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Published in:
Proceedings of the 21st International Conference on Extending Database Technology (EDBT)

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Analysis and Visualization of Urban Emission Measurements in Smart Cities

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ABSTRACT

Cities worldwide aim to reduce their greenhouse gas emissions and improve air quality for their citizens. Therefore, there is a need to implement smart city approaches to monitor, model, and understand local emissions to better guide these actions. We present our approach that deploys a number of low-cost sensors through a wireless Internet of Things (IoT) backbone and is thus capable of collecting high-granular data. Based on a flexible architecture, we built an ecosystem of data management and data analytics including processing, integration, analysis, and visualization as well as decision-support systems for cities to better understand their emissions. Our prototype system has so far been tested in two Scandinavian cities. We present this system and demonstrate how to collect, integrate, analyze, and visualize real-time air quality data.

1 INTRODUCTION

Urban emissions contribute over 60% to global greenhouse gas emissions. Cities aim at reducing their emissions through tailored policy and integration to Smart City approaches. Smart City approaches facilitate easier integration of emission sensing into city systems and fulfill city requirements through novel and low-cost approaches [5, 6, 8, 10, 11].

The overall aim of our project[1] is to fulfill the information needs of cities that need specific data for emission reduction actions by providing complementary on-the-ground emission data for improved understanding and decision making [2]. In short, the need based on future challenges faced by cities will be better and more high-granularity measurements to complement existing official measurement stations.

Some Nordic cities have specific challenges in that they have already implemented a range of climate actions, which means that future impact on a certain class of emissions can only be achieved by a more detailed and granular understanding and analysis of emissions, since many broad measures are already in place. The next step then is to get better insight into more difficult to measure components, also to be able to adapt policy in fast feedback loops and at varying scales. This includes impact assessment of measures ranging from small-scale such as closing down certain streets (and being able to observe spillover and evasion effects in surrounding parts of the city) to large-scale such as changes in public transport or denser urban development.

A high spatial granularity of sensor deployments is obviously not possible with the existing expensive high-quality measurement stations that are often provided nationally. Our approach, in contrast, is to use low-cost sensors to cover a city's spatial footprint with a much higher sensor density. This enables a trade-off of high number and high granularity of low-cost sensors that can compensate for their relatively lower accuracy.

Existing official measurement stations are equipped with high-quality sensors that cost up to $500,000. Our low-cost approach could provide a very dense coverage of a city with 250 additional sensors for the price of one additional station by using sensor units of around $2,000 each. For ease of installation, this requires standalone sensor units that do not need cabling for electricity or connectivity. We achieve that by deploying solar-powered sensor nodes with a wireless data link over the LoRaWAN standard for Smart City IoT applications, which also enables us to quickly scale up the sensor deployment. The approach allows to quickly prototype system components on the hardware and software side for the overall goal of linking the measurement data to the information needs of the cities for emission reduction both for baseline and continuous data collection.

After having built and deployed the general IoT sensor network before [2], we focus here on the integration of data sources and the data analysis infrastructure for Smart City applications.

2 APPROACH

Our approach is to build an ecosystem of relevant tools and methods to better understand city emissions and work with data, such as analytics [9, 12], visualizations [7], and decision support systems [5, 6, 11] around local emission measurements and the integration of external data sources. This is an important aspect of Smart Cities [9], and can also be used as a case study to understand and build similar systems. Our system is piloted in the two cities of Trondheim, Norway, and Vejle, Denmark.

In this paper, we describe key aspects of this ecosystem of data analysis and visualization that strongly relates to challenges and

[1] Carbon Track & Trace – CTT: https://www.ntnu.edu/ad/ctt

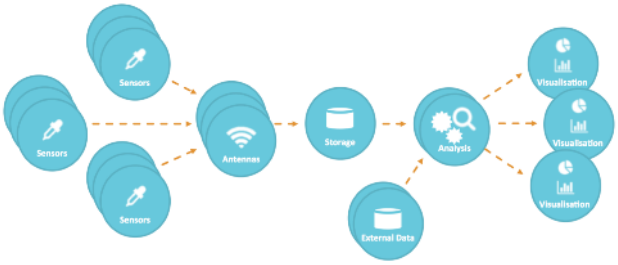

Figure 1: Overall system architecture

requirements of the cities. We further demonstrate the integration and aggregation of data sources for a smart city.

