Current trends in network based air quality monitoring systems

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Abstract. Air quality is a serious problem in modern cities due to the significant impact of air pollution on the health of the population, the global environment and economy. Recent studies point to the crucial role of information about pollution on micro level, which translates into direct exposure of people to air pollutions. To provide such information, it is necessary to create real-time systems with large spatio-temporal resolution, since such information cannot provide conventional measurement systems performing measurements according to the legislative regulations of particular countries. Current researches focus on the concept of a next-generation air pollution monitoring systems that use new measurement technologies and techniques for communicating and delivering data. These systems can be complementary to traditional air quality monitoring systems. The article presents current trends in the world in this area – the example of static, social and vehicle measurement systems. There are also shown Polish initiatives related to environmental quality monitoring.

1. Introduction

Air quality is a very important issue. The level of its contamination is important because of direct impact on the rest of the environment, as well as on all living organisms, including human health.

Normally, the situation of air pollution is monitored by conventional air monitoring systems with stationary measuring devices (automatic and manual) performing measurements according to the legislative regulations of particular countries. In order to guarantee accuracy and quality of data, these instruments use complex measurement methods and many auxiliary tools such as temperature regulators, relative humidity controllers, air filters and calibrators. This enables monitoring stations to be highly reliable, accurate and capable to measure a wide range of pollutants.

In Poland, conventional environmental monitoring is carried out by the State Environmental Monitoring (SEM). The SEM is responsible for the collection, processing and distribution of environmental data. On the basis of conducted measurements are made assessments and forecasts of environmental quality. Locations of measurement devices belonging to the SEM have been established in places where data can be obtained from various types of environment.

The disadvantage of conventional monitoring devices is their large size, heavy weight, large cost of purchasing station and its maintenance. This leads to the rare deployment of monitoring stations. In Poland, there are just over 100 automatic in SEM (5 in the capital city – Warsaw), which primarily measure dust concentrations, sulfur dioxide, nitrogen dioxide, nitric oxide, carbon monoxide, benzene
and ozone. On the other hand, many of state-of-art monitoring devices in conventional stations are measuring with high precision in real-time substances that cannot be measured with low-cost sensors.

In order to stations be effective, their locations should be carefully thought-out, as the urban air pollution is strongly associated with human activity and depends on location (e.g. communication stations in places where notoriously formed congestion may show worse values than the average for the area) [1-4]. Changes in urban planning, human activities, or regulation can affect the concentration of air pollutions, which may require the transfer or addition of new stations. Such low spatiotemporal resolution suffices to monitor ambient background but is inadequate for the public to report on exposure of air pollutions and cannot indicate a level of health risk. In [5], the researchers noted that concentration of pollutants within a street can change over several meters and in seconds. Typical monitoring systems cannot detect this phenomenon due to their limited number of devices, availability of data, and lack of scalability. Moreover, if traffic or local low level emitters are the main source of pollution, which often occurs in urban areas, increased exposure of residents to pollution is widespread [6]. Evidences indicate that strong exposure or even short-term change of pollution can cause or worsen some health parameters or cause illnesses [7-9]. But, it must be remembered that conventional monitoring networks are the only valid method to measure air quality until now.

To increase the spatio-temporal resolution of air pollution information, researchers and local communities tend to expand their measurement capabilities by using, in addition to traditional devices, low-cost, portable devices and sensors. They are characterized by small size and fast response time. Owing to this, the rapidly growing number of devices equipped with sensors, organized in networks of different structure and complexity provide new insights into the environment. The collecting of information by citizens through smartphones and gadgets fundamentally changes the traditional way of gathering data. The number of devices connected to the Internet has exceeded the size of the global human population already in 2008 and is expected to reach 50 billion by 2020 [10]. Such technological evolution has become the foundation of the Internet of Things (IoT). IoT, as well as the development of sensor mobility tools, provides the components needed to build advanced monitoring platforms, including in particular platforms for environment [11].

