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Development and Analysis of a Low-Cost IoT Sensor for Urban Environmental Monitoring

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Abstract

The accelerated pace of urbanization is having a major impact over the world's environment. Although urban dwellers have higher living standards and can access better public services as compared to their rural counterparts, they are usually exposed to poor environmental conditions such as air pollution and noise. In order for municipalities and citizens to mitigate the negative effects of pollution, the monitoring of certain parameters, such as air quality and ambient sound levels, both in indoor and outdoor locations, has to be performed. The current paper presents a complete solution that allows the monitoring of ambient parameters such as Volatile Organic Compounds, temperature, relative humidity, pressure, and sound intensity levels both in indoor and outdoor spaces. The presented solution comprises of low-cost, easy to deploy, wireless sensors and a cloud application for their management and for storing and visualizing the recorded data.

Keywords: Internet of Things, environmental monitoring, Air Quality, wireless sensor.

1 Introduction

Global urban population is projected to grow from 4.2 billion people in 2018 to 5 billion in 2028 and to 6 billion in 2041 [51]. This means that 68% of the world's population in 2050 will live in cities as a result of the accelerated pace of urbanization, a trend that started in the 1950s. Cities ensure economic growth and provide their citizens with opportunities and better public services, but these benefits come at a price, urbanization having a significant impact over the environment, especially affecting the quality of the water and the air, and generating noise pollution [56]. Water quality is altered by the dumping of domestic waste and industrial wastewater into rivers, poor air quality is caused by the burning of fossil or biomass fuels, while noise pollution results from sources like traffic, subways, and airports.

Among these environmental problems, ambient air pollution seems to be the biggest threat to human health, being estimated to cause around 4.2 million premature deaths globally per year. It is also the biggest environmental cause of premature deaths in the European Union (EU), leading to cardiovascular and respiratory diseases [14]. Air pollutants in Europe are generated and emitted in the atmosphere by transport, commercial, institutional and living buildings, energy production and distribution installations, industrial sites, agriculture activities, and waste management [13]. The main pollutants consist of particulate matter (PM), with particles of less than 10 μm (PM10) in diameter and especially particles of less than 2.5 μm (PM2.5) in diameter being the most dangerous, black carbon (BC), sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), volatile organic compounds (VOC), and ground-level ozone (O_3) [13].

Research has shown that urbanization, with its corresponding increase of population, leads to environmental problems and serious air pollution, and therefore it is expected that, as urban settlements grow, air quality will continue to represent a major issue for both authorities and citizens [44, 52]. However, the monitoring and recording of parameters related to cities environmental conditions other than air quality, is also crucial [6, 50]. In this direction, authorities governing over different geographical zones have developed legislation that regulates the monitoring of pollutants released into the environment. These are concerned with aspects like air pollution, the quality of the water, or noise control.

The EU directive on ambient air quality specifies the substances that have to be tracked, averaging periods, location of sampling points, and quality assurance for the measurements [17]. Based on this, an European Air Quality Index, which represents a map that shows short-term air quality levels (worst rating, on a scale with 6 values from Good to Extremely poor, of PM2.5, PM10, O_3, NO_2, and SO_2) in more than 2000 locations across Europe, has been set up [12]. In the United States the 1970 Clean Air Act created a framework for establishing a multitude of air quality observation systems, that resulted in a network comprising 3000 fixed platforms in the year 2013, that monitor a wide range of pollutants, including the ones mentioned earlier [7]. The U.S. Environmental Protection Agency has established the Air Quality Index (AQI) for the assessment of air quality on a scale with 6 indicators, mapped on an interval from 0 (Good) to 500 (Hazardous) [39]. The fixed stations installed by authorities provide high grades of reliability and accuracy, but the costs related to their installing and maintenance are high [43]. This results in a reduced number of measurement locations translating to a low spatial resolution of the measurements. For example, the city of Cluj-Napoca, in Romania, has four fixed measurement stations [12]. However, these stations can be complemented by modeling techniques or by measurement points having less strict requirements, for providing a better picture of the ambient air quality in a designated area. The research works tackle this problem through one of the two approaches, modeling [25] and less strict measurement points [36].

