URBAN NETWORK OF AIR QUALITY MEASUREMENT NODES

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Summary

Smart city is a city that increases the interactivity of its components and put emphasis on their functionality. Internet of Things technology (IoT) is an innovative solution in environmental protection. Usually, information on air quality is very scattered. This paper describes the test stages of pre-implementation works, focusing on the presentation of the technical design of the measurement nodes and the assumptions of the IT project. The goal of the project Intelligent Wireless Sensor Network Infrastructure (IIBSC) is, among others, to create a dense network of air quality measurement nodes at city, district or even street level. The concept is based on Internet of Things (IoT) technology using a matrix construction tool connected to multiple identical measurement nodes located in the test area. The project developed a hardware platform supporting sensors and resistant to external factors, and an ISIMPIO information platform based on edge processing technology for processing data from air quality sensors. Due to the use of Internet of Things (IoT) technology, an edge server using edge processing was designed. Edge server provides a complete ecosystem for building edge applications that are fully optimized for seamless field work. In addition, it allows the implementation of integrated Python software, the MQ Telemetry Transport support protocol (MQTT), time-series database, firmware update over a wireless network, and built-in security system. Measuring the concentration of particulate matter and other substances in the air will be useful for specialists assessing their dynamics. The technology and test installation selected corresponds to the leading solutions in this field in Europe and, in the future, should also be extended to less urbanised areas.

Key words

urban infrastructure • Internet of Things • air quality • environmental monitoring

1. Introduction

The unprecedented expansion of infrastructure supporting urbanisation offers opportunities for improvement of the welfare and productivity of residents and for sustainable urban development [Chang et al. 2021]. However, many of these opportunities remain unfulfilled in the face of existing and emerging significant urban challenges. One such challenge is an assessment of air quality and its impact on the health of urban residents [Demanega et al. 2021]. Addressing this issue will require obtaining

relevant data, and thus equipping cities with new types of sensors and measurement strategies. A growing body of research highlights the impact of both long-term and short-term human exposure to various aerial pollutants, prompting the World Health Organisation (WHO) to issue air quality guidelines [Evangelopoulos et al. 2020]. These guidelines are constantly being updated as new research on health effects of air pollution emerges. In Poland, air quality standards are defined by the relevant legislation (Rozporządzenie Ministra Klimatu i Środowiska z dnia 11.12.2020 r. w sprawie oceny poziomów substancji w powietrzu – Regulation of the Minister of Climate and Environment of 11 December 2020 on the evaluation of levels of substances in the air).

The assessment of health effects for residents resulting from air quality suggests the need for facilitating interdisciplinary teams the task of gaining better knowledge on the environmental impact of changing urban conditions. Initially, research focused on the relationship between air pollution and cardiovascular and respiratory diseases [Miller et al. 2007, Keetet al. 2018], while more recent studies have established a link between exposure to excessive dust concentrations – particulate matter (PM) and changes in brain structure [Chen et al. 2015]. Lately, the neurotoxicity of minor PM has proven to be a cause of a growing epidemic of cognitive disorders and related diseases, such as Alzheimer's disease [Kilian and Kitazawa 2018]. In most cases, the current studies have some methodological imperfections resulting from incapability to take accurate actual measurement, determining the degree of exposure of an individual to air pollution [Che et al. 2021]. Some gases and finer particles can dissipate relatively evenly across the district, additionally assuming ideal conditions [Xie et al. 2021]. However, the spatial distribution of pollutants in urban areas can be very uneven due to complex airflows caused by "built-up environments" such as skyscrapers, road networks and variable traffic patterns [Di Sabatino et al. 2018].

It should be noted that in the field of air quality monitoring there have been multiple projects, both commercial and civil. Among commercial solutions worth mentioning are the Polish apps Airly, Look O2, Syngeos or the international civil network Luftdaten. However, these platforms are limited to measuring particulate matter concentrations (PM). These solutions do not provide more detailed information on the quality of the measurement data. They usually provide the CAQI Air Quality Index for PM concentrations. The focus on PM measurements does not reflect the whole problem because the main urban air pollutants, also known as primary pollutants are nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), lead (Pb) and particulate matter (including PM10 and PM2.5). Secondary pollutants are those resulting from chemical reactions in the air between primary pollutants and natural gases, for example, ozone (O_3), sulphuric acid (sulfoxylic acid H_2SO_2) and nitric acid (HNO_3). Therefore, efforts should be made to provide more integrated information on air quality. Such a project carrying out the task of comprehensive pollution analysis is a platform called ArrayOfThings – an experimental urban measurement system consisting of programmable, modular "nodes" with measuring sensors and computational capabilities to collect real-time data on the environment (climate, air quality and noise), currently being implemented in Chicago, USA.