The spread of sensors often causes that environmental information, such as air pollution, can be updated in minutes or even seconds [12]. Low-cost sensors usually are characterized by small dimensions, the ability to connect to a microcontroller and thus build modular measurement stations. This makes possible to use them in a variety of situations and to build measurement networks based on different ideas for different purposes. Cheap sensors offer mobility, easy configuration and reconfiguration of sensing nodes. On the other hand, they are not as accurate as the reference methods [13]. Some have limited sensitivity and may be affected by humidity as well as many other substances. Often the sensors of the same manufacturer and in the same series give different measurements [14, 15]. Many of these sensors do not provide information on the conditions under which the calibration was performed (if carried out), quality maintenance procedures, or descriptions when sensors may generate inaccurate readings. The potential of low cost sensors is huge, but they can only be used in combination with valid methods and not as alternative. Under certain conditions, networks based on cheap devices can fill the gap between conventional monitoring systems and air quality models [16].

The aim of this article is to present current trends in the structure of environmental measurement systems based on non-reference devices. Section 2 shows the classification of the networks based on the location of the measurement nodes. In the next section are described networks of this type built in Poland. The last section is a summary.

2. Trends in environmental measurement networks
Increasing availability of low-cost measuring devices explains the dynamic development of air quality measuring networks in recent years. In these projects, lower quality of measurements results in higher spatio-temporal density of measurements, so sometimes quantity is replacing quality.

Existing solutions can be divided into three categories [17]:

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- Static Networks (SN), where measurement stations are stationary and usually mounted on masts, street lamps or other selected locations by individuals, companies, local governments or NGOs,
- Community Networks (CN), where measurement stations are usually carried by representatives of a particular community (usually by volunteers or people who are sensitive to air quality or are involved in some kind of environmental issues),
- Vehicle Networks (VN), where measurement stations are mounted on vehicles (e.g. cars or public transport).

![Figure 1. Examples of devices belonging to different types of networks: left – static, center – community (from [29]), right – vehicle (from [34]).](image)

2.1. Static networks (SN)
In SN systems, sensor nodes are usually mounted on street lamps or walls. By using low-cost sensors, the number of nodes in SN systems is much higher than in conventional monitoring systems. Owing to them, SN systems can obtain information about air pollution with high spatio-temporal resolution. Information about air pollution is usually available to the public through websites, mobile applications, etc. Various types of sensors are used in this type of networks (e.g. optical, electrochemical, semiconductor). The accuracy of the results is much smaller than from conventional networks, but still relatively good in comparison with the network types described in the following subsections.

An innovative air pollution monitoring system in Mauritius is proposed in [18]. This system consists of measurement nodes and communication system that sends air pollution data to the server. In order to minimize energy consumption, a special algorithm for data aggregation has been proposed and implemented. Moreover, hierarchical routing protocols were used to maximize the energy efficiency of measuring nodes.

In [19] is proposed an urban air quality monitoring system based on Wireless Sensor Network (WSN). The system consists of a set of measuring nodes, gateway and central control systems managed by LabVIEW software. Measurement devices include CO sensors, batteries, and use ZigBee wireless connection. The system has been implemented for major roads in Taipei, and the results of the experiment have shown that the system can provide real-time information on air pollution.

In [20] is presented a monitoring system for indoor air pollution. The focus is on minimizing power consumption at sensor and network node levels. Several ways have been proposed that will significantly improve the sustainability of the monitoring system. Measurement nodes are equipped with several sensors (temperature, relative humidity, CO and motion sensors), ZigBee wireless connection and batteries. During the simulation, 36 sensor nodes were placed on one of the floors of a 4-storey building in Bologna.