In this paper, we give the implementation details of an ambient monitoring system composed of easy to deploy, cheap sensor nodes. The solution we developed rely on state of the art hardware that gets cheaper and cheaper, including low-cost sensors [41], on technologies like wireless sensor networks (WSN) [26], and on the IoT (Internet of Things) vision [9, 24], that is gaining more and more traction nowadays, on the increasing coverage of wireless networks, such as cellular or Wi-Fi [31], and on the development of more efficient protocols providing low-power communication [22].

The developed monitoring system measures the atmospheric pressure, humidity, temperature, air quality, and sound levels. Due to the low-cost and simplicity of the sensing nodes, these can be deployed in large numbers for providing fine-grained measurements over vast areas. These leverage the advantages of an IoT approach for providing an easy to use platform that helps citizens and authorities assess the weather conditions and pollution levels in their living or working places or in the city. Finally, we discuss and highlight the lessons learned from the design, development, and exploitation of the developed system.

The main contributions of the paper are as follows:

- we present the implementation details of a scalable and cost-efficient functional system for monitoring the environment in smart city settings;
- we provide considerations regarding the design, manufacturing, and operation of the presented system, with an emphasis on ease of use and operating costs;
- we present the lessons learned from the development and the exploitation of the developed system, that can be used as a starting point for the stakeholders involved in manufacturing and deploying such monitoring systems.

The rest of the paper is structured as follows. In Section II we present some of the research efforts regarding the monitoring of environmental parameters within cities using inexpensive equipment. In the following section we describe our approach for building large-scale monitoring networks within urban areas, based on the system we developed. In Section IV, we highlight the advantages and drawbacks of the developed system and present the results obtained during the testing and operational phases. Finally, we give concluding remarks in the the last section of the paper.

2 Existing Solutions for Urban Environmental Monitoring

2.1 Official Air Quality Measurement Stations

One of the most important environmental parameters within cities is air quality [32, 38]. It is affected by the direct release into the environment of gases resulted from industrial, transport, or household activities, having as main source the burning of fossil fuels [20]. The established method for assessing air pollution is by using fixed stations having several cubic meters in size, which include standardized and certified measurement equipment that is placed within a controlled environment [10]. The enclosure, usually a container, is fitted with different inlets that feed the air to the analysers for different pollutants (PM, CO, NO_2, O_3, VOC, and others) and with weather instruments that measure conditions such as the speed and direction of the wind, rainfall, humidity, and temperature [10]. For assuring the accuracy and reliability of the measurements provided by these stations, strictly defined processes are used, and the instruments inside are checked periodically and are subject to rigorous quality control and calibration procedures [33]. Therefore, the values provided for the quantities of harmful substances in the air are legally valid and can be used for regulatory decisions and for mitigation actions. The use of such equipment is costly and requires intensive maintenance activities, this resulting in a sparse network of measurement points. For example, the equipment that monitors PM within many of the air quality platforms is cumbersome, heavy, and has a cost between 50 000 and 100 000 USD [53]. These drawbacks, combined with the recurrent maintenance activities that can be performed only by specially trained personnel leads to a low number of installation sites [53]. Due to this relatively low number of fixed stations, in case the concentration of pollutants in a specific place has to be assessed, estimations involving complex mathematical models or the deployment of intermediate, less strict, measurement points is needed [10]. The accuracy of these estimations is improving as algorithms become more efficient and more compact analysers are being developed. Furthermore, significant improvements have been achieved lately in the satellite monitoring of air quality and of different gases in its composition [7]. It is believed that in the near future satellites will be able to provide measurements relevant to urban sites, and to complement the data recorded by fixed stations. One example are the observations from the Copernicus Sentinel-5P satellite, that showed significant drops in nitrogen dioxide over China, Italy, and over major cities in Europe, like Paris, Madrid, and Rome, during the 2019–20 coronavirus pandemic [15].