Our "Intelligent Wireless Sensor Network Infrastructure" (Inteligentna Infrastruktura Bezprzewodowej Sieci Czujników, IIBSC) project's objective is to collect real-time data on the environment, infrastructure and city activities for research and public use. The sensor network allows local tracking of exceeding norms, providing day-to-day information to local communities about the state of the air and taking countermeasures e.g. reducing car traffic in a given area. IIBSC consists of nodes that measure the parameters of an urban environment and provide data available almost in real-time. Each node includes a measurement head that uses chemical sensors to measure the following gases: ozone, nitrogen dioxide, carbon monoxide, sulphur dioxide and hydrogen sulphide, polymer and MEMS sensors for temperature, humidity and pressure, and an optical sensor for solid particles. This project is different than current air pollution measurement methods as it presents a detailed approach to measurement by providing metadata that describe measurement results and features of the method, that is: precision, deviation, range, method detection limits and calibration. Metadata are important in determining the end use of air quality information. Currently, information on air quality is very scattered. Selected technology matches the leading solutions in this field in Europe and globally, and in the future should also be extended to less urbanized areas.

The Chief Inspector of Environmental Protection (Główny Inspektorat Ochrony Środowiska, GIOŚ), under the State Environmental Monitoring (Państwowy Monitoring Środowiska, PMŚ) program, maintains approx. 280 air quality measurement stations located mainly in cities. The stations are located in key sites of cities, but their number is small, for example there are only 8 in Krakow. The aim of the research was to show the operation of an air pollution monitoring system in urban areas.

2. General concept of air pollution monitoring system

The concept of air pollution monitoring system is based primarily on the Internet of Things (IoT) technology. In order to ensure a dense network of measurements, i.e. multiple measurement nodes in a relatively small area, a mesh network structure (MESH) was utilised. Mesh networks provide a reliable, safe and self-maintaining structure. MESH is a structure that uses one or more connections to create a full or partial mesh network topology. The wireless MESH structure is a network that establishes multiple connections between nodes and is able to dynamically update and optimize these connections. In the project, communication between measurement nodes and the edge server is organized by the DigiMesh® protocol and uses the unlicensed Industrial, Scientific, Medical (ISM) 868 Mhz band. This protocol, together with the supporting Xbee 868 LP radio modules, creates a homogeneous network in which all nodes redirect data packets along routes determined dynamically by the protocol. Since the established routes are remembered by the measurement nodes, the network does not have to sustain continuous routing. The routes are changed only in the case of lost communication with any measurement node. This is done as follows: each measurement node places a 64-bit address of the destination node, in this case the edge server,

in its data frame. The data frame with the address is forwarded to a neighbouring measurement node within the radio range, which together with other measurement nodes forms the proper network routing data packets to the edge server. The protocol supports low-power solutions, which means that all network nodes remain in a sleep mode and are awakened synchronously. Time synchronization is set by the user, nominating one of the nodes with a coordinator, which also remains in a sleep mode. As the use of the Internet of Things (IoT) technology is assumed, an edge server has been designed at the "edge" of the network of measurement nodes, using edge processing, one of the techniques of Internet of Things (IoT). Edge server implements edge intelligence providing a complete ecosystem for creating edge applications that are fully optimized for seamless field work, provides integrated Python software, support for data transmission protocol MQTT (Message Queuing Telemetry Transport), time series database, firmware updates over a wireless network, built-in security.

3. Methodology

Selecting sensors

Electrochemical gas sensors

Carbon monoxide (CO), nitrogen dioxide (NO_2), hydrogen sulphide (H_2S), sulphur dioxide (SO_2) and ozone (O_3) were measured by SPEC Sensors due to their size, low energy requirement, reliability. These are amperometric gas sensors that generate a current proportional to the gas concentration. The measurement node prototype uses the ULPSM-NO2 968-047 sensor (Fig. 1).

