Stadtlärm - A distributed System for Noise Level Measurement and Noise Source Identification in a Smart City Environment

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Introduction

Various types of acoustic scenes such as railway, road, airplane and industrial noise, construction sites, open air concerts, sport events and natural noise sources contribute to the overall rising noise perception in cities. While railway, road, airplane, industrial, and construction noise are well understood, leading to standards on how to access, and are legally regulated, the knowledge and the legal rules for other sources are incomplete. For musical events, there exist regulations to protect both musician and audience, but no rules for the total sound emission. Noise caused by children in schools and kindergarten by intention is neglected. Noise caused by nature, for instance from singing birds and waterfalls in general is accepted by everybody, but barking dogs and agricultural noise (cocks and chicken, cows, …) is usually "regulated" by court order on a more or less subjective basis.

Questionnaires asking which kinds of noise are most disturbing seem to indicate that legal regulation has already covered the most important noise sources [1]. However municipal administrations are often confronted with complaints about the other kinds of noise sources: Here complaints about sport events, music events and gastronomic sites (open air sitting, smokers in front of restaurant) are frequent, and, in contrast to planes, trains and main roads, the regulation of such events is in the responsibility of the municipal administration. Due to the fact that there are no rules on how to access the emission, the measurement is most often based on immission to the homes. However such measurements often contain the superposition of multiple sound sources, and it is difficult for the municipal administration to decide on how to improve the overall situation.

For municipal administrations it would be helpful to have measurement methods which analyze and decompose complex sound scenes into the different sound sources respectively sound types, measure these sounds independently, and finally combine these individual measurements to an estimate of the perceived distortion by noise. To make this kind of measurement possible it is necessary to capture spatial sound scenes in cities and to combine this noise information with administrative data of the past (which event happened when and where) and data about the reaction of the citizens ("complaints").

This paper is about the research project "StadtLärm" funded by the German Federal Ministry for Economic Affairs and Energy (BMWi, ZF 4072003LF6). The project focuses on a sensor network capable of performing distributed acoustic measurements and data analysis within urban environments.

Administrative Workflow

The target of the overall system is to assist municipal administration processes. Therefore, it is important to understand the roles and workflows concerning regularizing public events. In this context, events might be cultural events, sportive events, political events, and others. Figure 1 shows the main administrative workflow: The organizer asks for allowance to organize and carry out an event. The municipal administration checks the event declaration and defines possible requirements. Sometimes simulations of the noise distribution to the neighborhoods are requested. From a noise perspective the requirements are usually not only related to the event itself but also to the access and return travel of the audience. For sport events it is often important which way the supporters of the teams approach the sport stadium. While the noise distribution during an event can be simulated at reasonable efforts the noise pollution before and after the event is difficult to predict. The municipal administration requires the organizer to keep a noise report of the event. This means that the organizer must carry out (or delegate) noise measurements during the event and record these. However, these protocols usually only cover the event itself, but not the effect to the neighborhoods. This somewhat limited information is used by administrations to adapt their requirements and rules for future events of this kind.

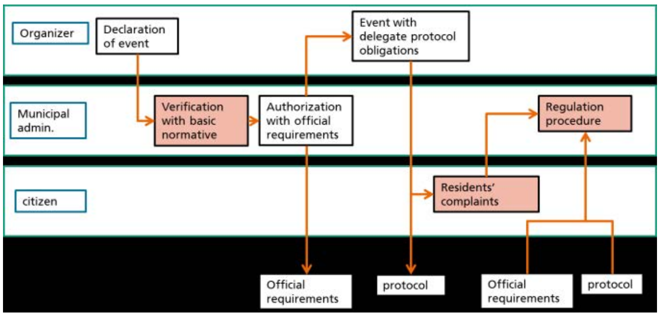

Figure 1: Administrative workflow for events.

System Parameters

Due to the fact that the sensor network will be installed in a city environment, several requirements need to be considered for the final system:

- **Environment**: The sensors will be installed outdoors and must function in a wide range of temperature and humidity. Some robust enclosure is necessary to avoid intended and casual damage.