2.2 Low-cost Air Quality Measurement Approaches

In recent years, significant research efforts have been carried out in the domain of environmental monitoring within cities, that focus on the observation of air quality through the use of small form factor, less expensive installations. This was made possible by the continuously declining price of electronics and ICs (integrated circuits) and by the apparition on the market of low-cost sensors, that can be used in portable or energy-constrained devices [29]. Another supporting element is the IoT vision that is gaining increased attention nowadays, smart cities seeming to be some of its prime beneficiaries, besides domains such as agriculture, energy, and localization [1, 2, 30, 40, 46]. Although the research works are diverse, almost all of them advocate the deployment of dense, high resolution monitoring systems for the assessment of ambient parameters within urban areas. Paper [3] presents the development and testing of a low-cost, low-power and low-size wireless sensor for detecting air pollutants. It communicates over ZigBee and sends data to the cloud using special gateways. It is intended for being used in large scale monitoring networks and has been tested in laboratory settings, successfully discriminating between BTEX compounds (benzene, toluene, ethylbenzene and xylene), which are chemical components (VOCs) found in petroleum products. The tests indicate 95% discrimination success rates and large-scale deployment for real-time air quality data reporting is intended as future work. The work in [4] proposes the design, manufacturing, and evaluation of a small, low-cost station for monitoring outdoor O_3 and CO concentrations. The system consists of two single-board computers, to which sensors measuring more gases than the targeted ones are attached for redundancy and cross-sensitivity reduction, and integrates IEEE 802.3 and IEEE 802.11 communication capabilities. The calibration procedure of the attached sensors is performed using data provided by different sensor combinations and a machine learning algorithm based on the output provided by a fixed station. The O_3 values that are obtained using this solution are close to the ones provided by a fixed air monitoring station compliant with the recommendations of the US EPA (United States Environmental Protection Agency). The carbon CO measurement did not achieve the same level of accuracy due to signal drift and sensor ageing. However, the results can be used in implementing a pollution monitoring network able to provide qualitative information to the public with low installation and maintenance costs.

The use of mobile measurement systems is a common practice too [8]. MoreAir is an IoT platform that comes in the form of nomadic or mobile sensor nodes, developed to collect data related to the quality of the urban environment [19]. It is a battery-powered system able to measure PM2.5, PM10, temperature, and relative humidity, and to store these data along with the location estimate for the development of reliable air pollution maps. Testing has shown that this affordable platform can be efficiently used for making available real-time information related to air quality to citizens and raise awareness about urban pollution. The idea of mounting low-cost air sensors sensors on cars has also been investigated. One approach is to use the cars and their built-in sensors as mobile pollution detectors [21]. The authors of this research designed CrowdsourceSense, a crowdsource-based monitoring system, that sends data about the air quality in a car, when its windows are open, through a mobile application to a cloud platform. The crowdsourcing model defines architectures in which users contribute with measured data from personal devices. A three-months experiment with 500 vehicles in Beijing city showed that the approach is practical for gathering urban air quality data.

Authors of [27] propose a multi-sensor platform for personal exposure monitoring, built using off-the-shelf devices. The platform focuses on data collection from portable devices while assuring high levels of privacy and data authenticity through the use of group signatures and secure storage. The developed node's main components consist of multiple sensors able to measure carbon dioxide, VOC levels, temperature, and relative humidity, a processing unit, and a 3G (third generation)/GPS (Global Positioning System) module. The work in [54] proposes a Modular Sensor System (MSS) architecture for urban air pollution motoring, focusing on portability, energy efficiency, compatibility with multiple communication technologies and standards, and configurable and adaptable multiple sensing capability. The developed device solves the problem of fixed hardware configuration of current solutions through a modular architecture and an Universal Sensor Interface (USI), but this flexibility leads to larger dimensions and higher design complexity. However, this flexibility enables micro-level air pollution monitoring through the possibility of deploying large numbers of stationary, wearable, and/or vehicular sensor nodes. The calibration and testing of a design incorporating temperature, relative humidity, atmospheric pressure, CO, and NO_2 resulted in measurements with acceptable accuracy. The personal pollution trackers suite is completed by a large number of start-ups and projects funded through crowdfunding campaigns. There are also studies focusing on indoor air quality [45, 47, 55]. This is important because people spend most of their time indoors, where, in many cases, the concentration of pollutants is higher than outside [37]. The 2019-20 coronavirus pandemic has also brought real-time air quality monitoring into focus, since such an indicator could give general guidelines to help people avoid unhealthy situations at the office, for example [28].

