# Sensor network for $PM_{2.5}$ measurements on an academic campus area

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**Abstract.** Fine particulate matter ($PM_{2.5}$) pose a serious threat to health. Therefore it should be monitored to assess its health impacts and to take actions to reduce its pollution. However, the traditional regulatory measuring stations are not able to capture the spatial and temporal variability of $PM_{2.5}$ concentrations. The opportunity to improve the resolution of $PM_{2.5}$ data is based on dense networks of miniaturized low-cost sensors. The article presents the sensor network for campus area of Wrocław University of Science and Technology. This system consists of 20 sensor nodes, distributed both on a narrow scale (14 devices on the main campus area) and on a wide scale (devices on campuses in distant parts of the city). Sensor devices have been equipped with optical sensors A003 from Plantower company and with heated inlets. Dedicated website with a map is used to present the up-to-date information about air quality to the public. Messages on air quality are based on air quality index, calculated every 15 minutes. The article demonstrates also few results of preliminary measurements, when episodes of elevated $PM_{2.5}$ concentrations were observed. Sensor nodes proved to be an useful tool to monitor the changes of air pollution during such events.

## 1 Introduction

Poor air quality is one of the most important factors that affects human health and quality of life [1]. Exposure to air pollutants has been linked with many harmful health effects, such as respiratory and cardiovascular diseases, but also with premature deaths and increases in mortality [2–6].

Nowadays, many cities and regions in Europe are struggling with air pollution problems [7]. This issue concerns especially Poland and particulate matter (PM) pollution. In Polish cities, the dominant PM emission source is the residential sector and the key factor is the heating of dwellings (based mainly on the combustion of fossil fuels and biomass) [8]. Events of air quality deterioration occur usually in the autumn-winter season and the biggest threat is related to emission of fine particulate matter (i.e. $PM_{2.5}$) [9]. That fraction

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of PM deposits throughout the respiratory tract, penetrate to the lower parts and alveoli and has a serious negative impact on health [2].

The most accurate information about the elevated levels of $PM_{2.5}$ is accessible to the public through the regulatory measuring stations. Such monitoring networks operate on the basis of strict regulations, such as the European Directive 2008/50/EC [10]. The standard (reference) method of $PM_{2.5}$ measurements involves sampling PM on filters and weighing them on a balance (so-called: gravimetric method [11]). However, this procedure allows only to obtain daily average values and data are available after a long period of time. More frequent data is collected by stations with automated measuring systems (AMS), i.e. instruments that were proved to be equivalent to reference method [12]. Such systems are capable of measuring hourly PM averages, but their spatial coverage is rather sparse. For example, in Poland (~312 000 $km^2$) there are only 61 governmental automatic stations for $PM_{2.5}$ monitoring, which constitutes less than 35% of all stations for automatic air quality measurements. That type of monitoring system is not able to capture the fine spatial variability of $PM_{2.5}$ pollution [13–15].

Recently, the technological advances has resulted in an increase in accessibility and popularity of miniaturized, low-cost, low-powered sensors for air pollution measurements [16–18]. Such devices might improve spatial and temporal resolution of air quality data when they are used in widely dispersed sensor networks [19–21]. That kind of systems may be useful for indication of elevated PM concentration events or PM “hot-spots” [22].

In the last few years, many projects have been undertaken to create air quality sensor networks. Some of them were dedicated to gaseous air pollutants [23–25], but systems for PM have also been tested by research groups [20, 21, 26, 27]. The easy availability of low-cost optical PM sensors has even led to the emergence of commercial systems for air quality monitoring (e.g. Air Quality Egg [28], Looko2 [29] or Airly [30]). Moreover, some projects are based on the application of cheap, self-built, monitors (see luftdaten.info project [31]). Such measurement systems are part of the idea of citizen science, where nonprofessional researchers participate in collecting data about the state of the environment [16, 19, 32].

Those programs provide citizens with opportunities to monitor the local air quality in near real-time. This contributes in raising awareness about air pollution variability and potential pollution sources. Further, such actions may initiate different strategies to decrease air pollution exposures (e.g. by wearing filtering facemasks). Beyond that, they may encourage communities to engage in dialogue with researchers and regulatory authorities to develop pollution reduction policies [16, 32].

The above-mentioned options have become a motivation to create a sensor network for $PM_{2.5}$ measurements on a campus area of Wrocław University of Science and Technology (WUST). This paper presents briefly the construction of sensor devices, characteristics of the WUST campus and opportunities of informing the academic community about the air pollution. Few examples of measurement results were also presented.

