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Distributed, low-cost particulate matter sensing: scenarios, challenges, approaches

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Abstract

The observation and control of particulate matter (PM) pollution in ambient air is increasingly being recognized as an important topic in societies across the globe. Classic measurement approaches provide accurate daily means but are static, expensive and suffer from low spatial resolution and high latency. Distributed measurement grids using real-time capable instrumentation not only can provide spatio-temporally fine-grained readings, but also have the potential to enable novel applications. However, in order for them to be feasible, sufficiently accurate low-cost measurement devices are needed. The noise as well as typically low sensitivity and stability of commercially available low-cost dust sensors result in additional challenges that need to be solved when basing distributed measurement grids on them. This includes signal processing, sufficiently frequent recalibration, suitable data processing and – where applicable – incentivization of users. In this paper, we present different scenarios enabled by distributed PM measurement, discuss the major challenges in such systems and show different approaches that can be used to address them.

Keywords: Environmental sensing; fine dust; pervasive sensing; low-cost sensors; overview.

1. Introduction

In the past, medical science has revealed severe adverse health effects of particulate matter (PM) pollution. As a result, societies around the globe have developed an increasing awareness and people have started to gain an interest in the levels of air pollution that they are exposed to. This is especially true for large metropolises with relatively bad air quality. In the last decade, governments around the world have implemented regulations regarding the permitted PM concentrations, based on the size classes PM₁₀ and/or PM_{2.5}, as defined by the U.S. Environmental Protection Agency (EPA). Basis for the classes – and therefore

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the standard method of monitoring the limits – are gravimetric measurements, which provide 24-h-mean values. As monitoring stations are large, static and expensive, they are sparsely deployed and readings are often only available after a delay. Distributed networks for ambient fine dust monitoring have the potential to deliver readings with a high temporal and spatial resolution and low latency which enable novel application scenarios. However, they entail a number of challenges that need to be addressed and cannot be viewed decoupled from one another and also depend on the specific application scenario:

- **Instrumentation:** The key component of any measurement system is the employed devices or sensors and there are different classes to choose from. In our work, we focus on very cheap commercial off-the-shelf (COTS) dust sensors.
- **Calibration:** Depending on both the employed instrumentation and the collection scheme, suitable means of (re-)calibrating and maintaining the devices, ideally in-situ and with as little user involvement as possible, may need to be implemented.
- **Coverage:** Directly affecting the choice of instrumentation is the implemented collection scheme, i.e. how sensors are deployed and who the sensing “agents” are. The latter also may raise *Privacy* issues as resulting second-tier challenge.
- **Processing:** The former aspect is also related to selecting suitable means of data dissemination, interconnecting the devices and intelligently processing their data. Again, protecting user *Privacy* may present itself as a resulting challenge.
- **Incentivization:** Whoever carries out the actual sensing may need to be motivated to do so. If end-users are involved in the data collection, resulting challenges are general *Usability*, suitable interaction design and appropriate, flexible *Visualization*. Gamification could be a possible approach to complement intrinsic motivation with external incentives, as discussed below.

This work discusses interesting scenarios for distributed fine dust sensing and compiles some approaches that can be employed to address the aforementioned challenges.

2. Scenarios

Distributed particulate matter monitoring can be applied to a wide range of scenarios. The classic use case is *regulatory compliance monitoring*, but the accuracy and stability requirements are very high. Nonetheless, complementing classical measurement grids with fine-grained low-cost dust sensing may provide municipalities with important information, ranging from *source / hotspot detection* to means for finding and selecting areas in which measurements with more accurate measurement equipment seem prudent. Another novel use case would be enabling *reactive systems*, such as dynamic pollution-based traffic control, to not only monitor, but also effectively combat PM pollution.

For end-users, cheap measurement devices can be used for *personal monitoring*, as informal readings generally have lower accuracy constraints. With sufficient density and appropriate networking, such individual sensing can be extended to realize *participatory monitoring* by communities and pollution maps for entire urban areas.