- **Size**: The sensors must be small to make installation feasible.
- **Power Supply**: At an early stage it was decided to use lighting poles of the city. However measurement should work 24/7 but parts of the lighting poles might be powerless. Therefore battery backup is necessary.
- **Precision**: The sensors should collect as many acoustical data as possible with precise timing information. This way, triangulation of sound sources should be possible in the data analysis. To make the triangulation precise, the distance of sensors must not be too large.
  Furthermore, it is important that the frequency range covers the major part of the human auditory range, and that the signal to noise ratio is sufficient for further processing.
- **Privacy**: The collected data of each sensor must be reduced in a way to make it impossible to understand dialogs of citizens. However the information that the audio data originally was speech should be preserved.
- **User Groups**: The total system should be prepared to give access to different user groups: researchers need detailed data but city administration need only pre-processed data. An interface should make a subset of the data available to the citizens (web interface). The issue of user groups is related to the administrative workflow in towns, and will be explained in the next section.
- **Grid Structure**: The sensors should send their data to a server for further processing. The structure must be flexible in respect of number sensors, servers, users and processing units. At the same time it must be able to ensure the reliability of data and avoid illegitimate access to data.
- **Prize**: Finally such a system must be at reasonable costs to make it affordable for small, medium and large cities.

Some of the requirements make compromises necessary: Precision in triangulation is in contrast to prize and privacy: Using a large number of sensors the combined information of all sensors might be used to re-create an intelligible speech signal. The number of sensors is influencing the prize, too. A way to achieve a reasonable coverage of a city is to have a smaller distance of sensors where many sound sources are expected and a larger distance in suburbs where not many sound sources are expected. The need for a battery backup is increasing the prize, but loosing data due to incomplete power supply is not an option. The need for robustness of the sensor node is in contrast to size and prize. However in most cities, investment costs (robustness) are easier available than maintenance costs (repair).

Project Partners

There are two research institutes, two enterprises, and the city of Jena as a supporting partner. The Institute for Microelectronic and Micromechanical Systems (IMMS) is responsible for the hardware design and the communication between components. The Fraunhofer-Institute for Digital Media Technology (IDMT) is responsible for acoustics, signal processing, and the server component. The SME Bischoff Elektronik (BiE) designed and manufactured the robust sensor node. The SME Software Service John (SSJ) contributed their 3D geographic information system and enriched it with the acoustic measurement data to provide a user interface for the different user groups. The city of Jena is supporting the project. Traffic routes go through the town, living areas, production, and sport cites are close together. Due to the valley-like geographic location of Jena, the noise distribution is not easy to predict. Figure 2 shows the layout of the target area in Jena.

Figure 2: Layout of the target area in downtown of Jena (based on [2]); source: City of Jena

System architecture

Figure 3 shows an overview of the system architecture. The recording and pre-processing of the acoustic signal is done in the distributed sensor units. In the current pilot test 15 of these sensors will be distributed in Jena. The preprocessing in the sensors includes the detection of acoustic scenes and events and implements the privacy-by-design requirement. Only the classification results are transmitted to the server. In addition, the sound pressure level is measured and pre-processed for the further calculation of sound quantities according to “TA Lärm” (German technical guidelines for noise reduction) [3]. The first prototype can detect musical events (subtypes: applause, busking, open air concert), sport events (subtypes: applause, singing supporters), pedestrian noise in streets (subtypes: dialogues, shouts), construction sites and traffic noise (subtypes: automotive, honk, trains, trams, sirens). Note that airplane noise is not an issue in the pilot town Jena.

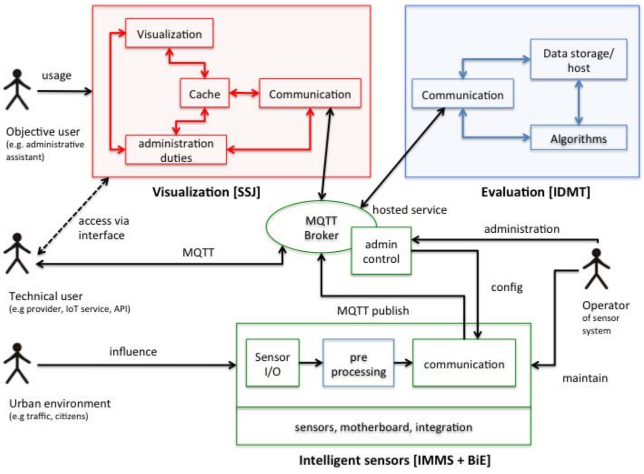

Figure 3: Overview of system architecture, stakeholders and project partners.

The list of classes detected in the sensors will be extended later. The sensor nodes also make some preprocessing for measurements according to TA Lärm. Note that these measurements are only valid for a minority of the classes. To enable triangulation of noise sources all features are time aligned based on the precision time protocol (PTP) [4]. The data of all sensor nodes is sent via a Message Queuing Telemetry Transport (MQTT) broker [5] for recording and further processing to the StadtLärm data-server. The raw data, but also the post processed data from the server is also send to the visualization component. The MQTT broker is a component originally developed for IoT environments. It enables the distribution of information between huge numbers of stations, and also handles issues of access control and data integrity.