Being considered a health hazard, noise is also the subject of regulations. The EU Environmental Noise Directive requires that member states map this type of pollution and take action for reducing the exposure of their citizens to high levels of environmental noise [16].

As can be seen, the literature presents many implementations of monitoring systems based on low-cost hardware. All these compensate the limitations regarding measurement accuracy and precision through the use of large numbers of sensors or continuous calibration with reference data obtained through more rigorous measurement actions. Some of the most important factors that have to be considered when using such sensors is their set of specifications, deployment location, complexity of the additional hardware required and of the software algorithms required for obtaining outputs as close to the reference values as possible. Periodical calibration is also very important for such sensors, and, depending on the used device, it can be automatically performed or by the user.

In the following section we present the design and development of an environmental monitoring system that supports the deployment of large-scale measurement networks. Furthermore, we present the results and lessons learned after more than three years of operation, while the developed nodes have been operation continuously. As the previous paragraphs showed, most of the the majority of the solutions in the literature consist in promising prototypes and experimental systems, and further steps are requires for achieving mature products. The system we developed has been build considering a product approach, taking into account scalability, ease of deployment and exploitation, and costs.

3 The Developed Environmental System

3.1 Requirements

The main requirement for the developed system is the gathering of high resolution data regarding the environment within a city or in indoor places. This requires the deployment of large numbers of sensors, that have to be cheap and easy to manufacture and install. Therefore, low-cost sensors were manufactured for giving indicative measurements about environmental conditions in the system's vicinity. The developed sensor's architecture is based on the BME680 produced by Bosch Sensortec for performing this action [5]. The gas sensor in its structure is a metal oxide semiconductor sensor that measures the quantity of VOC in the air and outputs a value from 0 to 500, where 500 represents the higher end of the scale, the highest level of pollutants in the air (Table 1). The other physical units measured by BME680 are temperature, relative humidity, and pressure. The second sensor attached to the device is a ICS-43432 digital microphone produced by InvenSense, allowing the measurement of the relative loudness of sounds in the air as perceived by the human ear (A-weighted decibels). [23].

Index Value	Air Quality
0-50	Excellent
51-100	Good
101-150	Lightly polluted
151-200	Moderately polluted
201-250	Heavily polluted
251-350	Severely polluted
>351	Extremely polluted

Table 1: Gas sensor output [5]

Wi-Fi was chosen as the technology used for transmitting the measurements, for achieving ease of deployment, scalability, and maintainability. Wi-Fi-based sensors are easier to deploy and maintain since they take advantage of the existing IEEE802.11 infrastructure, have native Internet Protocol network compatibility, and do not require additional devices and applications for transmitting their data to the Internet [34].

3.2 System Architecture

We designed a system for achieving the continuous measurement and recording of environmental parameters data that is based on Wi-Fi sensors. The parameters that are tracked are the temperature, relative humidity, atmospheric pressure, air quality, and sound pressure level. The developed monitoring system consists of Wi-Fi beacons that sample attached sensors, connect to a previously defined network, and send the acquired data using http (Hypertext Transfer Protocol) requests to a cloud platform, where it is processed and stored in a NoSQL (non-Structured Query Language) database. The recorded data can then be viewed in different forms, such as a heat map, line charts, or time series, by users through a web page. The architecture of the developed system is presented in Fig. 1. The main advantage of such an approach lies in the fact that no gateways are required for sending the data to the cloud platform through the Internet. The sensing devices connect directly to the Internet through existing IEEE802.11 access points, that are almost ubiquitous in current urban settings, and have native IP-network compatibility.

