TITIE : NOISE POLLUTION MONITORING

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a number of limitations, notably regarding the requirements of the European Noise Directive [13] - or END for short.

Spatio-temporal data granularity: computational models often produce results with an unknown error margin, which may lead to incorrect conclusions regarding caused uncomfort [33]. As stated by the EU practise guide [14], real data with high granularity in both time and space is required. However, data collection at sparse locations hardly scales to meet such requirements. Furthermore, strategic noise mapping only allows detecting general noise conditions. How can we monitor unusual local or short-term noise pollution?

Cost: the cost of such noise mapping campaigns is high due to need of expertise and human resources, the deployment of expensive sound level meter devices and the processing effort. This restricts cities with limited budgets from conducting such assessments.

People noise exposure assessment: the EU practise guide [14] requires detailed assessment of the level of noise citizens are actually exposed to. However, few efforts have been done to combine noise mapping and population data to assess the noise exposure of citizens [34].

Indoor noise assessment: current noise mapping only covers environmental noise, i.e. outdoor noise. However, most people spend a significant portion of their time indoors and such indoor exposure is reported in the maps (Fig.1: area in gray with no information).

Figure 1. Official noise map of Paris generated using a computational model and measurements made at a limited number of locations and times. Quiet areas are coloured in green while noisy places are in purple. Gray areas represent places for which no information is available (e.g. in buildings).

2.2 Alternative Approaches

2.2.1 Wireless sensor networks

Recent years have seen an increasing interest in wireless sensor networks for environmental monitoring [31] and urban sensing [7]. A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor environmental conditions, such as temperature, sound, air pressure or air quality, at different locations.

Wireless sensor networks have the potential to revolutionize environmental assessment, notably with regard to spatio-temporal granularity. Rather than relying on a limited number of expensive, accurate, stationary equipment, sensing, a WSN uses large numbers of cheap, simple sensor devices. Sensors can be directly embedded into the environment and operate continuously, enabling a real-time monitoring of environmental phenomena (or human activities).

A recent example of using WSNs for noise monitoring is discussed in [32]. In this project noise sensors were placed at fixed locations in an urban environment. However, it remains questionable whether this method is cheaper than traditional approaches for large-scale deployments. Furthermore, the sensors are static and the way they communicate constrains their placement to certain topologies. Moreover, the involvement of citizens is not considered in this project.

2.2.2 Participation of citizens

To implement the requirements of the END [13], involvement of citizens is key. This is especially important with regards to local action plans, which often directly affect people living nearby. But citizens can also contribute in earlier phases, such as during the actual assessment of noise pollution.

In geography and urban planning there is a trend towards support for such participation. Under the flag of *participatory GIS* [6] and *participatory mapping* new methodologies are being researched to better support the participation and involvement of citizens in projects that are typically tackled using geographical information systems (GIS), such as the mapping of spatial phenomena or land use and urban planning.

Some interesting examples in the context of noise pollution monitoring are [16] and [10, 21]. In the latter project researchers reached out to citizens concerned with noise pollution in their neighbourhood. The citizens were trained, coached and equipped with noise level meters to create noise maps accessible through an online GIS system.

While such projects focus more on methodologies for reaching out to citizens and less on technical advances they have equally inspired our approach.

3. APPROACH

Taking inspiration from wireless sensor networks and the trend towards participation of citizens in mapping and urban planning, we have developed a novel approach for the monitoring of urban noise pollution, based on mobile phones.

Concretely, in the NoiseTube project we intend to use mobile phones as noise sensors and actively involve the citizens that carry them by allowing them to provide additional qualitative input (noise source tagging, annoyance rating, ...).

In the remainder of this section we discuss and motivate this approach in detail.

3.1 Mobile phone as an Environmental Sensor

The growing popularity of *smart phones* with significant computational power, always-on Internet connectivity and integrated sensors (e.g. microphones, cameras, GPS, motion sensors) opens the door to a wide range of new applications. These devices represent a cheap but powerful WSN platform that is readily available and widely deployed. In this perspective mobile phones can serve as sensors which are carried by humans rather than placed at static locations. In addition to carrying around sensors, citizens can also be involved in the sensing process by entering qualitative inputs (e.g. tagging sources of noise, indicating a level of annoyance and giving contextual information). Thanks to the aggregated mobility of users, this approach enables sensing coverage of large public spaces and over time. This allows the collection of targeted information about the daily life of citizen or for specific local campaigns.