This type of device uses catalytic metal as a sensor electrode, which is selected separately for each gas to optimize the reaction to a corresponding gas. This reaction produces or attracts electrons, generating electric current. An analogue current signal appears at the output of these sensors. The circuits are designed in such way that the flowing current generates voltage on a suitable resistor, and then after processing by an analogue-to-digital converter (ADC), so that the resulting voltage changes can be used to calculate the gas concentration.

The technical specifications of the ULPSM-NO2 968-047 sensor are as follows:

- Measurement range: 0–20 ppm
- Lower detection threshold: < 0.1 ppm
- Resolution: < 0.1ppm
- Accuracy: < ∓2% of measured value
- Time response: T90 < 30 sec.
- Operating temperature range: –20 to +40 °C

The target gas concentration is calculated by the following method:

$$Cx = 1/M \cdot (Vgas - Vgas0)$$

given that Cx is gas concentration (ppm), Vgas is signal output voltage (V), Vgas0 is voltage in a clean air environment (without analytical gas), and M is sensor calibration factor (V/ppm).
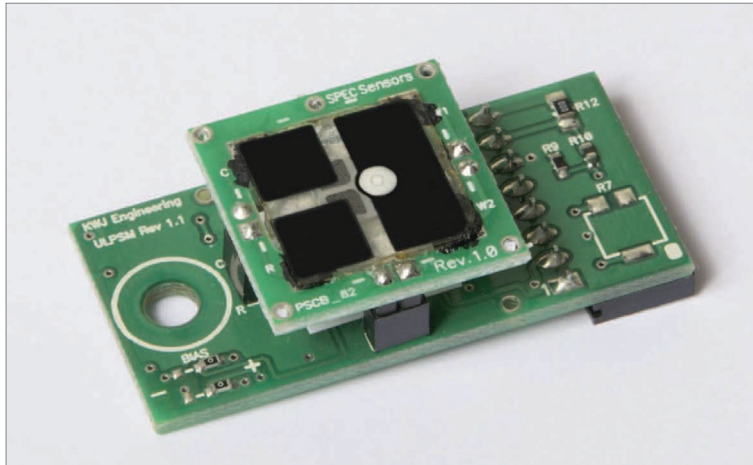
Source: Producer: Spec-Sensors, www.spec-sensors.com

Fig. 1. NO2 ULPSM-NO2 968-047 from SPEC Sensor

The M value is calculated by the following method:

$$M \text{ (V/ppm)} = \text{Sensitivity Code (nA/ppm)} \cdot \text{TIA Gain (kV/A)} \cdot$$
$$\cdot \, 10^{-9} \text{ (A/nA)} \cdot 10^3 \text{ (V/kV)}$$

the sensitivity code is given on the sensor label, and the TIA gain is a boost of the transimpedance of the amplifier degree (TIA) of the ULPSM circuit.

Table 1 contains standard gain configurations. The Vgas0 value can also be represented by:

$$Vgas0 = Vref + Voffset$$

where Vref is output voltage reference signal (V) and Voffset is voltage shift factor.

The Vref output serves as a reference voltage for zero concentration, even when the battery voltage drops. Vref *in-situ* measurement compensates for fluctuations in battery voltage or power supply, minimizing its effect on Cx gas concentration. You can use a differential amplifier or a measuring amplifier to subtract the Vref from Vgas. The Voffset takes into account the small voltage shift that is caused by a normal sensor background current and a circuit background voltage. Voffset = 0 is an appropriate approximation initially. For more precise measurements, Voffset must be quantified.

When the sensor is switched on and left to stabilize in a clean air environment (without analytical gas) and provides a stable output within the application's measurement targets, the Vgas value can be stored as Vgas0 and used in subsequent Cx gas concentration calculations.