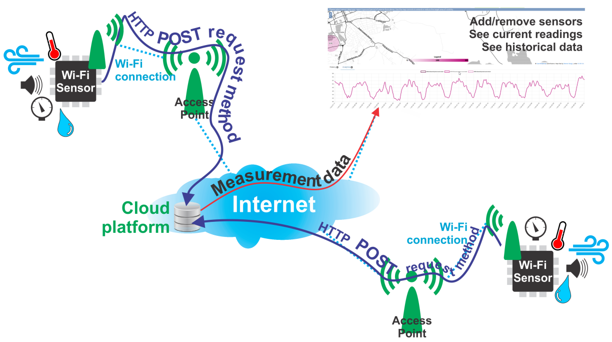

Figure 1: Wi-Fi environmental monitoring system architecture

3.2.1 Hardware Architecture

The hardware architecture of the sensing device has as core the Expressif ESP32 wireless module [11]. This was chosen because of its simplicity and ease of use. It acquires data from a BME680 sensor and an ICS-43432 digital microphone produced by InvenSense [23]. The device is powered through a mini USB-C (Universal Serial Bus Type-C) port and a LM1117 LDO (low-dropout regulator) for providing a 3 V voltage level to the components on the board [48]. This solution was chosen, and not one with a battery or energy harvesting elements, because the sensors are small enough to be installed in the immediate vicinity of access points (APs). They can actually be powered through an USB port and therefore they can be placed near the APs that provide Wi-Fi access in a smart city. A small factor PCB (printed circuit board) was obtained, measuring 7.5 cm in length and 3.5 cm in width. The generic architecture of the Wi-Fi node is presented in Fig. 2. The BOM (bill of materials) for a sensor is approximately 20 Eur for a single device and 15 Eur per device for a quantity of 100.

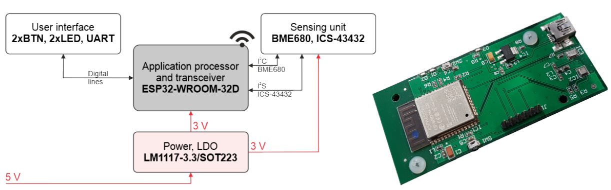

Figure 2: Wi-Fi sensor – generic architecture

3.2.2 Firmware

The application running on the wireless node is written in C and follows a simple duty-cycled pattern (Fig. 3), where the device samples the attached sensors each three seconds and saves the data in RAM (Random Access Memory). Each minute, the device connects to a know Wireless Local Area Network (WLAN), previously set by the user, arithmetic averages of the measured values are computed, and a JSON (JavaScript Object Notation) package is prepared for being sent through an http POST request to the cloud platform. The JSON contains the MAC (Media Access Control) address of the device and the averages for the measurements, namely atmospheric pressure, index for air quality, sound pressure value in dBA, temperature, and relative humidity. The fact that the system is externally powered through a mini USB-C cable simplifies the firmware, since no extreme techniques for assuring low-power operation are required.