Next real-time air quality monitoring system is presented in [21]. In this system, concentrations of O₃, NO₂, CO and H₂S are detected and transmitted every minute to the server via GPRS. Verified air pollution information is publicly available through web and mobile applications. To power sensor nodes were used solar panels. The system was tested in capital city of Qatar – Doha.
In [22] is presented the CitySense project. The article states that most of the WSN research teams evaluate their ideas on the basis of simulations, small test deployments, or large test deployments with a narrow range of target applications (one domain), which can lead to potential problems later in real world large-scale applications. The CitySense project's motivation is to create a city-wide wireless network that can handle a wide range of applications, including air pollution monitoring. Each sensor node consists of a PC with Linux, which uses 802.11 a/b/g protocols for communication as well as a wide range of sensors. Measurement units can be powered, for example, from street lighting. The project was implemented in Cambridge.

Another air quality monitoring system for industrial and urban areas is proposed in [23]. Measurement units consist of a set of gas sensors (O₃, CO and NO₂) and a ZigBee wireless connection. Verified air pollution information is available via e-mail, SMS and web application. Special mechanisms have been developed to effectively detect damaged nodes and to minimize the energy consumption of measurement devices. Moreover, a simple communication protocol is proposed, which seems to be effective in terms of network power consumption, network viability and data transfer.

In [24] is proposed the architecture of air pollution monitoring system for indoor and outdoor applications. The article presents the implementation of the system in indoor conditions. Each measuring node consists of several sensors and Wi-Fi. To reduce the impact of factors that affect the quality of the gas sensors, a neural network is used to obtain the correction values for temperature and humidity. Measured data is published on the website.

The advantage of this type of network is usually the great flexibility in a method of power supply. They can be connected to energy lines, and often, due to low power consumption, they are powered by batteries or solar panels. Similar to reference devices, they do not need to contain a localization module, because they are usually mounted permanently in one place. The use of street lamps, walls of buildings makes the weight and size of the device irrelevant, although they are usually significantly smaller and lighter than reference devices. Robust installation and most often difficult access for outsiders causes measurement nodes possible to be supplemented with equipment that support the quality of measurements. There are also many potential ways of communicating such devices with central server: communication of each device through e.g. GPRS or different mix of techniques (e.g. WiFi + GPRS, local, urban telecommunications networks, etc.).

The disadvantage of such networks, in a certain sense, is the inefficient use of sensors. Often, the sensor in a node is in sleep mode most of the time, because it is pointless to update the data in one place. The sensor makes measurements e.g. once a minute and remains idle for the rest of the time. In order to obtain the appropriate spatio-temporal coverage of area by measurements, it is usually necessary to place multiple devices. This increases the requirements (including costs) for maintenance and calibration of equipment, because specialists must visit all stationary measurement nodes, which is time-consuming and labor intensive. Another disadvantage is quite high requirement for network resources - in the extreme case, each device must have a module to communicate with the central server, in other cases, for example, if it is not possible to use the cellular network – it requires to build special wireless or wired networks.

2.2. Community networks (CN)
In CN systems, measurement nodes are usually carried by people – most often by volunteers or people for whom air quality is somehow important, so this type of network may have an impact on development "citizen science". Because of awareness of inhabitants and they engagement, this may influence their habits, making the air quality better through the learning effect. By using portable measuring devices and smartphones, users can gain, analyze and share information about air pollution [25]. Data may also be made available to the public via websites, mobile applications, etc.

In [1] is presented a mobile detection system (outdoor), called GasMobile, based on low-cost, low-power devices. The measuring node consists of a small, cheap O₃ sensor and a smartphone. The sensor communicates with the smartphone via the USB port. Data is transferred to the server via the cellular network. Measurement information is available through web and mobile application.
In [26] is proposed and described the implementation of the external noise monitoring system in Paris, called NoiseTube. Although it is not an urban air pollution monitoring system, the architecture and implementation of the system are very similar to it. Each measuring node is an intelligent smartphone. Data about noise (with location from the built-in GPS module) is collected by the built-in microphone. Data is transferred to the server via the cellular network. Information about measured noise levels is available publicly via the website and mobile application.