Table 1. The transimpedance amplifier gain in the circuits of various sensors

Gas tested	TIA gain (kV/A)
Carbon monoxide (CO)	100
Hydrogen sulphide H_2S	49,9
Nitrogen dioxide NO_2	499
Sulphur dioxide SO_2	100
Ozone O_3	499

In the case of electrochemical gas sensors, the currents of several possible redox reactions are measured, and thus several possible similar gas types. There may be potential errors in the measurement of the target gas in cases where the presence of similar gases is possible. This is called cross sensitivity of the sensor. Table 2 lists the relative reaction of the commonly occurring interfering gases and the concentration at which the data were collected.

Table 2. Relative response of NO_2 sensor to interference gases

| Gas tested	Concentration (ppm)	Typical response (ppm NO_2)
Nitrogen dioxide NO_2	5	5
Hydrogen sulphide H_2S	5	< 0.02
Ozone O_3	1	< 0.1
Nitrogen oxide NO	5	< 0.1
Sulphur dioxide SO_2	5	< 0.02
Carbon monoxide (CO)	100	< 0.2
Chlorine (Cl)	10	< 0.5

Particulates sensor

The Sensirion SPS30 sensor was chosen for PM concentration measurement (Fig. 2). The measurement principle is based on laser scattering and uses the innovative Sensirion contamination-resistance technology (Fig. 3). The laser scattering principle and advanced algorithms allow for a very accurate and wide measurement range of particles in regard to air quality:

- mass concentration expressed in ($\mu g \cdot m^{-3}$): PM1.0, PM2.5, PM4 and PM10
- numerical concentration expressed in (number of particles cm^{-3}): PM0.5, PM1.0, PM2.5, PM4, and PM10

Source: Producer: Sensirion the Sensor Company, www.sensirion.com

Fig. 2. PM sensor SPS30
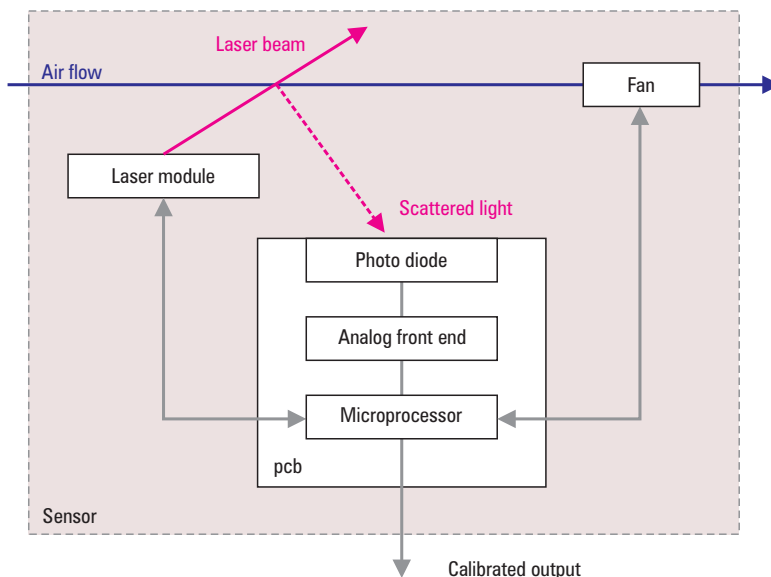
Source: Producer: Sensirion the Sensor Company, SPS30 sensor datasheet

Fig. 3. SPS30 sensor – block diagram

The technical parameters of the SPS30 and the particle measurement accuracy are as follows:

- Measurement accuracy $\pm 10 \mu g \cdot m^{-3}$; 0 to 100 $\mu g \cdot m^{-3}$
- Measurement accuracy $\pm 10 \mu g \cdot m^{-3}$; 0 to 100 $\mu g \cdot m^{-3}$

- Measurement range: 1 to 1000 $\mu g \cdot m^{-3}$
- Lowest particle measurement size: 1 $\mu g \cdot m^{-3}$
- The minimum interval of reading the measurements: 1 second
- Lifetime: > 8 years of continuous operation 24 hours a day
- Operating temperature range: –10 to +60°C