In industry, interest is also growing regarding low-cost mobile PM sensing, especially when looking at the Asian market, where urban air quality is generally more problematic. A use case may be the introduction of cheap PM sensing into air purifiers, smart items or even cars to monitor the *interior air quality* and demonstrate the effectiveness of employed

filtering measures. Another aspect is the monitoring of industrial equipment that is exposed to outdoor air, as part of machine health monitoring, e.g. cellphone towers.

Last, but certainly not least, cheap PM sensing presents a powerful tool for *environmental research*, enabling measurement at an unprecedented scale. Depending on the use-case and environmental conditions, accuracy and stability demands may vary.

3. Challenges and approaches

In this section, the outlined key challenges are discussed in more detail, along with possible ways to address them, depending on the sensing scenario. While some device or calibration technique may be suitable for a controlled sensor network, it may not be applicable to other approaches, such as Participatory Sensing, which – by involving citizens in the data collection – can potentially enable sensing networks at a much larger scale.

3.1 Instrumentation

Both in industry and academia, alternative PM instrumentation has been developed. Fig. 1 shows a (non-exhaustive) overview of different device classes. Standard equipment uses gravimetric measurement. Professional devices are available that mostly use laser scattering to enable mobile real-time measurements. These devices often include a means of size segregation and generally are still very accurate, some of them even certified by the EPA for official PM measurements. However, they are still prohibitively expensive for dense measurements (tens of thousands of dollars). For participatory citizen science projects that involve individuals, communities and/or researchers, alternatives are needed. Our research therefore focuses on very low-cost commercial off-the-shelf (COTS) sensors, as presented in Budde et al. (2012a, 2012b).



Fig. 1. Instrumentation for particulate matter measurements today covers a wide range and tradeoffs need to be made depending on the application scenario that it is employed for.

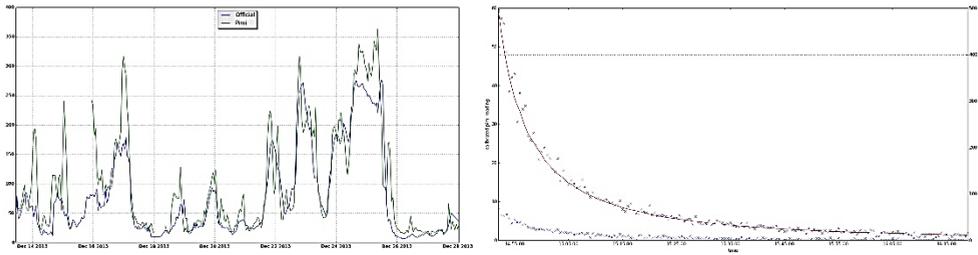


Fig. 2. *Left*: Two weeks of raw data (scaled) of a SYhitech DSM501 sensor placed on a window ledge compared to that of the official Hai Dian Wan Liu station, Beijing (distance ~2 km). *Right*: Time series of one of the DSM501s two output channels fitted to a PM_{2.5} reference device by 5-segment piecewise linear approximation (upper lines).

While their low cost in the range of tens of dollars enables large-scale distribution, they are generally very noisy and have low stability. On the other hand, they are small and require relatively little energy, making them suitable to be embedded into handheld platforms and – some with certain restrictions – for mobile measurements (i.e. the sensors are generally portable, however, depending on speed and dynamics of movement, additional measures may be required to ensure correct sensor data). They can also be sampled at high frequencies, enabling a high temporal resolution even when averaging consecutive readings to increase measurement stability and accuracy. It is noteworthy that these cheap sensors (as does some professional equipment) samples the Total Suspended Particles (TSP) rather than specific size classes, so that readings are PM class equivalents rather than exact data. Still, for their price range they can achieve remarkable results.

