High-Resolution Large-Scale Air Pollution Monitoring: Approaches and Challenges

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ABSTRACT

The measurement of environmental data in city areas has become an important issue to municipalities due to several national, European and even international climate directives. However, fixed measurement stations are inflexible, cost-intensive and limited to monitoring environmental data in distinct key areas only. Large-scale data collection with a high spatial resolution requires mobile measurements, which are an active area of research but still offer many challenges. In this paper we give an overview of current approaches and challenges.

Categories and Subject Descriptors

Computer Applications [**PHYSICAL SCIENCES AND ENGINEERING**]: Earth and atmospheric sciences

General Terms

Design

Keywords

Air Pollution Monitoring, Environmental Data, Mobile Measurements, Air Quality Monitoring, Delay Tolerant Networks, DTN

1. INTRODUCTION

Air pollutants caused by vehicular and industrial emissions have a negative effect on human health. Especially in agglomeration areas air pollution may have a direct impact on mortality [1, 2]. In combination with certain geographical and meteorological conditions, air pollution causes dangerous smog. In 1952, the Great Smog of London caused 12.000 premature deaths [3]. This cataclysmic event initiated emission research, government regulations on air pollution and monitoring of air quality. Today, most developed countries have implemented effective processes to control air pollution. These comprise long-term measures such as land use planning, regulation, and tax incentives for clean air technology, as well as short-term measures like traffic management and road space rationing. Nevertheless, it is not uncommon that legal threshold limits are exceeded.

Air pollution control requires constant air quality monitoring in order to develop and evaluate pollution countermeasures. The state-of-the-art approach to monitoring is the sparse deployment of fixed measurement stations. However, it is more desirable to acquire data with a high spatial resolution, but that would require a large amount of well distributed measurement stations, and therefore be very expensive. A more cost-effective approach is to perform mobile measurements. By constantly moving the monitoring equipment, a high spatial resolution can be gained with just a few measurement devices. In the past this approach was not feasible due to the physical dimensions of the monitoring equipment and due to the lack of appropriate mobile communication infrastructure. Nowadays, advances in sensor design, mobile computing, and pervasive mobile communications make it possible to implement measurement devices that can be mounted to vehicles or even be integrated into smartphones.

This paper gives an overview of the multidisciplinary field of mobile air pollution monitoring. We present several different approaches and research projects. The purpose is to stimulate research on systems and architectures for high-density and large-scale air pollution monitoring.

2. APPLICATIONS AND REQUIREMENTS

Air pollution monitoring is implemented for various reasons with different requirements. The most important application is probably to check if legal limits are exceeded, so that countermeasures can be initiated and the population can be warned if pollutant values reach a health critical level. Often laws and directives make pollution monitoring mandatory [4, 5, 6, 7]. Therefore, the measurement equipment and process used for this purpose has to be standardized, calibrated and certified for legally valid results.

Monitoring is also necessary to evaluate measures against pollution. For this purpose, it is important to record weather conditions, since wind, humidity and precipitation have a significant influence on the distribution and accumulation of air pollutants. Therefore, results of different points of time are only comparable at similar weather conditions. Another application is land-use planning and traffic planning with the aim to reduce pollution in areas in which the levels are regularly exceeded. This requires that local pollution and its

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causes are examined, and that the effectiveness of the measures has to be evaluated afterwards. Usually several measurement campaigns with portable equipment are required to obtain a spatial resolution high enough to assess local effects. An application with similar evaluation requirements is dynamic road traffic control. The basic idea is to develop traffic control strategies that help to avoid exceeding limits, such as traffic redirection or reduction in critical areas, ban of certain vehicles from low emission zones[1], or emergency measures like road space provisioning and even general driving bans.

An important application for the citizens is being informed if pollutant values are getting critical. Especially very young and elderly people, but also patients suffering from heart or breathing conditions are more sensitive to pollutants. But also healthy people should avoid to work out at places or at times of high pollution. Therefore, such a citizen information system needs to distribute localized and personalized information. Existing systems use websites with interactive maps and short message services[2]. Future systems will likely be implemented as smartphone apps.