At the design and construction stage of the prototype, the metrological properties of the SPS30 sensor were assessed using tests conducted by the American government agency South Coast AQMD. The basic criteria for selecting a sensor for our application were: measurement accuracy, the minimum difference in measurement results between the units, resistance of the measurement to changes in temperature and humidity. The accuracy of Sensirion SPS30 was > 95% when the mass concentration of PM1.0 was < 100 $\mu g \cdot m^{-3}$ and decreased to ~77% when the mass concentration of PM1.0 was >100 $\mu g \cdot m^{-3}$. For PM2.5 by mass concentration, the accuracy ranged from 81% to 96%. The tests were carried out in laboratory conditions at 20°C and 40% relative air humidity using the GRIMM reference instrument. The difference in measurement results between the units did not exceed 2.4% at all particulate concentrations.
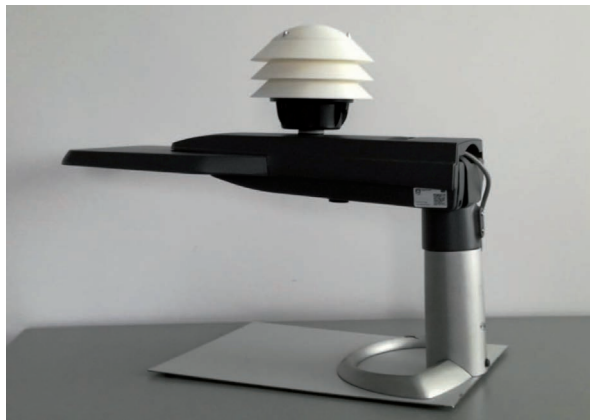
Measurement Node

Our project uses the existing, modernized or new urban lighting infrastructure. This solution has advantages of high density of lighting poles, access to electricity required for the measurement node, the installation height important for radio transmission between measurement nodes and no additional costs of raising a separate infrastructure. The use of Lumawise-Zhaga connectors (Fig. 4), which are becoming a standard in new generation luminaires, e.g. Philips luminaires, quickens the installation. As part of the tests, a special housing (Fig. 4 and 5) was designed and made of carbon fibre reinforced polymer. The housing provides IP67 protection and chemical protection. The sensors were attached to the measurement head (Fig. 4) and covered with a Stephenson radiation shield (Fig. 5). The operation of the sensors was governed by a Microchip PIC18LFxxxx microcontroller using the NanoWatt® technology (e.g. in sleep mode with a working "timer" the power consumption is 750 nA with a 3V supply), located on the motherboard along with the required system environment and fitting connectors for sensors. The unit responsible for radio transmission is the Xbee 868 LP radio module from Digi RF. The radio module works in the ISM band with the frequency of 868MHz and the power consumption in the sleep mode of 1uA. The operation of the measurement node is based on two events:

The first event is an interruption from the "timer", which wakes up the processor, then power is supplied to the sensors, and after the time required for stabilization of the sensors, the processor reads the measurement results (with interfaces appropriate for individual sensors), performs the averaging operation and updates the data packet prepared for sending. The operation time is approximately 1.2 minutes due to the long stabilization time of electrochemical sensors. The processor then goes into sleep mode. The project adopted a 5-minute measurement cycle.
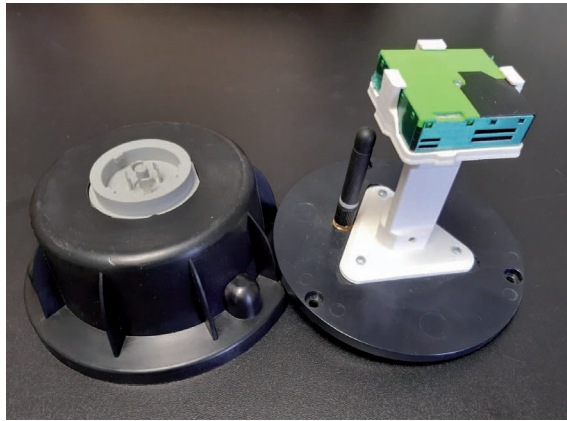
Source: Authors' own photo

Fig. 4. Housing with Lumawise-Zhaga socket and measurement head

Source: Authors' own photo

Fig. 5. Measurement node located on a street lamp holder

The second event is an interruption from a synchronously awoken radio module. In this event, the processor sends a data frame to the radio module via the serial interface. As the project uses transmission with ACK confirmation, the operation time depends on the size of the network and ranges from 50 ms to 1 s. Assuming that the transmitter and receiver are in the line of optical sight (LOS), 1 km point-to-point transmission range can be assumed, which, using the DigiMesh® network protocol, allows to cover a large area.