3.1.1 Mobile sensing

This idea is closely related to the concept of *participatory sensing* [3], which advocates the use of mobile devices to form sensor networks that enable public and professional users to gather, analyze and share local knowledge.

At the same time, people as individuals or in groups can apply these new sensing networks with a more personal focus. Their individual stories of everyday life can be aggregated to document the urban environment, fed back into a collective experience in urban public spaces, enabling *people-centric sensing* [4] for personal, peer or public purposes.

3.1.2 Democratising noise pollution measurement

"How much decibel am I exposed to now?" This kind of information is currently hard to obtain for a citizen. By turning smart phones into personal environmental instruments, we are essentially taking advantage of the democratisation of technology to achieve a democratisation of environmental information.

Previous participatory sensing projects (e.g. air pollution monitoring [25]) have been conducted in the context of a controlled, local and short-term monitoring by selected volunteers as a proof of concept. However, due to a lack of scale, the full potential of the participatory sensing paradigm in an environmental context has yet to be validated empirically by real world use. How will the practice of pollution monitoring change if not just few volunteers but every citizen has access to mobile environmental measuring devices?

In the context of noise pollution, by turning mobile phones into noise pollution sensors, we strongly lower the entrance barrier of such environmental measurement technology. NoiseTube has the potential to set up new kinds of experiments by enlarging the scope of potential participants. Furthermore the growing influence of Web 2.0 culture [23] the notion of "user-generated content" in the digital world will likely gain acceptance and facilitate the adoption of similar principles in a real world and environmental context, fully opening the potential of *citizen science* [26].

As a consequence, we expect novel mobile device applications and networked participation models to emerge.

3.2 Measuring pollution at the individual level

3.2.1 Personalizing environmental information

Giving the possibility to any citizen to measure their personal noise exposure in their daily environment could influence their perceptions and potentially support the raising of awareness of environmental issues, the first stage in the adoption of new behaviour [30]. This is important because citizens are often – indirectly and sometimes directly; collectively and sometimes individually – responsible for part of the noise pollution they experience. Changing their behaviour could thus solve a part of the problem. With its ubiquity, the mobile phone has already demonstrated its value as a persuasion tool in several cases (education, health and marketing [15]). The new application of mobile phones we propose has a big potential in an environmental context: personalized pollution information has a bigger impact than general statistics provided by environmental agencies to change habits towards a more sustainable lifestyle.

3.2.2 People- vs. Place-centric exposure

As described in [3], people can use this instrument in the context of grassroots campaigns to collect pollution measures at specific locations. This is the mobile extension of the common practice for wireless sensing networks [32] where the deployment is static and the network monitors the exposure at specific places. But the cell phone is situated in an environment, typically co-located with the user. As a consequence, it can be also used as a tool to self monitor their short/long term exposure and inform the community about it. The usefulness of such people-centric data has been demonstrated in medical projects such as [38], in which children were equipped with sensors for air pollution to understand the factors affecting asthma. Measuring the real impact of noise pollution, not only from a geographical point of view, but also through the people's exposure gives a new social perspective in the understanding of this urban problem and opens potential links with epidemiological studies at a larger scale.

3.3 Enabling a participatory culture

3.3.1 Supporting local democracy and citizen science

The participatory sensing paradigm supports local campaigns and citizen science. In this sense, the NoiseTube project is situated in the growing movement of local democracy, providing instrumentation tools for citizens to collect fine grained data (e.g. evidence of harmful noise exposure levels) to convince local authorities and influence decision making on local issues, without waiting for officials to gather the data [26]. We envision that the NoiseTube web platform can serve as a tool to help existing organisations (e.g. groups focused on well-identified noise pollution problems, such as in communities close to airports) to gather credible data.

3.3.2 Social Translucence Mechanism for Motivation and Accountability

NoiseTube uses the concept of social translucence consisting in making participants and their activities visible to one another. The role of social translucence is to inform, to create awareness and to enforce accountability [11]. By enhancing the social perception, it also contributes to the coordination of groups as well as stimulating participation [37].