2.1 Architecture

The system architecture and data flow is sketched in Fig. 1, which consists of four components: a city-wide IoT sensor network, cloud-based systems for data collection and storage, integration of external data, and analysis and visualization platforms for stakeholders. The architecture is flexible through an ecosystem approach and accommodates different components for a range of related tasks. Our technology stack follows common concepts for IoT and Smart City systems [10] with project-specific adaptations.

The sensor network is composed of sensor nodes deployed within the city, which measure emissions and air parameters: CO_2, NO_2, PM_x (particulate matter); temperature, pressure, and humidity. The data is transmitted to the IoT backbone, which forwards collected data to the cloud storage, from where it is available for analysis and visualization, using relevant external data sources. The backbone uses LoRaWAN as a radio-based urban sensor networks through a number of gateways covering the pilot regions [2]. Data forwarding and cloud sensor management was built through the event-driven MQTT communication protocol.

Visualizations and analyses are connected to all stages of the data processing. Examples are network monitoring and early data validation close to the sensors, stream processing on measurement data, up to C&C centers, satellite measurement grounding, integration into GML-based 3D city models, and other forms of mapping and integration that we describe in the following.

2.2 Data Integration

Apart from the direct sensor data, there is a range of municipal and national data sets available as well as other external data sources that need to be included in the data analytics and visualization to support analyses and improve data quality. Table 1 gives an overview of these sources and how they can be utilized. They range from direct measurements of air quality that can be used to validate and calibrate the sensor network to other data sources that help to understand emissions in the context of a city, for example through traffic patterns [12] or integration into city tools and systems.

The sensor network has the usual issues of missing data that is dealt with on a technical monitoring level and being handled by standard methods in the analyses, as well as the aggregation of data from multiple sensor units. More interesting are the challenges posed in the data integration. The sources contain highly heterogeneous data, with different timescales, measurement frequencies, spatial distributions and granularities, measurement technologies, and a complex set of related uncertainties and inaccuracies in the data.

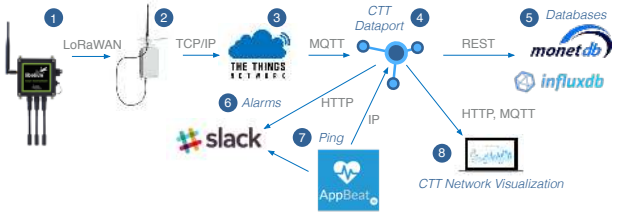

Figure 2: Dataport Protocol Diagram

2.3 Network Metadata Analysis and System Status Monitoring

The network, server components, gateways and sensors are subject to transient and permanent failures, which can ultimately result in missing data. Although the later analysis tasks can detect such losses of data, they do not analyze the cause for the error, or prevent further losses. Instead, failures in the system should be detected as quickly as possible, so that data loss is kept at a minimum. We therefore built a monitoring application (the *dataport*) to monitor the status of all sensors, gateways and the network [3]. It is built with the Akka framework, which facilitates the creation of fault-tolerant applications based on the actor model [4]. Actors are independent, supervised processes that encapsulate data and control logic and communicate via messages. Each device in the real world corresponds to a dedicated actor that acts as its digital twin, which is a virtual model of the sensor or gateway. It keeps track of its state in real-time, monitors all communication and triggers alarms if data is not received as expected. Incoming data contains meta-data that identifies the originating sensor and the gateway from which it was received. In this way, the digital twin for a gateway can detect if a gateway operates as expected.

Faults of a more complex nature, such as decaying sensors, erroneous behavior of sensor nodes, or missing data patterns need specific analysis. For example, a single missing measurement is expected occasionally. Based on the measurement frequency of individual sensors, it takes some cycles to determine a failure with certainty. As sensors nodes can adapt their frequency based on battery levels, a complex model of the sensor node and its status is needed for detection. Actors are organized hierarchically. On higher levels, failures can be grouped so that for example a distinction can be drawn between sensor failures versus a gateway outage that would make a set of sensors invisible.

The dataport also monitors the larger system, such as the The Things Network (TTN) cloud backend and the MQTT connection. If any of the components on the data path from the sensors to the data storage fails, the dataport generates a notification. If the dataport itself fails, it is detected by an external watchdog service, in this case AppBeat. The dataport further drives a visualization of the network itself, shown in Fig. 3, of the structure of digital twins for sensors and gateways, their location, the connections and live data transmission between sensors and gateways. Apart from the practical value of monitoring the network, it is also a useful illustration of the spatial and measurement characteristics.