Different user groups have different rights inside the system. A special role has the technical user, who is not only receiving data but also providing data to the system. This data includes for instance the number of visitors, the type of event, the weather conditions and finally the protocols of the measurements done on-site. The system is already designed so that service companies could provide such systems as a service for communities.

Noise Estimation and Analysis

The intelligent sensor units captures the environmental sound using a MEMS microphone. The noise level is monitored by computing several parameters in accordance to the German TA-Lärm norm (table 1). These parameters are considered as a starting point towards better algorithms to estimate noise loudness.

In addition, 17 different acoustic scenes and corresponding acoustic events can be automatically classified. These classes were selected based on the relevant soundscapes and sound emission types in the target area in Jena. Figure 4 gives an overview of the signal analysis:

The main approach is to use a hybrid deep artificial neuronal network [6]. The network processes two-second long spectrogram excerpts using a sequence of convolutional layers with ReLU activation function and intermediate max pooling layers. Finally three fully-connected layers combine the extracted feature representation from the previous layers and implement an individual classification of all 17 acoustic scene and event classes.

Table 1: Sound quantities measured or calculated in the StadtLärm system in accordance with TA Lärm.

	Parameter	Explanation	Sensor/Server
L_{AF}	Sound event level	A-Frequency and F-Time-weighted sound pressure level	Sensor
L_{Aeq}	Average sound level	Mean sound level over a given time period	Server
L_{AFT}	Takt maximal sound level	Peak sound pressure level within five seconds. Necessary for impulsiveness surcharge	Server
K_i	Impulsiveness	Surcharge for short-term sound pressure levels	Server
L_r	Rating level	Average sound pressure level with surcharges and rating time over 16h/8h (day/night)	Server

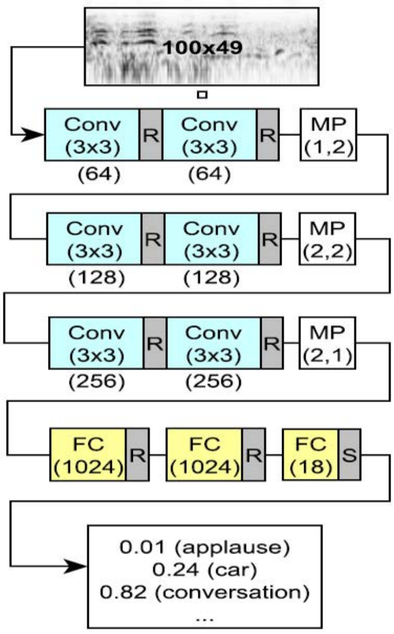

Figure 4: Overview of the noise source detection [6]. Abbreviations: Convolutional layers (CONV), ReLU activation function(R), pooling layers (MP), fully-connected layers (FC).

Using automatically learnt feature representation allows for a better adaptation towards new classes in the future as well as for a higher robustness to environmental background noise such as rain and wind. Since the noise source classification is performed already on the sensor units, the privacy-by-design requirement is full filled as only the activity of pre-defined classes is transmitted to the server and no speech recognition of passing-by residents is possible.

Conclusions

The issue of noise remains an interesting and challenging topic in cities. To enable reasonable trade-offs between different demands of citizens who would expect silence for recreation and concentrated work, of citizens who want to have cultural and sportive events nearby, and who both want to work and to travel it is necessary to measure and rate all sound sources present in cities. Current standards are incomplete. Knowledge about the combination and interference of different types of noise is still missing.

In this paper we presented an outline of research topics towards a more holistic approach to noise: complete noise scenes have to be captured 24/7, decomposed in different noise sources and related to subjective data and metadata about what happened at that time in the city.

As a first step we presented here a sensor network to capture acoustic scenes. The network consists of robust sensor nodes designed to work 24/7, and central units to store and analyze (pre-processed) acoustic data and metadata about events in the city. Both in the nodes and the central units processing of the audio data is done; both sensor nodes and central units can be extended easily to incorporate knowledge obtained from the post-analysis of captured data. A prototype of this network will be installed in Jena and used over the next years.

In parallel it is necessary to obtain more insights about the perception on noise in different situations [7,8] and to get a more formal description of the feedback of citizens to multi-source noise exposure [9].

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