As part of the research, measurement nodes for air parameters were installed on Philips luminaires in Lumawise-Zhaga connectors in the John Paul II Park in Lublin (Fig. 6).

Source: Authors' own photo

Fig. 6. The measurement node is located on the John Paul II park lamp holder in Lublin

Edge Server

The edge server, which is also a DigiMesh® network coordinator (Fig. 7), is a single-board mini-computer based on the Sitara AM3358 ARM Cortex-A8 processor, with a clock rate of 1 GHz and 512 MB of RAM memory. The server is equipped with 4 GB Flash memory and USB interfaces, Ethernet and I/O connections. The computer used has a high temperature resistance (it can work in a temperature range from –20°C to 85°C). The operating system used is Debian GNU/Linux. The server is equipped with sockets for connecting a radio module that coordinates networks of measurement nodes and receives their data from a GPRS modem, providing access to the server, time series database, MQTT broker and ecosystem for creating user applications (e.g. Grafana, Node-RED). An external 5VDC/2.5A power supply is also provided. The radio module operated in the ISM band at 868 MHz with adjustable power from 2 mW to 32 mW. In one network identifier, after taking the network delays into account, the possible rational number of measurement nodes was estimated to be approximately 250. Communication with the server is possible via Ethernet, WiFi or GPRS transmission.

Source: Authors' own photo

**Fig. 7.** Sensor network coordinator and edge server

4. Field technical work

The installation in Lublin was a pilot and its main aim was to test the quality of radio transmission between a node and the edge server in real conditions. In Kraków, at 24 Jastrzębia Street, a measurement node was installed on the building's facade, powered by a special timer simulating the lamp's power supply mode. The nodes were powered by batteries charged while the lamp was on (in the evening and at night). The research consisted in observing the measurements made by a node in terms of the occurrence of anomalies in the measurements. To examine an anomaly, a comparison with the indications of the automatic station of the Provincial Inspectorate for Environmental Protection (Wojewódzki Inspektorat Ochrony Środowiska, WIOŚ) (national station code MpKrakBujaka) located on Bujaka Street at a distance of approx. 3 km and below the test point by approx. 30 m. The station performs automatic measurements of gases and concentrations of PM10 suspended dust. The measurement node was also monitored (tightness of its housing, preservation of the radiation shield during strong winds and precipitation).

Measurements in a node were performed at 5-minute intervals, and the data was sent to the server at 2-minute intervals. The measurement node has been operating continuously since November 2019. Data in the edge server's time series database is retained for 52 weeks. For the purposes of comparison with the WIOŚ station, averaging was run hourly.

5. Results and discussion

Sensirion SPS30 sensors have shown moderate to strong correlations with the reference instrument in the field for PM2.5 (0.64 < r < 0.85) and very strong correlations with the reference instrument in laboratory tests (r > 0.99 for PM1.0 and PM2.5). As to PM10, Sensirion SPS30 sensors showed weak correlation with the reference instrument under field conditions (0.10 < r < 0.25). The concentration of PM10 suspended dust did not show any particular measurement anomalies (Fig. 8) compared to the data from the WIOŚ station (Fig. 9). Measurements of nitrogen dioxide NO$_2$ showed some anomaly in the studied area (Fig. 10).
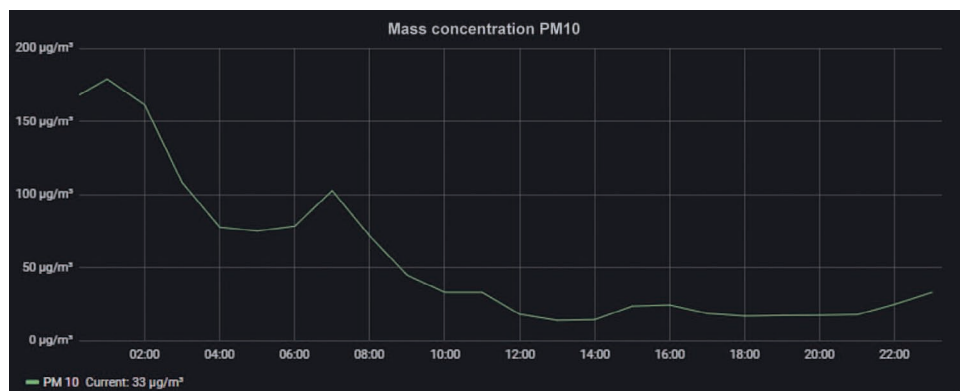
Source: Authors' own study

