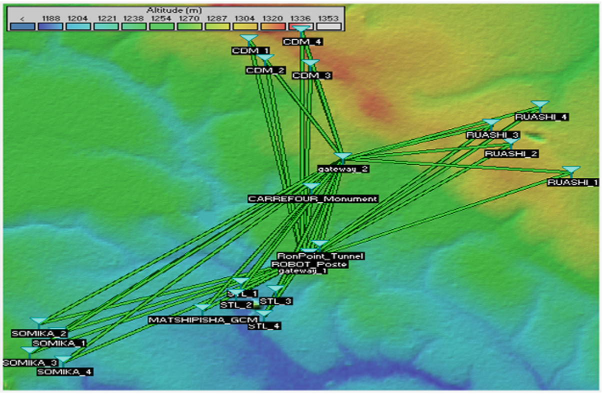
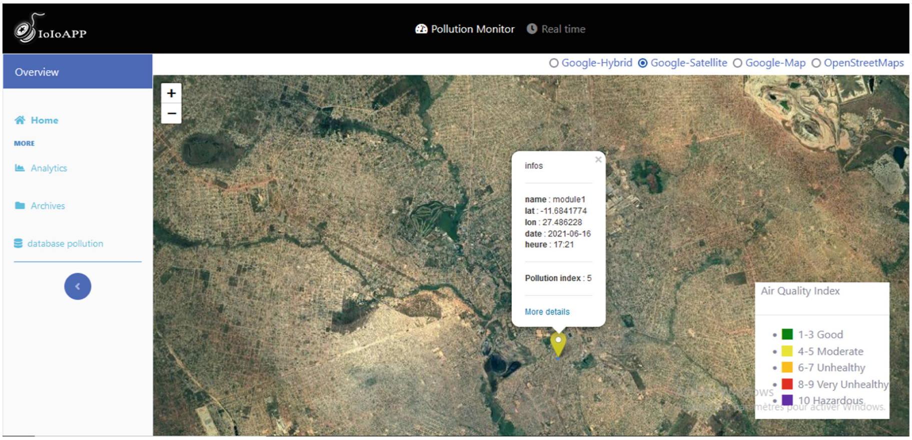


Fig. 9. Simulation of LoRaWAN Radio links deployed in Lubumbashi

3.4 The User Interface

In designing an user interface for our pollution monitoring solution, we created a web application using django framework, OpenStreetMap API and Chartjs Tools (to render interactive geographical data on different maps). The map shows the location of the sensors as dots of different colors (classified according to pollution index [20]). A mouse click on each location activates a tabbed information window. The tab displays the latest data from the corresponding location. A daily summary section is also included, to track the historic observations. This user interface is shown in Fig. 10.



infos

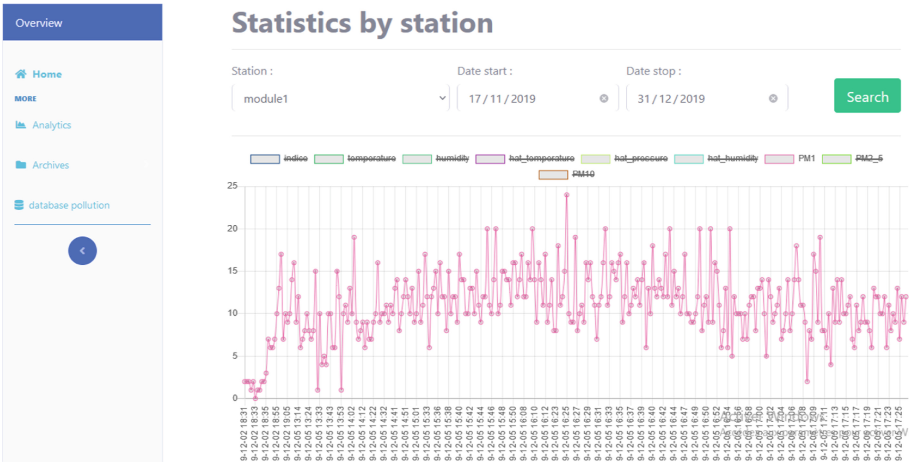
name : module1
lat : -11.6841774
lon : 27.486228
date : 2021-06-16
heure : 17:21

Pollution index : 5

More details

Fig. 10. Presentation of data on the map.

The web platform contains interactive graphics showing sensor data in the "analytics" tab; the graphs present the data from the sensors chronologically according to the evolution of the environmental situation. By clicking on a point on the curve, the value of the pollutant corresponding to time Y is displayed. By plotting this data on the graph, we also calculate the minimum, average, and maximum of the observations for the chosen period. The selection of a date range is also provided to view the history of the environmental situation, as shown in Fig. 11. A report generation tab, avails users the option of downloading accumulated data, which could be useful for a variety of reasons.



Station : module1

Date start : 17 / 11 / 2019

Date stop : 31 / 12 / 2019

Fig. 11. Statistics per station over a fixed period

4 Conclusion

Our preliminary experimental tests were carried out according to relative comparisons; we considered Golf Lido as a benchmark with clean air and low noise level, to identify places with a high level of pollution in the city. We thus show that participatory monitoring of the environment is feasible and makes it possible to cover this difference in visibility gap. We use small, inexpensive, commercially available equipment to monitor pollutant concentrations. However, it should be noted that the accuracy of the data depends on the sensor(s) used in the device and the design of the device's outer cover. If a more precise sensor is used on our prototypes, we believe that the accuracy of the data generated could be improved. The experiments carried out in this work are therefore part of the iterative development of ongoing research which extends in several different directions, including: 1) Use of calibration techniques and development of correction functions for sensor calibration; 2) Development of machine learning techniques for the prediction of the environmental situation; 3) restructure the pollution monitoring architecture to be integrated into national Cyber- Physical Systems following the models proposed in [22,23] with integrated orchestration to build national digital infrastructures and 4) extend the state of the art on methods of capturing, processing, disseminating and visualizing these data; by complementing the terrestrial pollution network by an airborne network of drones used for data muling and surveillance as proposed in [24,25]. In practical deployment scenarios, the redesign of the terrestrial pollution network into a multi-sink network with an efficient gateway as suggested in [26,27] and revisit of bandwidth-aware data transport techniques proposed in [28] to piggyback the transport of IoT data on conventional networks is another avenue for future research.

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