3. DATA ACQUISITION APPROACHES

There are several approaches to the acquisition of measurement data on air pollution. Currently, the measurement of air pollution is realized on the basis of few fixed measurement stations. The concentration of harmful substances in the air is predicted based on the measured data in combination with complex mathematical models. Nevertheless, this predictive approach goes along with inaccuracies and is not very well suited for realizing a sustainable traffic management in order to avoid exceeding prescriptive values and a complete information of the population. Deploying additional stations to obtain a higher spatial resolution is not really an alternative, since this would require high investments. But instead of using only a few fixed measurement stations, a mobile measurement network can be used to gather area wide measurements of the air pollution. Both the fixed monitoring stations and several approaches to mobile measurement are described in the following.

3.1 Monitoring Stations

Monitoring stations are widely used and well proven. They usually comprise some kind of container or shelter with a size of several cubic meters, which holds racks of measurement devices and a supply of calibration gases and other consumables. Air inlets feed the sample gas from the outside to the measurement devices for NO, NO_x, O_3, CO, CO_2 and particulate matter. For the particular matter usually only the amount for different classes of particular size is measured. The composition of the particulate matter is then determined off-site, by chemical analysis of air filters which collected particular matter at the measurement station. A local computer collects and processes the measurement results, which are then transmitted to a remote central database. Moreover, a measurement station also comprises meteorological devices, since weather has a significant influence on the concentration of emissions. Usually, there are at least devices for wind speed and direction (anemometer and a wind vane), as well as humidity and precipitation (hygrometer and a rain gauge), and temperature.

For economical reasons, monitoring stations are very sparsely distributed. It is often criticized that the local results are not representative and therefore not necessarily correlate with the pollution that citizens are exposed to in daily life. However, it is possible to use numerical models to extrapolate air pollution for other locations based on meteorological data, although the accurateness of these models is hard to verify. Nevertheless, monitoring stations are a proven, reliable technology and the state-of-the-art method to gauge pollutants.

(a) aerosol monitoring station

(b) air quality monitoring at an airport

(c) measurement equipment within a monitoring station

Figure 1: diffent types of fixed monitoring stations developed and manufactured by Breitfuss Messtechnik GmbH, Germany

[1] `http://www.tfl.gov.uk/roadusers/lez/default.aspx`
[2] `http://airtext.info/`

3.2 Mobile Devices and Crowdsourcing

The idea behind using mobile devices (such as smartphones or stand-alone mobile sensors) is to make use of peoples' daily mobility. The main advantage is that this mobility comes free (people move anyway) and that measurements are performed where people are, therefore the results correlate to real pollutant exposition (what people breathe in). Furthermore, a large amount of well distributed measurement values can be gained if there are multiple users carrying sensor-enabled devices. However, there is also a strong challenge: People have to be motivated to carry these mobile devices. Moreover, performing a measurement may require user interaction. Therefore, users have to be offered some kind of incentive for participating in the crowdsourcing of air pollution measurements. Another challenge is the development of sensors that are small enough for the integration into smartphones. This is already possible for some pollutants like CO, CO_2 and NO_2, but sensors for some other pollutants (e.g. particulate matter) are a big challenge. There are several approaches to mobile measurements, which range from off-the-shelf smartphones to dedicated mobile sensors.

In [8] a very notable approach to measuring particulate matter concentration is proposed. Its strength is that it uses off-the-shelf smartphones without any additional hardware. The neat trick is using the camera: a picture of the sky is sufficient to gauge atmospheric visibility, which correlates with particulate matter concentration [9]. Determining the exact position and angle at which the image is taken is quite easy, since nowadays almost all off-the-shelf smartphones feature GPS-receivers as well as a compass and accelerometers. This data and the image is transmitted to a central server, which performs most of the processing tasks. The remaining challenges of this approach are that it requires a radiometric calibration of the camera and that the model that derives pollution from visibility has not yet been verified. However, the proof-of-concept evaluation shows very promising results.