In previous work, we have compared low-cost COTS sensors against reference equipment in order to determine their suitability for distributed sensing applications. We have shown that the Sharp GP2Y1010 dust sensor, while not meant to be used for fine dust measurements, can actually be employed for environmental sensing, provided that its signals are appropriately processed and they are frequently re-calibrated (Budde et al., 2013b). In the PiMi Airbox project (Li et al., 2014), we explore air quality sensing using a different low-cost sensor, the SYhitech DSM501. Our current experiments and lab calibration efforts show that its readings correspond reasonably well to that of an official Beijing measurement station even without calibration and can be mapped to the data of a real-time capable reference device (TSI DustTrak II 8530) using 5-segment piecewise linear calibration (see Fig. 2). We are currently testing the calibration stability. Other work on PM and activity sensing with COTS sensors includes (Olivares et al., 2012), (Weekly et al., 2013), and (Holstius et al., 2014).

We believe that for Participatory Sensing, a PM sensor would ideally be part of a smartphone to eliminate the need for an additional device carried by the user. As current sensors are not small enough to be embeddable, we are looking into a smartphone clip-on approach, in which the flash and camera are used as light source and receptor of a light scattering PM sensor respectively (Budde et al., 2013a).

3.2 Calibration

In principle, there are two means of calibrating a sensor: either the sensor is exposed to a of constant, defined concentration (or a series thereof) or it is co-located with an already calibrated device whose readings are used for calibration. Mass calibration of low-cost dust sensors is possible with both approaches under lab conditions and also required, as the COTS dust sensors used in our work come with large inconsistencies amongst each other

generated during the manufacturing procedure. However, as the previous work that assesses the performance of low-cost PM sensors has shown, these sensors do not only need to be calibrated before operation, but also re-calibrated in certain intervals. In the outlined scenarios, this step needs to be performed *in-situ*, as collection and re-deployment is not a feasible option. This is even more important when looking at scenarios in which sensing devices are operated by average citizens rather than trained technical staff, as discussed in the next subsection. In order to deal with calibration issues in volatile low-cost sensing scenarios, cross-calibration algorithms, in which sensors calibrate each other have been proposed. A distinguished example for this is on-the-fly calibration of low-cost gas sensors based on their calibration age, which delivers high accuracy that even exceeds the specifications of the sensors (Hasenfratz et al., 2012). This approach should also be feasible for PM sensor calibration and possibly be extended to include additional parameters, such as the sensor type, to be applicable in sensing networks with heterogeneous devices. In a scenario with centralized processing, as discussed below, the approach could also be *virtualized* and carried out on the data level in order to remove the need for direct communication between devices. Constraints for calibration schemes may also differ depending on the measurement mode of the employed sensors, i.e., whether they deliver continuous data or short measurements with more of an event-like character.

The calibration of cheap COTS dust sensors used for *indoor* measurements, such as the *PiMi Airbox* (see above) is an especially challenging task, as usually no rendezvous with reference equipment occurs. In order to reach acceptable re-calibration quality for these sensors, a possible approach could be to place them outside from time to time for calibration against the nearest official station (similar to the setup shown in Fig. 2) and assume that the dust composition is largely consistent within the geographical vicinity.

3.3 Coverage and processing

A major aspect of distributed networks are the implemented deployment, collection and processing schemes, all of which affect the coverage. There are several possibilities for this, many of them established in wireless sensor networks (WSN). In WSNs however, there are often dedicated data sink nodes and direct (possibly multi-hop) communication between nodes, leading to different challenges, such as contact detection and mobility control (Di Francesco et al., 2011). In our approach to distributed PM sensing, we focus on direct data dissemination (e.g. via mobile broadband) and centralized processing, as this facilitates low latency processing and hybrid approaches with heterogeneous devices as well as fusion with other data sources, e.g. traffic density (Yu et al., 2013), and calibration.

On the top level, collection can be differentiated into *static* and *mobile* schemes. Using statically deployed sensor nodes has the benefits that the measurement environment is well-known and there is often the possibility to power the sensor devices directly. However, to cover a large area, many nodes need to be deployed and, more importantly, maintained. This means that either (potentially more expensive) sensors with strong calibration stability need to be employed, or frequent re-calibration with high personnel cost – or again mobile agents – is necessary. The alternative to fixed deployment is the attachment of sensor devices to mobile entities. In contrast to some WSNs, in the outlined scenarios there is usually no coverage control, i.e., no control over the movement of these entities.