The P-Sense air quality test system for outdoor use is presented in [27]. Each node consists of a set of sensors (CO₂, CO, VOC, H₂, temperature and relative humidity) and Bluetooth. Data acquired by sensors is transferred to the smartphone via Bluetooth and then is sent to the server. Information about air pollution is available to the public through web and mobile application. The article also pays attention to several research issues that need to be resolved before the practical implementation of the P-sense system.

In [28] is presented a personalized indoor air quality detection system - MAQS. Each measuring node consists of several sensors (including CO₂, CO, O₃, temperature and humidity) and Bluetooth. Information about air pollution is available to the public through web and mobile application. Three new techniques have been proposed and implemented to improve data accuracy and energy efficiency.

In [29] is presented a system that primarily measures volatile organic compounds (VOC) with high selectivity and sensitivity. Nodes also have the ability to measure temperature and relative humidity. A mobile application with quite advanced data visualization has been implemented to read the data. The prototype version of the system has been tested at the University of Arizona.

Another hardware-software platform for air quality monitoring in outdoor applications, called N-SMART is presented in [30]. The measuring node consists of sensors (CO, NOₓ, temperature) that communicate with the smartphone via Bluetooth. The article also discusses several community-based measurement challenges, such as unpredictable user behavior, movements, and privacy issues.

The advantage of this type of network is primarily the ability to integrate a measurement station, e.g. with a smartphone, so that the GPS module of the mobile phone and the cellular network is used, and sometimes even the computing power. Such integration has a positive impact on cost. Due to the fact that the device is carried by the user, it is possible to provide information about the closest environment of the “carrier”. In other words, the user has the opportunity to receive information from the place where he is located.

An important advantage, from a network operator's point of view, is that the cost of mobility and data transmission is borne by the user, and thus such a network is “community”. Without the participation of users, the scale of the system would often be too costly and impossible for one entity (e.g. NGO).

Advantage and disadvantage this type of networks is the automatic “placement” of nodes. Measurement nodes are densely distributed in places where people gather. In this case, it is possible to obtain a higher spatial resolution in places of particular relevance to the inhabitants. The disadvantage in such cases is the fact that it is possible to obtain a small number or no measurements in an area where there is no one with a mobile measurement node. The great advantage of this type of network is also the high mobility of measuring nodes, which increases the coverage of the measurement area and the ability to study population behavior. On the basis of the data, it is also possible to collect other types of information, such as traffic patterns, interaction between air quality and people behavior, etc.

The main disadvantage of community networks is the low accuracy and reliability of the data. The network operator has no information about place, where the device is located - measurement nodes are often placed in pockets or bags. Moreover, users spend considerable time indoors and inside cars. Incorrectly transferred, stored and maintained measuring devices affect the quality of results. In such situations, it is practically impossible to calibrate the sensors professionally. Having such a device requires a user's permission to share their location, which for many can be a problem because they do not want to betray their privacy.

The fact that this type of device is designed to be carried has an influence on significant weight and size limitation - the user will be interested in the measuring device when it is small, lightweight and...
easy to maintain. And that in turn has a direct bearing on the accuracy, reliability and number of sensors the device can be equipped with.

2.3. Vehicle networks (VN)

In VN systems measuring nodes are placed on vehicles, usually on public means such as buses, trams, trains or taxis. Owing to the use of inexpensive sensors and vehicle mobility, one measurement node can test a significant area [31]. The data collected in this way is generally available to the public through websites, mobile applications, etc.

In [12] is presented a project of distributed infrastructure based on WSN for real-time monitoring of air pollution. This system uses two types of measurement nodes, namely mobile nodes and static nodes. The measuring node allows measurements of SO$_2$, NO$_x$, O$_3$ and VOC, and also allows connection to other nodes via ZigBee or Wi-Fi. Mobile nodes are mounted on public transport and send data to static nodes. Nodes can perform data acquisition and integration, and then transfer data to the central server. The paper also describes a distributed data-mining algorithm to identify the relationships between urban transport and the environment. Currently air pollution information is only available to the research team.