In the CamMobSens[3] project dedicated devices were used for portable measurements of CO, NO and NO_2. These devices connect via bluetooth to the users mobile phone, in order to upload the measurement results to a database. The developed visualization is based on Google Earth. Another project using dedicated devices is Common Sense[4][10], in which a cellphone-sized device with sensors for CO, O_3 and NO_x was developed. At the moment a deployment at a community action group is prepared.

3.3 Vehicle mounted Devices

Measurement equipment can also be mounted on vehicles to obtain a high spacial resolution of the measurements. The advantage over user carried mobile devices is that there are not so many restrictions regarding physical dimension and energy consumption. However, it is not possible to measure an individual user's exposition. On the other hand, vehicles move at higher speeds and larger distances, thereby enabling a much higher coverage area per device. Moreover, it is possible to chose special purpose vehicles with high usage rates that operate in the target areas, such as sweep vehicles [11] or public transport vehicles [12]. Several projects that follow this approach are introduced in the following sections.

[3] http://www.escience.cam.ac.uk/mobiledata/

[4] http://www.communitysensing.org/

3.3.1 Info-Regio

The Info-Regio [13] project has been carried out in the run-up to the world fair EXPO 2000. Its aim was to develop a sustainable and efficient traffic management system. Although this project finished ten years ago, it is notable for two reasons. Firstly, because it has been shown that the approach of monitoring environmental data on moving vehicles is feasible and a sensor prototype was developed. And secondly, because the project was not fully realized due to problems with the communication infrastructure. Therefore, this project is a nice example showing that multidisciplinary research and engineering efforts are required for the realization of mobile air pollution monitoring.

Being the first project which successfully developed and deployed a suitable bus mounted sensor was one of the projects' achievements. For this purpose an air inlet was installed at the roof of a public transport bus. From the inlet the sample air was pumped through a hose to a carbon monoxide measurement device. Two fixed measurement stations were used for comparison and showed the feasibility of the mobile measurements in an extensive evaluation.

An unsolved problem was the communication infrastructure. It was planed to use the existing private mobile radio of the local public transport carrier. However, the project members realized very quickly that the bandwidth of this private mobile radio was not sufficient to transfer the additional measurement information. At the end of the project, two options for realizing the data exchange remained. On the one hand, the measured data might be transmitted via cellular radio networks at high operating costs. This possibility was used for the system's prototype, but was not feasible for the planned large and long-term deployment. On the other hand, the project partners proposed to install a separate private mobile radio system dedicated to the exchange of measurement data. However, this solution would have led to high investment costs and was therefore not realized.

3.3.2 AERO-TRAM

In the AERO-TRAM[5] project, measurement equipment similar to that of monitoring stations was installed on a tramway in Karlsruhe, Germany. This project focuses on very precise measurements, therefore the equipment choice was relatively uncompromising: the roof-mounted container weights roughly two metric tons and includes a supply unit with consumables such as calibration gases and chemicals. The lab-quality equipment measures NO, NO_x, O_3, CO, CO_2 and particulate matter. A custom, carefully designed aerosol inlet regulates volume current. This unit is mounted in the front of the tramway's roof and avoids that emissions from the tramway are influencing the measurements. Moreover, the constant volume current ensures speed-independent measurement results.

The tramway operates on a 30 km long route that covers the city center as well as the hinterland. This allows for an analysis of urban effects and the spatial distribution of pollutants. Moreover, models used to extrapolate a spatial pollutant distribution from stationary measurements can be evaluated. The results of mobile measurements are also of great value for evaluating the validity of stationary measurements, since critics often question the representativeness of local pollutant values.

[5] http://www.aero-tram.kit.edu/

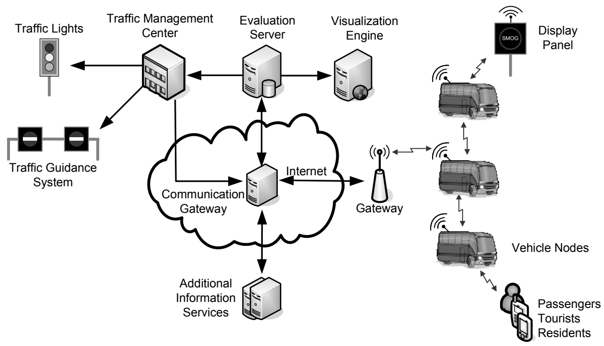

Figure 2: Basic architecture of EMMA

In conclusion AERO-TRAM is to the best of our knowledge the most precise and sophisticated design for mobile air pollution monitoring, but also the largest, heaviest and most expensive solution. However, these drawbacks are unavoidable, because the high precision is required for the purpose of evaluating the effectiveness of stationary measurements and distribution models.