## 2 Characteristics of the sensor network

### 2.1 Characteristics of the sensor node

The core element of the node was the optical sensor A003 from Plantower company, which was the latest device from their product family. Sensors from Plantower company were chosen on a basis of previous tests, where high reproducibility between units and high linear correlation with comparison instrument were found [33].

PM sensor was connected with single-board microcomputer. This component was responsible for data logging and for control over the rest of the sensor device. Data transmission was made via GSM network and an external antenna was used for this purpose. The whole device was supplied from the mains, with 12 V/1.5 A power supplier. The additional elements of node were two sensors for temperature and relative humidity (RH) measurements. One sensor was fixed in close proximity of A003 inlet and it was used to control the surrounding conditions of PM sensor. The second sensor was mounted outside the enclosure of measurement node – it was used for measurements of external conditions.

The housing of a node (see Fig. 1) has a shape of cuboid, printed in 3D technique from ABS. The whole thing was covered with a rainproof lid, made from PVC. The box was equipped with air inlet with metallic mesh filter and air outlet, where fan was attached.

**Fig. 1.** Sensor node in a rainproof housing.

An important novel element of sensor node was the heated inlet. This feature was added in order to prevent the negative impact of high levels of humidity (e.g. possibility of hygroscopic growth of particles or detecting the fog droplets [34]). Heaters were attached to mesh inlet and the heating was controlled on the basis of the internal RH sensor readings. The level of 60% RH was set as a threshold for heater activation.

Sensor nodes were calibrated in two steps, during a few weeks of comparison. In the first step, individual correction factors were established to adjust the sensor nodes signals to uniform level. In the second step, calibration coefficient were calculated on the basis of averaged values from two nearest regulatory monitoring stations ("Wyb. Conrada-Korzeniowskiego" and "Wiśniowa/Powstańców Śląskich St." in Wrocław).

## 2.2 Characteristics of the WUST campus area and sensor nodes locations

The WUST campus consists of a few parts which are spread throughout the Wrocław city (see [35] for details). The main campus is located in Plac Grunwaldzki area, east of the city centre of Wrocław, between high-traffic streets: Plac Grunwaldzki (north-western boundary of campus) and Curie-Skłodowskiej (north-eastern boundary). WUST buildings are bounded from the south by Wybrzeże Wyspiańskiego street and Odra river. There are no large point sources of particulate emission nearby, but PM emission may derive from transport and individual heating systems in tenement buildings located on Wybrzeże Wyspiańskiego street and in other parts of the city. 14 sensors were located in that area. They were arranged near the campus borders (near Plac Grunwaldzki street and Wybrzeże Wyspiańskiego) and inside the main campus zone.

The other 6 nodes were located at: Na Grobli street (campus located between Odra and Oława rivers, south of the main campus), Bujwida street (campus "Gdańska St.", in an area of tenement buildings, near cemetery and allotments; north-east of the main campus), Prusa street (campus in a district of multi-family houses, tenement houses, near small city park; north-west of the main campus), Długa street (campus in a north-west part of the city; near Odra river and area of allotments), campus "Wittiga St." (area of multi-storey student dormitories; east of the main campus). A general arrangement of sensor nodes is shown in Fig. 2.

Sensor devices were fastened to external window sills, balconies or rooftops with the air inlet slightly extending or in line with their edges (see Fig. 1 for example). Most of the measurement points were located at an altitude of circa 2 m to 4 m above the ground level. In two cases, few sensor devices were placed on one building, but at different heights.


**Fig. 2.** Locations of sensor nodes: a) main campus area, b) Wrocław city area (green circles – sensor nodes, red triangles – regulatory automatic $PM_{2.5}$ monitoring stations).

## 2.3 Characteristics of the air quality messaging

Air quality messaging at WUST campus is based on concept of Polish Air Quality Index, created by Chief Inspectorate of Environmental Protection [36] and adapted by Municipality of Wrocław as Wrocław Air Index [37]. Six classes of air quality were considered in this approach: (1) Good, (2) Moderate, (3) Below standards, (4) Unfavourable, (5) Bad, (6) Critical. For each air quality class an appropriate colour code with a set of pictograms, health information and activity recommendations has been assigned [37].

Generally, that air quality index is determined on the basis of 1-hour data from automatic monitoring systems for individual pollutants: $SO_2$, $NO_2$, CO, $C_6H_6$, $O_3$, $PM_{10}$ and $PM_{2.5}$, by comparing the measured concentrations with the specified thresholds for air quality classes. Those boundaries were based on a probability of exceedance of long-term air quality standards. The overall index is established at the end by taking into account the worst-case scenario (i.e. by taking the lowest of individual classes) or by taking into account the dominant pollutant (particulate matter in autumn-winter season or ozone in spring-summer season) [36].