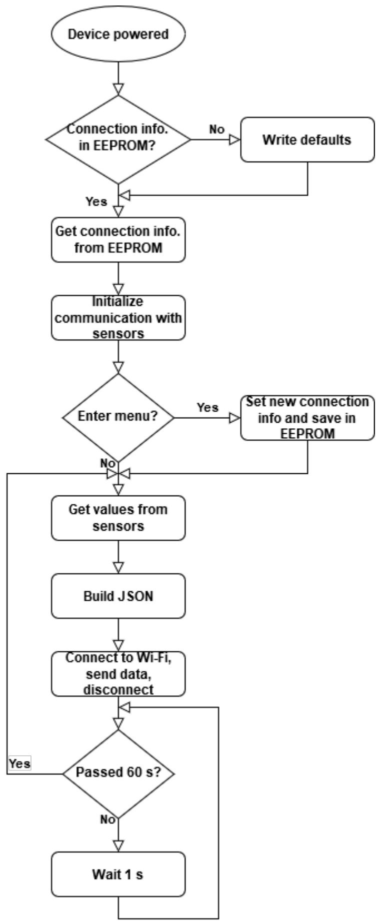

Figure 3: Application flowchart

3.2.3 Web Interface

The data from the Wi-Fi sensors is received by the cloud platform each minute, it is stored and can be accessed any time by end-users. The front end allows the addition of measurement devices, with corresponding data associated to each one of them (location and description). If the cloud application receives data from a sensor that has been registered to the system, then it will be stored in the NoSQL database. In case the MAC of the sensor that is sending the data is not known the device will appear in the section of the web page that manages the sensors, for allowing the possibility of enrolling it. The user can specify the intervals and periods between recorded points for historical data representation. The application was implemented in Java as the main programming language and it uses Angular for the front-end part. The chosen NoSQL database is MongoDB. The cloud application was deployed in the Heroku cloud platform. Fig. 4 shows the daily air quality for a location for a period of one month and Fig. 5 shows the recorded sound pressure near a road in a quiet neighbourhood of Cluj-Napoca during a one week period, measured using the developed Wi-Fi system.

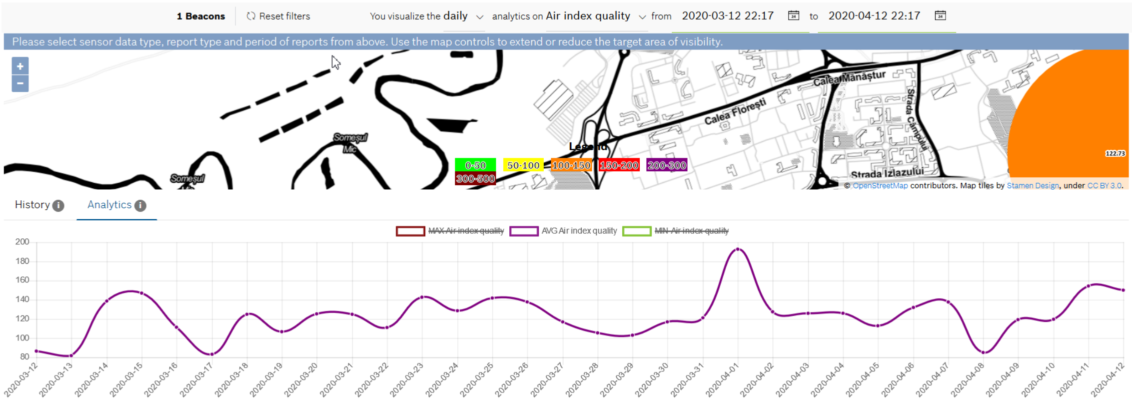

Figure 4: Air quality in an outdoor location for a one month period, daily average

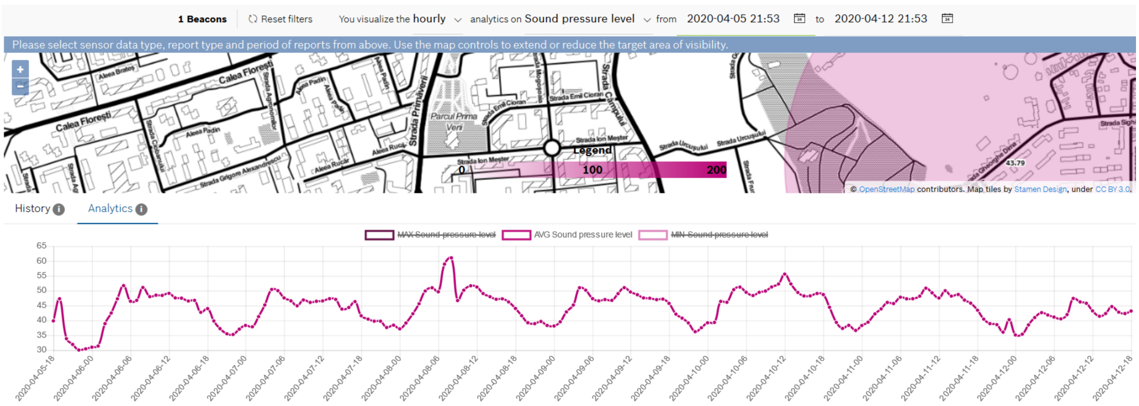

Figure 5: Sound pressure recordings (dBA) in an outdoor location for a one week period, hourly average

3.2.4 Testing

A setup consisting of 10 sensors has been made and has been running for more than two years. The testing period showed that the system is robust and there are no interruption in the operation as long as the access point is up and power is supplied to the nodes. The operation of the system revealed that it can be successfully used for the acquisition of weather and ambient data, and provide reliable indication of the level of noise and air quality pollution in urban outdoor and indoor environments. The addition of Wi-Fi sensors to the system is straightforward, the user having only to setup the SSID (service set identifier) and password of the WLAN where the sensor will be deployed. When the sensor is powered, it will automatically send the data to the cloud platform.