However, knowledge concerning their mobility patterns may exist. Mobility can be either *unpredictable*, i.e. the mobility properties (speed, direction and future positions) of the sensing agents are unknown and possibly highly dynamic. This is the case in Participatory Sensing scenarios involving end-users and/or unscheduled vehicular

platforms, such as taxi cabs (Zhang et al., 2011), logistics fleets or bicycles, such as the *Aeroflex* (Elen et al., 2013). These scenarios potentially offer great coverage, but re-calibration is difficult, as co-location of sensors cannot be predicted well, if at all. However, in the case of city bikes or taxis, periodic re-calibration may be implemented at taxi stands or – if present – bicycle drop-off stations, that already have an uplink anyway. Calibration is much easier in scenarios using *scheduled* entities that travel along fixed paths, e.g. by deployment on public transportation infrastructure such as trains, trams or buses, which have regular and reliable routes. Example projects that employed such platforms are *OpenSense* (Aberer et al., 2010) or *PMetro* (Castellini et al., 2014) where PM measurement equipment was installed on the roof of trams.

Table 1. Constraints, benefits and drawbacks (rated +, o, –) of different collections schemes.

| Collection Scheme | Instrumentation | Coverage | Calibration | Privacy |
|-----------------------|-----------------------------------|-------------------|-------------------|------------------|
| Static Infrastructure | Weak size and power constraints | – | – | + |
| Vehicular | Possible power constraints, GPS | o (scheduled) | + (scheduled) | – (personal) |
| | | + (unpredictable) | o (unpredictable) | + (non-personal) |
| Participatory Sensing | Handheld, battery operatable, GPS | + | – | – |

An important challenge that arises in some collection schemes is *Privacy*, as sensor data is only useful with accurate location data, which may in turn reveal sensitive information about individuals (*personal vs. non-personal collection*). Interestingly, some of the presented schemes feature a sort of “intrinsic privacy”: Taxi drivers do not reveal personal information and public city bikes are not used by the same person for an extended period of time (and are tracked anyway, so no additional information is collected).

3.4 Incentivization

Incentivization mostly applies to scenarios involving citizen participation. Within the first 24h of the recently started *PiMi* project in Beijing, over 500 people applied for a *PiMi Airbox*, a cheap, networked indoor air quality monitor. This shows the large social attention and intrinsic motivation that can be harnessed. However, to maintain high motivation, adding extrinsic incentives, e.g. through Gamification, is an interesting option. An approach that makes very strong use of this (bordering on being a pervasive game) is employed by *Noisebattle* and *Noisequest* (Martí et al., 2012) where different game interfaces are presented to different player types for noise pollution monitoring with smartphones.

But not only general participation can be enhanced, it may also provide a means to exert some control over unscheduled moving entities, prompting them to go out of their way for better coverage or to re-calibrate when in the vicinity of each other. Implicit incentivization, by providing usable, self-explanatory interfaces that e.g. show the current calibration status and make possible additional measures transparent – such as the use of activity recognition to determine the measurement quality – can further educate users on how to measure right.

4. Conclusion

In this work, we have compiled scenarios, challenges and approaches for distributed low-cost dust measurements. Today, most real-world projects employ relatively expensive equipment instead of low-cost sensors. For truly large-scale scenarios, hybrid approaches,

with many low-cost sensors and some professional reference equipment for re-calibration seem to be promising. In order to reach this, we argue that the presented challenges cannot be addressed separately and a combination of smart approaches on different levels has the potential to realize systems with an overall performance beyond that of the mere employed instrumentation. We expect that addressing the presented challenges in a combined, holistic approach could be most suitable for low-cost, distributed PM sensing: Motivated citizens, traversing the city they live in, operate cheap mobile instrumentation, the data of which is centrally combined to ensure stable re-calibration as well as high data quality and coverage.

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