Next example of an existing mobile sensor network is BusNet in Sri Lanka [32]. The network consists of Crossbow MICAz sensor nodes equipped with GPS modules and sensors for air pollution, mounted on buses. Data, together with the GPS coordinates, is transmitted by radio to the access node. Data exchange occurs only when the sensor node is within the access node.

Another example of a mobile sensor network is the MESSAGE system (Mobile Environmental Sensing System Across Grid Environments) implemented in London. Mobile sensor nodes have been installed on public transport vehicles, private cars and bicycles. The system monitors concentrations of pollutants such as carbon monoxide and nitrogen dioxide. MESSAGE also collects data on temperature and humidity and noise levels [32].

In [2] is shown MAQUMON - Mobile Air Quality Monitoring Network. This system consists of car-mounted measurement nodes measuring O$_3$, CO and NO$_2$ concentrations in Nashville. Each sensor node uses the GPS module to obtain time and location information and Bluetooth to communicate with the laptop inside the car. The collected data is then transferred to the server via Wi-Fi connection. Information about air pollution is available through the LCD display mounted on a measuring node or via a web portal.

In [31] are proposed and presented test results of a mobile prototype of a measuring node that can be mounted on a vehicle. The measuring node consists of a set of sensors (CO, PM, NO, NO$_2$ and VOC), GPS module and GPRS or Wi-Fi module for communication with the server. The analyzed data is publicly available through a web application. In the article is stated that the proposed system is characterized by greater spatial coverage.

Another vehicle-based system is presented in [33]. The proposed architecture can integrate various types of mobile measurement nodes, including the proposed CO and PM sensors and the GPS module. Real-time data is received and analyzed by a server located in the cloud. Information about air pollution is available to the public through web and mobile application. The system has been tested in New York.

In case of mobile devices mounted on public transport vehicles, occurs the problem of determining the number of devices needed to cover the desired area of the city by providing the appropriate frequency of measurements. Analysis of this type of problems on the example of the tram network in Zurich is in [34].

The advantage of a vehicle networks is that usually there are no connection and power consumption constraints since the measurement stations are mounted on vehicles that can directly get the electricity. There are not too many restrictions on the weight and size of the devices - they are quite small compared to the means of transport. Like for stationary networks, it is possible to equip a measuring station with additional devices to obtain better data quality, and it is also possible to use
more professional, and therefore usually larger devices. This positively affects the ability to obtain fairly accurate and reliable data.

One of the main advantages of this network type is the high mobility of measuring nodes. Vehicles make possible to obtain a large area that is covered by measurements. In case of placing devices on public transport vehicles it is possible to obtain a fairly even coverage of the area by measurements. It is easy to carry out maintenance and calibration of the sensors. Vehicles equipped with measuring nodes can be stationed in a specific location - for example, buses in a depot. Qualified workers can then carry out maintenance work on many measurement nodes grouped on a small area.

The disadvantage is an uncontrolled or difficult to control mobility. In case of public transport, the routes of the measuring nodes are pre-defined, but for various reasons there may occur a concentration of multiple nodes in a small area (for example, because of a traffic jam). On the other hand, some places may not be visited at all. In situations of using vehicles other than public means, social network phenomena may occur – namely redundant data collection when vehicles stay in traffic jams or park in parking lots. Another disadvantage is cost efficiency - to mount the device and make the power supply may be necessary to make some changes in a vehicle, which sometimes may not even be possible, for example, if a vehicle is under warranty. The assembly site must be selected very carefully so that the vehicle's own emissions do not affect the readings from the device. Problems may require the use of communication and localization devices. The mobile device system requires GPS and wireless or cellular access modules. If it is not possible to use publicly available networks, it is necessary to build special solutions. Sometimes, standard network connections may not be available due to vehicle mobility. These networks are also featured by variable spatio-temporal resolution. Typically, larger spatial coverage is achieved at a lower temporal resolution.