4 Results and Lessons Learned

The presented solutions is intended to raise awareness about the problems encountered in urban environments and indoor spaces and enable citizens to live healthier lives. It could be easily included in larger ecosystems that combine regulatory-grade data with that generated by less complex and less costly devices, as the one promoted by the authors of [42]. The main goal of this research is to provide a basis for future works in the direction of IoT-based solution for smart cities and smart buildings and to provide practical considerations regarding the presented architectures.

4.1 Data transmission

The use of Wi-Fi for communication offers reduced infrastructure costs while improving TCO (total cost of ownership), and provide fast sensor deployment on pre-existing 802.11 networks, that are wide-spread in the case of smart cities. Furthermore, there is a vast pool of network management tools, an extensive knowledge base, and protocol familiarity and native IP-network compatibility [49].

Being a reliable protocol, http guarantees a satisfactory message delivery ratio that depends mostly on the availability of the wireless network to which the sensors connect. Anyway, the proposed system relies on large numbers of measurement points that can overcome eventual package losses.

The approach is based on low-cost hardware, that can be mass produced. The deployment of large numbers of such sensors is necessary because the measured values, like air quality, can vary drastically in just tens of meters from the measurement points [36]. In terms of scalability, the presented solution is open and supports the installation of virtually unlimited numbers of measurement points. A possible problem could be represented by the ability of the server platform to receive large numbers of packets in a short period of time.

4.1.1 Power Consumption

The use of a batteries for powering Wi-Fi sensors is possible, but, since http is a power-hungry protocol, this requires the implementation of thorough energy-reduction techniques [18, 35]. In the case of these systems, it is possible that data transmission consumes more energy than the actual operation of the attached sensors. As Wi-Fi sensors connect to a predefined wireless network, they have to be within the range of the corresponding access point, so mobility is not a requirement. This was the reason for opting for an external power supply. Adding more sensors to the developed embedded devices is also possible, but this would increase the required energy budget for battery-powered systems. Therefore, this is straightforward only in the case of the sensors that are connected to power lines.

4.1.2 Data Management

The active monitoring of the environment generates large volumes of data in relatively short periods of time. The developed system generated almost 200 MB of environmental data in 1.2 million recordings during a period of several months. Processing such volumes of data requires a specialized infrastructure for generating statistics and high resolution graphs. The application of sophisticated machine learning and artificial intelligence algorithms could offer a better insight into the information provided by the system, and could help in estimating one physical unit from the others that are measured. For example, long time measurements revealed that the values related to air pollution are strictly related to the noise generated by the presence of people and their activities.

4.1.3 Measuring Noise Pollution

The monitoring of noise pollution is unfeasible in the case of battery powered systems, because the continuous acquisition and analysis of data are power hungry operations. The development of a wireless device that triggers the measurement action only when a certain threshold is exceeded is problematic. However, continuously measuring sound pressure levels, where there are no stringent energy consumption requirements, provided satisfactory results.

5 Conclusion

As the urbanization trend intensifies, more people living in cities are experiencing discomfort and health problems related to different factors affecting their environment, such as harmful substances in the air or background noise. In this context, we provided a brief analysis of current environmental monitoring solutions within cities, and presented the development, operation, and the corresponding lessons learned of an environmental monitoring system that measures parameters such as atmospheric pressure, relative humidity, temperature, air quality, and sound levels. The system we developed can be deployed in large numbers for providing fine-grained measurements over vast areas with minimum installation and maintenance costs. The analysis of its operation and the lessons learned from its development and exploitation could help designers in the field of urban environmental monitoring take decisions regarding their own approaches.

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Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest. The views and opinions expressed in this article are those of the authors and the sponsors had no role in the design, execution, interpretation, or writing of the study.

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