In the case of WUST messaging system, air quality index is related only to 1-hour averaged $PM_{2.5}$ values (see Fig. 3). Importantly, the hourly values are calculated as moving averages, updated at 15-minutes increments. This way of calculation ensures that current changes in air quality are provided without significant time delays. Information about air quality are communicated by means of a dedicated website (www.powietrze.pwr.edu.pl) with map and animated banners. That kind of messaging might be useful for planning outdoor activities (e.g. walks, cycling) or in the choice of mode of transport.

| Air quality class | Air quality index | Colour code | $PM_{2.5}$ hourly mean, μg/m³ |
|---|---|---|---|
| 1 | Good | | [0; 13] |
| 2 | Moderate | | (13; 37] |
| 3 | Below standards | | (37; 61] |
| 4 | Unfavourable | | (61; 85] |
| 5 | Bad | | (85; 121] |
| 6 | Critical | | > 121 |

**Fig. 3.** Characteristics of Wrocław Air Index with $PM_{2.5}$ breakpoints.

### 2.4 Possibilities of the use of the WUST sensor network

WUST monitoring network has several important features: 1) is dense in the selected area (main campus), 2) is widespread in the city territory (covers few districts in the city), 3) data are collected with a high time resolution, 4) some of the nodes are located at different altitude levels. Such arrangement opens new opportunities for air quality monitoring. Possible applications of that system include:

- air pollutants monitoring at fine spatio-temporal resolution,
- up-to-date public messaging about air quality and activity recommendations,
- conducting studies on the impact of urban development and transport system on air quality,
- conducting studies on the transfer of air pollutants in an urban scale (quasi-macroscale) and in a scale of street/buildings-canyons (quasi-microscale),
- conducting studies on vertical distribution of air pollutants.

## 3 Results of preliminary studies

High variability in $PM_{2.5}$ concentrations may be observed both in time and space. Fig. 4 presents examples of two episodes of elevated $PM_{2.5}$ concentrations, characterized with such fluctuations. The first event (Fig. 4a) took place on the evening of 2$^{nd}$ February 2019 and was characterized with rapid growth of $PM_{2.5}$ values, observed at regulatory monitoring station "Wiśniowa/Powstańców Śląskich St.", situated in the southern part of the city. During this episode, measured concentrations changed from the level of 30 μg/m³ to circa 100 μg/m³ (i.e. from "Moderate" to "Bad" air quality index) within one hour (17:00–18:00) and then they decreased to the level of 60 μg/m³ at 19:00 ("Below standards" index). Afterwards, new peak of $PM_{2.5}$ was observed at 20:00 (~65 μg/m³; "Unfavourable" index). The reduction of $PM_{2.5}$ concentrations (to level of 30–40 μg/m³) was noticed in the late evening and night hours. On the other hand, such extreme changes were not observed at regulatory station "Wyb. Conrada-Korzeniowskiego" in the northern part of Wrocław. Between 17:00 and 18:00, $PM_{2.5}$ values changed from 28 μg/m³ to 44 μg/m³ (from "Moderate" to "Below standards"). The second peak was also measured at 20:00, but it was lower than the previously described (~51 μg/m³). As in the previous case, $PM_{2.5}$ values decreased in the following hours to 30–40 μg/m³. What is important, $PM_{2.5}$ changes measured by WUST sensor nodes were very similar to the trend from "Conrada-Korzeniowskiego" station. Air quality classes determined by means of sensor nodes agreed with information from that regulatory station. The second episode (Fig. 4b) started in the afternoon of 18th February and lasted until the morning of 19th February 2019. Around 16:00, concentrations of $PM_{2.5}$ began to rise gradually from the level of 20–30 μg/m³ at all measuring points. However, the maximum value (~90 μg/m³; "Bad" air quality index) at the southern monitoring station ("Wiśniowa/Powstańców Śląskich St.") was observed at