2.4 Data Analyses and Visualizations

A range of analyses work on the collected data streams as illustrated in Fig. 1 apart from the more operational network analysis. Examples are ongoing data collection and analysis, understanding of patterns, as well as comparison of sensor measurements to air quality measurement stations to ground the network and calibrate the sensors. There are very few official stations; to

Table 1: Examples of external data integration

Type	Example	Description
Official air quality measurements	NILU data (Norwegian Air Quality Institute)	Ground truth for certain pollution types, grounding and calibrating measurements to high-quality reference stations
Remote sensing	NASA OCO-2 satellite CO_2 measurements	Ground truth top-down measurements for certain emission types, large-scale coverage, low spatial resolution, coupling to large-scale modeling and validation
Traffic data	Traffic density from here.com	Estimate traffic emissions by correlating continuous external traffic density to emission measurements
	Municipal traffic counts	Validate traffic estimations, but only available for short periods
3D city models	Municipal 3D model of Vejle	Integration into existing visualization tools. Use of city geometry in future emission modeling
National statistics	GHG emission estimates from national statistics office	down-scaled national GHG emission data, often with high uncertainties
Other municipal data and tools	GIS, statistics, decision support, etc.	Understanding emissions in the context of the city

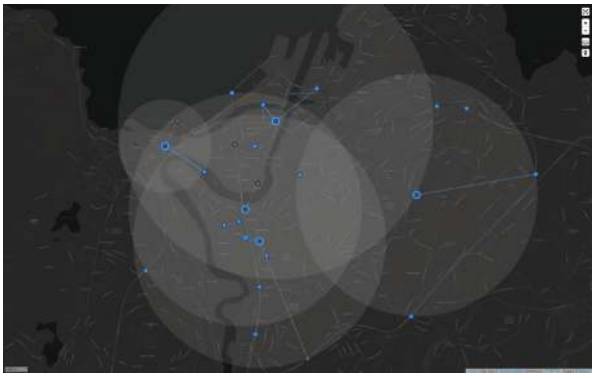

Figure 3: Visualization of sensors, gateways, and links

support the grounding and calibration, we have co-located one of our sensor units to the only station in the pilot area. This allows to compare both absolute and relative accuracy and calibrate the local sensor and, through larger-scale correlated trends, the network, but with lower certainty. In connection with the network monitoring, it also allows the identification of outliers and malfunctioning sensors. Main ongoing work is modeling dependencies of NO_2, PM_x, and CO_2, especially from transport emissions, which therefore also looks at linking to traffic patterns [12]. We discuss some analytics around this data in the following.

Battery levels depend on the charging of the autonomous sensor units through their solar panels. Charged occurs during daytime, and is affected by weather conditions. It is important to monitor the battery level to keep the nodes running. Fig. 4 shows the battery level as a function of time (left), and the difference in battery-level from previous sent package versus time of day, and where red indicates whether the nodes could have been charged by sunlight since the previous package (right). This allows to estimate battery depletion.

Dynamics of CO_2 emissions and possible links to traffic in the form of a traffic jam factor (from here.com data) is shown in Fig. 5. According to the plots, we can conclude for this sensor location that traffic is not the only factor that accounts for the dynamics of the CO_2 emission as they exhibit different patterns, and have no apparent correlation. In fact, CO_2 emission dynamic is a more complex issue that may be affected by many factors, including traffic, wind speed, temperature, humidity and other weather conditions, as well as daily and seasonal patterns, which we will further investigate in our future work.