3.3.3 EMMA

EMMA (Environmental Monitoring in Metropolitan Areas) [6] [14, 12] builds on previous projects that have shown the feasibility of mobile air pollution monitoring. Its focus is not on the development of sensors and transducers for environmental data, but on implementing a cost efficient, self-organizing and maintenance-free communication infrastructure for large scale deployments. In previous projects like Info-Regio, communication was an unsolved problem. It turned out that there was no technology with both low investments and low operational costs. In consequence a profitable operation was not possible.

In EMMA, a decentralized architecture for environmental monitoring with vehicle mounted sensors using Car2X communication techniques was developed. It can be integrated in ,e.g., existing public transportation networks by equipping buses with sensor nodes that communicate with each other. The system is able to obtain area-wide measurements that are distributed by an ad-hoc network. Buses provide almost complete coverage of the whole metropolitan area (at least for mayor roads), so that a relatively small number of measurement devices is sufficient and hardly any data network infrastructure is needed, as the sensor nodes spread their data all by themselves. The whole system is self-organizing and thus requires little to no setup efforts. Whenever a node discovers another node within its transmission range both start the data exchange process. Beginning with the newest set of measured data, each node sends all stored information to every other node within communication range. This makes EMMA an inexpensive and flexible solution that is easy to implement.

4. DATA TRANSMISSION, PROCESSING AND PRESENTATION

High spatial resolution measurements with mobile devices require a high sampling rate of the moving sensor. Therefore, a large amount of data needs to be transmitted to a central database which stores and processes the results. The amount of data of a single sample is in the order of some hundred bytes. It contains the GPS position, date and time, sensor identifiers, and readings of several sensors. A realistic sampling rate of current sensors is between two seconds for carbon monoxide and six seconds for particulate matter. With regard to the amount of data generated by a single mobile device the requirements on the communication system are not to demanding. Nevertheless, a large-scale deployment with many vehicles puts high demands on the communication system, because wireless communications is a shared medium. Moreover, it is very important that the communication system has low operational costs.

The load on the central database scales with the amount of vehicles. For a large-scale (e.g., nation-wide or even planet-wide) deployments it will be necessary to implement a hierarchical architecture, e.g., with databases limited to certain regions. This approach would prevent bottlenecks, but the drawback is that a cross-region database request would suffer from bad performance. However, such requests are relatively rare, since the usual use-case is location-centric.

Pollution alerts and the visual representation of the pollution is important for the information of citizens. The visualization engine's task is to aggregate this data and prepare it in a fashion that allows the key implications to be understood intuitively. As a lot of information in this data is location specific it is especially useful to chart it on a map. That way it is easy to get a global overview but also have location specific details. It is necessary to make this map easily accessible to residents as well as to visitors of a city. This can be realized, e.g., via Internet services, display panels or novel mobile information systems such as apps for smartphones. Thus, people who are sensitive to specific pollutants can easily get informed about the current situation. Such maps are also powerful tools for traffic-flow and land-use planing.

Figure 3: Vehicular measurement and communication device

5. CONCLUSIONS

There are several promising approaches to mobile air quality monitoring. The basic feasibility of small sized sensors mounted to vehicles or as stand-alone mobile devices has been shown. However, the demanding requirements of a large-scale deployments need a joint effort of multidisciplinary research. In the near future, datasets of first prototypical deployments will be available, and hopefully a common data repository will be established. This data will be a key contribution to the understanding of the complex distribution, aggregation and resolving of pollutants in urban areas.

[6] `http://www.ibr.cs.tu-bs.de/projects/emma/`

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