21:00 and after that, the $PM_{2.5}$ concentrations began to decrease. Such situation lasted until 04:00 on 19th February, when the next increase started, with another peak of 90 µg/m$^3$ at 07:00. Fluctuations in $PM_{2.5}$ were also observed at "Conrada-Korzeniowskiego" station and at WUST measuring points, but there were quite different. First of all, when decrease in $PM_{2.5}$ values was observed in the late evening hours in the southern region of city, the level of pollution was still increasing in the north. Maximum values reported at "Conrada-Korzeniowskiego" exceeded 121 µg/m$^3$ ("Critical" air quality index) between 00:00 and 03:00 on 19th February. Slightly lower values were measured by WUST sensors – around midnight, $PM_{2.5}$ pollution reached the level of 90–110 µg/m$^3$. However, such "Bad" air quality was observed generally on campuses located farthest to the north (campuses: "Długa St.", "Prusa St.", "Gdańska St."), as well as in the north-east part of main campus (near Plac Grunwaldzki and Curie-Skłodowskiej street) and on "Wittiga St." campus (student dormitories; east of the main campus). In general, lower $PM_{2.5}$ concentrations were measured in the southern part of the main campus (near Odra river) and in the centre of the main campus. The spatial variability of air quality classes during the second episode was presented on maps on Fig. 5 for two time points (21:00 and 00:00). This type of visual messages were presented on www.powietrze.pwr.edu.pl website.

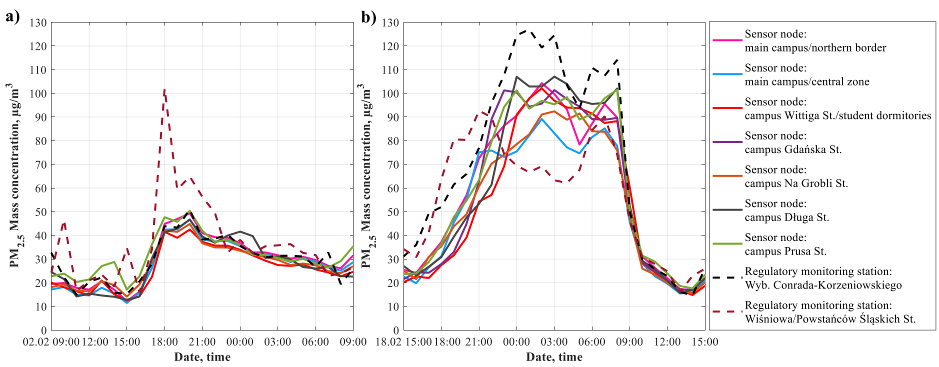


**Fig. 4.** Examples of episodes of elevated $PM_{2.5}$ concentrations, observed by regulatory monitoring stations and WUST sensor nodes. 1-hour averaged data for selected nodes were plotted for clarity.

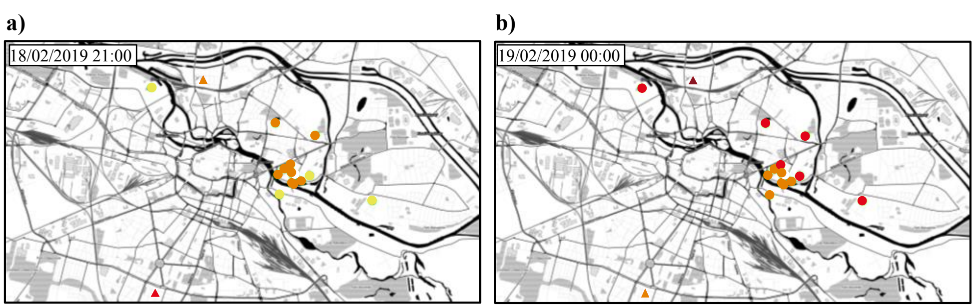


**Fig. 5.** Examples of spatial variability of air quality classes during episode of elevated $PM_{2.5}$ concentrations (circles – sensor nodes, triangles – regulatory automatic $PM_{2.5}$ monitoring stations). Colours refer to air quality indexes according to Fig. 3.

This results show that episodes of $PM_{2.5}$ increments may sometimes occur only locally (the case of first episode) or may change dynamically in time and space (the case of second episode). In each of such cases, the sensor devices may be used to monitor $PM_{2.5}$ concentrations and to inform the public about the current air quality.

## 4 Conclusions and future works

Low-cost sensors for air pollutants measurements have become very popular in recent years. They are characterized by small size, low power consumption and short response times. For these reasons they might be used in widely dispersed networks and supplement the conventional regulatory monitoring system. Sensor network at WUST campus areas provides the opportunity to present the up-to-date air quality information to the public. This system consists of 20 sensor nodes, that cover a quite large part of city of Wrocław, but also enable measurements at a smaller scale of main campus. The air quality messaging is based on hourly air quality index, but calculated as moving average in 15-minutes steps. Dedicated website with map with colour points and pictograms is used to give citizens activity recommendations. WUST sensor network presents wide opportunities for air quality monitoring at fine spatio-temporal resolution. This sensor system will we used to investigate and understand the phenomena of pollutants spreading. In the near future, it is planned to extend the system by adding sensors for measurements of gaseous pollutants like ozone.

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