3. Environmental measurement networks in Poland

Also in Poland, over the past few years, measurement networks based on non-reference devices began to be created. These are usually combination SN and CN networks. People buy measuring devices, mount in a specific location, then make and share measurements. Probably in some of these networks, devices can be mobile.

![Figure 2. Examples of Polish air quality monitoring initiatives (Airly, Ecolife, Smogly, LookO2, Syngeos).](http://airly.eu/)
Very similar idea characterizes the Ecolife\(^2\) system. It also consists of dedicated devices that together create measurement network. The devices are generally intended for indoor use. Measured parameters are PM\(_{10}\), PM\(_{2.5}\), PM\(_1\), VOC, temperature and relative humidity. Measurements are presented through the appropriate colors on the device housing (red - alert, green - norm), through the "cloud" to the owner's smartphone and to the web application. There are no marked measurement points (access 6.06.2017) on the map available on the project site, perhaps measurement data is available after purchase subscription.

A slightly different idea is the Smogly\(^3\) initiative. Also in this project, the main goal is to build a community network, but the developers go a step further and all elements of the system are available as "open" - open source for software and open hardware for measuring device. All documentation is put in Github, so that the user has an access to a complete technical description, for example, measurement station components, and even links to individual offers of particular parts on Alibaba. The authors suggest to use the Plantower PMS3003 sensor, which costs about $15, making it one of the cheapest sensors in the low cost sensor family. Unfortunately, the quality of measurement given by the authors (2%-5% in relation to reference devices) is not to be obtained by the sensor of this class.

Dedicated measuring device is offered in the LookO2\(^4\). It measures PM\(_{10}\), PM\(_{2.5}\), PM\(_1\) concentrations, is powered by the MicroUSB port, has an LED notification system and like the others - assumes that all users will share the results of the measurements. Measurements made by each device are available on the map. In June 2017 on the map there were about 100 measurement points concentrated mainly in the southern and central parts of the country. After clicking on a point marker, additional information is displayed. It is shown, among others the exact location of the measurement point, the measured dust values for the last hour, and the hourly averages of dusts, temperature and humidity for the last 24 hours. Additionally, there is also shown the value of the air quality index (based on CIEP air quality index).

The Syngeos\(^5\) project offers the largest group of measured substances – over 20, there are also available sensors measuring water parameters. According to information on the website, the platform is built on communication standards that allow build IoT networks. Currently (June 2017) the project is probably under construction and beyond the general characteristics there is no detailed information on the implementation and operation of the system.

4. Conclusions
The main features of each network type are presented in the table below.

| Table 1. Comparison of the characteristics of presented types of networks. |
|---------------------------------------------------------------|
| SN | CN | VN |
|-----|-----|-----|
| Mobility | high, predictable | high, but usually unpredictable | highest, sometimes unpredictable |
| Temporal resolution | medium | high, but usually predictable | high, but sometimes unpredictable |
| Costs | easy | sometimes impossible | easy |
| Maintenance | highest | lowest | medium |
| Data quality | medium | highest | medium |
| Exposure calculation |

\(^2\)https://ecolife.eu.com/  
\(^3\)http://smogly.pl/  
\(^4\)http://www.looko2.com/  
\(^5\)http://www.syngeos.pl
The development of alternative air quality monitoring networks is very important from the perspective of city residents. Researchers predict that real-time air pollution information can help to advise the public on appropriate actions according to their individual health needs (e.g. asthmatics can choose an alternative route to minimize personal exposure to air pollution) and raise public awareness of air pollution, which in turn will lead to a change in certain habits (e.g. drivers through the right driving style can reduce the emission of pollutants). As shown in the article, these networks are developing very intensively, both in Poland and in other countries. They also take a variety of forms, depending on local needs.

Although quality of data obtained in this way is worse than that received from reference devices, the fact of increasing interest of surrounding environment can have a positive impact on human behavior and put pressure on the authorities to improve air quality. It remains to be hoped that the demand for sensors will also mobilize manufacturers as well as the scientific community to build solutions of ever higher quality.

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