Fig. 8. Data as of 12 January 2021. 24 Jastrzębia Street measurement node – PM10
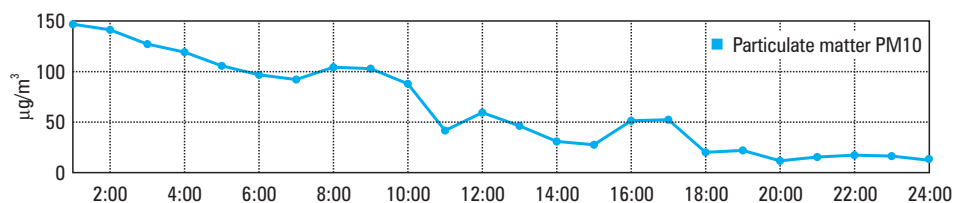
Source: Authors' own study

Fig. 9. Data as of 12 January 2021. WIOŚ station, Bujaka Street – PM10

The paper presents research with the use of Intelligent Wireless Sensor Network (IIBSC) infrastructure collecting data about the environment over time, informing local communities about the air quality to enable remedial actions. Each node includes a measurement head that uses chemical sensors to measure the following gases: ozone, nitrogen dioxide, carbon monoxide, sulphur dioxide and hydrogen sulphide, polymer

and MEMS sensors for temperature, humidity and pressure, and an optical sensor for solid particles.

Source: Authors' own study

Fig. 10. Data as of 12 January 2021. 24 Jastrzębia Street measurement node – NO_2

Measurements of nitrogen dioxide NO_2 were significantly overestimated with the same trend. This result requires additional research and discussion on the suitability of low-cost electrochemical gas sensors for air quality monitoring. It is important to take into account the price of sensors due to their large number as consequence of the assumed density of measurements in municipal installations.

Unusual peaks were observed in the measurements, not related to temperature, humidity or insolation (Fig. 10). Such incidents suggest an error in calibration of zero. These peaks interrupted the mean, therefore the data presented were not averaged (it may be a feature of the used device, a different one should be examined).

Particular attention should also be paid to the ozone cross sensitivity (Fig. 12). Installing an ozone sensor in the measurement head and registering both gases should be an appropriate solution. Measurements of temperature, humidity and pressure did not show too much fluctuation and were comparable with the meteorological data of WIOŚ with slight deviations stemming from the geographic location of the measurement point.

When comparing with the WIOŚ measurements, the conversion factor $ppbNO_2$ per $\mu g \cdot m^{-3}$ should be calculated according to the formula:

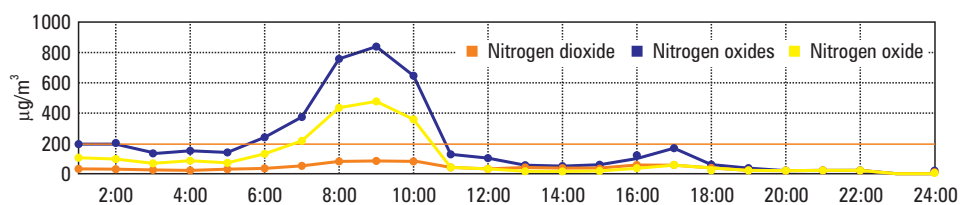$$\mu g \cdot m^{-3} = (ppb) \cdot (12.187) \cdot (M) / (273.15 + t)$$

where:

M – molar mass of gas 46.0055 g/mole for NO_2

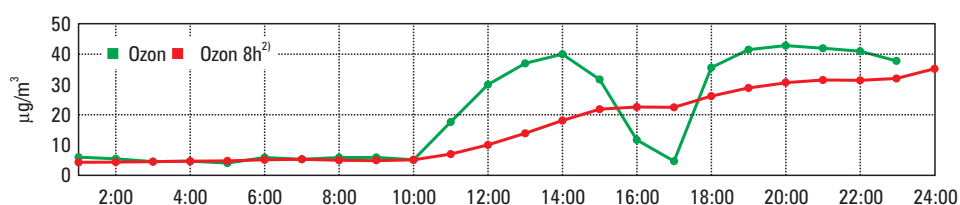t – ambient temperature for reference conditions of 20°C

pressure for reference conditions 101.3 kPa

1ppb = 1.9125 $\mu g \cdot m^{-3}$ (Fig. 11 and 12)