These mechanisms also influence the level of the motivation of the individual and the group via social stimulation happening via social comparison [17], by reinforcing the perception of self-efficacy in a social context [1] by displaying the value of contribution [29]. This effect has for instance been demonstrated by [19] in the case of user-generated content on YouTube: "the productivity in crowd sourcing exhibits a strong positive dependence on attention, measured by the number of downloads. Conversely, a lack of attention leads to a decrease in the number of videos uploaded and the consequent drop in productivity".

3.3.3 Building weak and opportunistic cooperation

Even though the ubiquity of mobile phones makes mass participation feasible, as attempted in [4 & 27], it remains questionable how the general public can be motivated to voluntary participate. How to involve the hidden majority of citizens who do not participate in local organizations but who want to use such technology for personal purposes? Interesting examples of such user-generated practises are the Web 2.0 services like Flickr, YouTube or Wikipedia. As pointed out in [5] the Web 2.0 phenomenon contradicts many predictions regarding the form of cooperation and community that were encouraged by the promoters of Internet. As shown in studies of bloggers [24] or Wikipedia [2], the user's motivations do not fit with the two opposite conceptions: volunteering and belonging to a community vs. utilitarian maximising personal interest. Users generally first have individualistic motivations when they begin to publish personal production. But this public self-production appears to develop a greater number of interpersonal relations than was expected, although the link between individuals is weak. From such dense interaction emerge opportunities of cooperation, transforming users' goals from individual interest to more collective concerns.

In our noise pollution context, the public sharing of personal exposure is an opportunity to test this new articulation between individualism and altruism in a real world and environmental context. Making individual noise exposure public will give the opportunity to forge new relations among people facing to similar problems. This way, cooperative opportunities can emergence and collective action could be facilitated to overcome the cold start effect and allowing the participants to assess the value of the platform in the context of a very engaging activity.

4. NOISETUBE PLATFORM

The prototype consists of an application that the users must install on their smart phones and a server collecting, analysing and visualising the information sent from the phones.

4.1 Design overview

The current prototype on the NoiseTube platform consists of an application which the participants must install on their mobile phone to turn it into a sensor device. The mobile sensing application runs on GPS-equipped mobile phones. This application collects local information from different sensors (noise level, GPS coordinates, time, user input) and sent them to the NoiseTube server. The server centralises and processes the data sent by the phones.

Figure 2. The Mobile sensing application. Including 3 components: (1) The visualization of the loudness measured and a color representing the danger (2) The noise tagging (3) The tagging of the location (for indoor location for instance)

4.2 End-user features

4.2.1 *Measuring loudness in real time*

The mobile application contains a real-time signal processing algorithm which measures the loudness level of the microphone recording the environmental sound (at 22500 Hz, 16 bits) over 1 second at a chosen interval. An A-weighting filter is then applied to the recorded sound and the equivalent sound level (L_{eq})[2], measured in dB(A), is computed.

On top of the sensing of the loudness a real time visualization is displayed on the phone with the decibels. To add meaning to this value it is associated with a colour that represents the health risk of the current exposure level: < 70: green (no risk); > 70 and < 80: yellow (be careful); > 80: red (risky).

4.2.2 *Tagging*

In addition to measured loudness, public noise maps often only provide very limited information regarding the source or context of noise. This sort of semantic information is vital to make such maps meaningful for end-users. Especially because the appreciation of sound and loudness is a subjective matter – i.e. the perceived annoyance (or pleasure) does not always correlate with its loudness (see 6.2).

Environmental tagging: In order to better support this we are tackling this problem from the source by enabling users to directly annotate sound measurements using the mobile application. Users can specify the source of a noise (e.g.: cars, aircraft, neighbours) and give an annoyance rating or any additional contextual information in the form of free words (*tags*).

Geo-tagging: Furthermore, the lack of indoor positioning is also particularly problematic because people spend a large portion of the their time indoors and noise pollution has effects indoors as well. Therefore we allow users to describe their location using pre-configured ("favourite") place tags (such as "home", "work", the name of the subway station, ...), as an alternative for GPS-positioning. Thanks to this geo-tagging feature we can reconstruct the geo-coordinates afterwards notably for indoor locations (cf. subway noise map in figure 3).