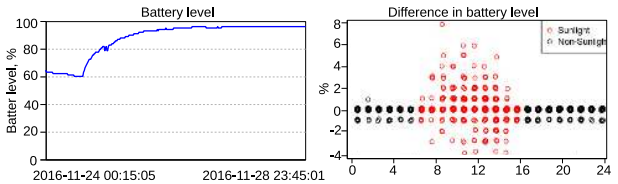

Figure 4: Battery level analysis

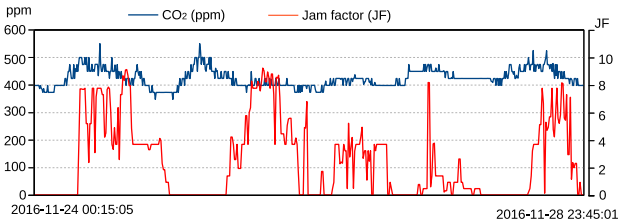

Figure 5: A study of CO_2 dynamics

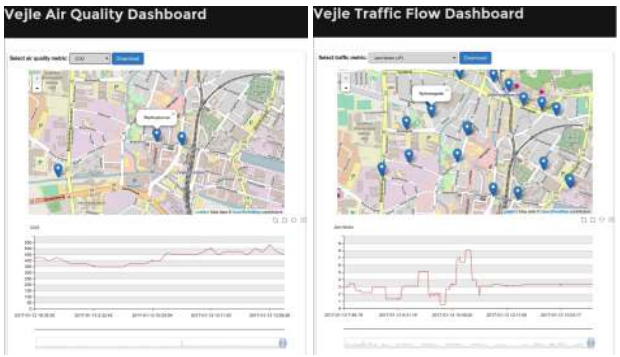

Figure 6: Example of dashboards for air quality and traffic

Visualizations and Dashboards for real-time monitoring. Fig. 6 shows the air quality and traffic flow dashboard, respectively. The dashboard is implemented using Apache Zeppelin as the visualization platform and accesses the data from the OpenTSDB time series database. The mapped sensors show the real-time data and analytic results for each location. Examples are the the air quality and traffic indicators in Fig. 6. This was further integrated into a 3D CityGML model as seen in Fig. 7 and also into a full network and data overview wall display shown in Fig. 8.

3 DEMONSTRATION

In this first full demonstration of the CTT air quality system, we show the architecture and implementations of IoT and analytics

Figure 7: Integration of sensor data into 3D city model

Figure 8: Network monitoring and data visualization dashboards

technologies in air quality monitoring and explore insights. We use two use cases of deploying our systems in Vejle, Denmark and Trondheim, Norway, where two and twelve sensors were deployed respectively to collect air quality data. We demonstrate our system from the perspective of developers, city policymakers, and citizens. For developers, we explore the system in detail, demonstrate the building blocks of the system, and show how to build similar IoT systems; for policymakers, we aim to assist them in decision making for smart cities with the proposed IoT technologies, e.g., urban planning; for citizens, we aim to raise the awareness of environment protection and greenhouse gas reduction for better city life.

We use real-time data collected from the deployed sensors from both cities, as well as traffic data sets streamed from the third-party traffic flow monitoring operator, here.com. The sensor data consist of the CO_2, NO_2, and PM_x, and weather data including humidity and temperature. The sensor data is collected at a five-minute interval. The demo also uses historic data saved in our time-series database, collected since January 2017.

Developers' point of view: We show the architecture and components used by our air quality monitoring system, including sensors, IoT sensor network, cloud storage for sensor data and external traffic data, analytics, and dashboards. We demonstrate how to collect, process and visualize high-frequent sensor data in our system developed on the Zeppelin platform; and how to streamline the whole data flow, including segmentation, chaining, and automation. Finally, we demonstrate how to generate dashboards and integrate analysis algorithms in the web interface. Attendees can vary system and analysis properties, and observe the reflection on the dashboard; and change the dependency of the data flow to evaluate the flexibility of the data stream analysis.

City officials' point of view: We show an interactive dashboard to analyze CO_2 dynamics using real-time and historic measurement data, and demonstrate the pattern and its correlation to the traffic flow (see Fig. 5–6). In addition, we demonstrate the 3D CityGML model integrating different measuring points of air quality (see Fig. 7). In this demo scenario, we can inject synthetic data showing different pollution levels. We interact with attendees by discussing urban planning issues such as construction sites of roads, buildings or factories, and see how different pollution levels will affect their decision makings. Also, we consult with attendees about choosing the sites of air quality monitoring, e.g., according to the road network and building density.

Citizens' point of view: We demonstrate air quality and traffic flow on the dashboard using the real-time data. Similarly, we use synthetic data with different pollution levels, and discuss the influence on routing planning, and citizens' approaches for emission reduction. Attendees can browse historic data in the system to investigate anomalous emission levels.

4 CONCLUSION

We have described the possibilities for urban emission monitoring and our approach and the prototype system we have developed together with the approaches to data flows and analysis. The flexible and scalable solution allows to quickly prototype different analysis approaches on top of the sensor streams to link measured data to cities' information needs for emission reduction.

In future work, we plan to improve the measurement network and the real-time and aggregate dashboards. Further, with more data collected, we will be able to tune models for emission distribution and dispersion to overcome some of the issues and provide improved analysis with better models. Integration into decision support systems is a far goal. Urban emission monitoring needs a range of heterogeneous data and we are continuing to build useful urban systems around it.

ACKNOWLEDGEMENTS

This paper is part of the Carbon Track & Trace (CTT) project. Funding for this project was in part provided by the LoCaL[2] Climate-KIC flagship programme. We thank all our project partners and specifically VCS[3] for the 3D city model demo. Parts of this article are based on project deliverables [1].

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