Source: Authors' own study

**Fig. 11.** Data as of 12 January 2021. WIOŚ station, Bujaka Street – measurements of nitrogen oxides NOx

Source: Authors' own study

Fig. 12. Data as of 12 January 2021. WIOŚ station, Bujaka Street – measurement of ozone O_3

The small number of stations spread over a large area resulted in a low measurement density, thus different modelling techniques must be applied to assess local pollution levels [Bai et al. 2018]. However, the accuracy of such models will deteriorate at smaller scales such as neighbourhoods, especially for pollutants that do not remain in the air for long periods, suggesting that such hazards will be more accurately measured in areas where there is a denser monitoring network , than in sparse network areas [Ailshire et al. 2017].

The results can be streamed directly into the society (Fig. 13), because a modern management system should be treated as a supporting service, which is in line with the concept of sharing economy. This procedure is important for optimizing the use of resources as a method in planning urban development. The created database will also be used for air pollution forecasts. The presented research method differs from current air pollution measurement techniques as it allows a detailed approach to measurement by providing metadata that describe the results with precision including variance, range, method detection limits and calibration. Metadata are important in determining the end use of air quality information. The developed methodology is in line with the new concept of citizen science, as some of the results can be managed by the user.
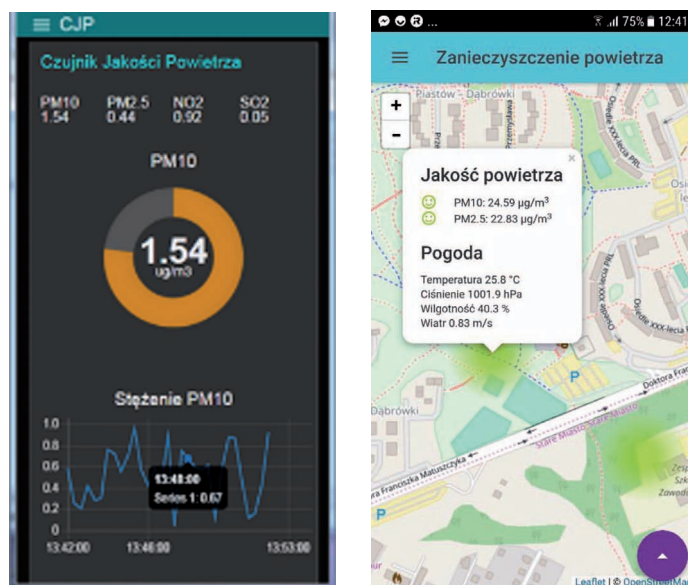
Source: Authors' own study

Fig. 13. Web application interface for data access from monitoring

6. Summary and conclusions

The results showed that measurement nodes operating in a network are efficient tools responding to the need for air protection in cities. The Intelligent Infrastructure Wireless Sensor Network (IIBSC) system for industrial and municipal installations will allow defining contaminated areas. By building such systems, a formal basis will be provided for improvement of the quality of life of residents in accordance with the principles of environmental protection. Fully automated services allow to enter data transparently, making it easier to trace graphically their dynamics on diagrams. A solution based on IoT monitoring is of great significance for promoting the right attitude in people, raising public awareness of the problems of air protection and their impact on the quality of life. At further stages of the research, however, other environmental sensors with higher measurement accuracy should be tested. Also, their location, closer to the reference station, will allow for better verification of the obtained results. Then, the created database will also be used for air pollution forecasts and thus the possibility of early warning of residents of areas at risk or taking more radical remedial measures by municipal services.

Sensor Network for industrial and municipal installations" (Inteligentna Infrastruktura Bezprzewodowej Sieci Czujników dla instalacji przemysłowych i komunalnych). Co-financing agreement RPMP.01.02.01-12-0384 / 16.

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