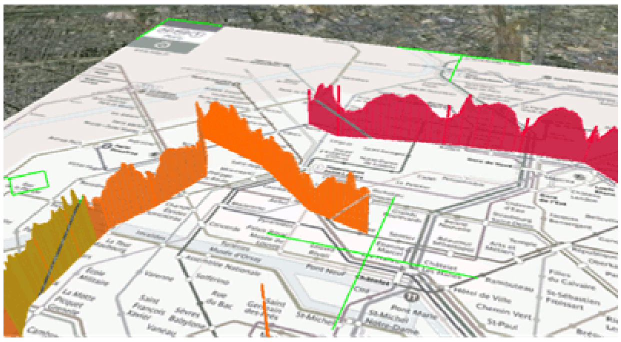

Figure 3. Noise map of two subway lines (indoor location) reconstructed thanks to the geo-tagging feature in the mobile sensing application

4.2.3 *Visualising Noise Maps*

Once the measured data is sent the server, any user can see his own contributions or exposures by going to the NoiseTube website and visualize them on a map thanks to Google Earth. A

[2] L_{eq} is the standard loudness measure required by the END [13].

collective noise map is also publicly available. This map is constructed by aggregating all the shared measurement by the participants. Each map can show a layer of tags entered by participants to add context and meaning to the loudness data. A real time monitoring of the loudness readings of all participants is also available.

Figure 4. Visualisation with Google Earth. On the left, the collective noise map generated by all the measures. On the right, a real time visualization of the collective noise exposure experience of the participants

4.2.4 *Making visible user's measures in existing social networks ecosystem*

As mentioned before we have attempted to develop features related to the concept of social translucence to motivate and create accountability in the community. Inspired by the concept of blogs we developed the idea of an *Elog*, or "Environmental Log". In our noise pollution context, an Elog would enable individuals to show their life through their current noise exposure or their contributions to the noise monitoring of their city. Thanks to this public profile we also attempt to support opportunistic connection and interaction among people facing similar problems and environments or leading similar lives.

We also provide a way to let users embed this as a web widget into their personal web pages or into their profiles in social network ecosystems (e.g. Facebook) to enable each user to make it visible to their friends or to any audience. By making this data public, and thus also their commitment to environmental and citizenship values, they are implicitly encouraged to build/maintain this component of their public identities.

At a global level, the use of the network effect to spread information through social relationship provides a simple and efficient way to raise awareness about noise exposure issues and attract new potential users.

4.2.5 *Web API to access public data*

Currently, raw measurement data on environmental phenomena such as noise is generally not directly accessible for the public or scientists, limiting exploitation by third-parties. The EC directive [13] only requires a web user interface to increase the accessibility of noise maps for the public. However, to avoid creating an inaccessible information silo we want to go further than that. Therefore, the NoiseTube platform exposes a simple web API for publishing or accessing data. Using this API third parties such as scientists or developers can use individual or collective noise exposure data to create web mash-ups or analyse data for scientific purposes.

4.2.6 *Data ownership & Privacy*

A user is not always a contributor. He or she is free to put or not his or her measures in the public domain so they can be used for a scientific purpose or to build a collective noise map. The user owns his/her data. Thus, for each session of measurement, or by default, he can decide to make his measures public and thus contribute or not to the collective noise mapping.

4.3 Implementation

The current version of the mobile application was written in Java and is aimed primarily at smart phones running the Symbian/S60 operating system. The program was mainly tested on a Nokia N95 8GB smart phone. Although untested, many other phone brands[3] and models are supported as well, as long as the device supports the Java J2ME platform, with multimedia and localisation extensions[4]. A GPS receiver (built-in or an external unit that is connected via Bluetooth) is needed to localise measures.

The server runs a web site where the users can visualise this data on maps. The server component is implemented using Ruby on Rails, MySQL, Google Maps and Google Earth.

5. DATA CREDIBILITY

A fundamental issue of low-cost sensing is the credibility of the gathered measurements. Therefore we must evaluate the correctness of the sensor data generated using the mobile application.

5.1 Mobile phone as Sound Level Meter

Without proper calibration, sensor devices produce data that may not be useful or can even be misleading.

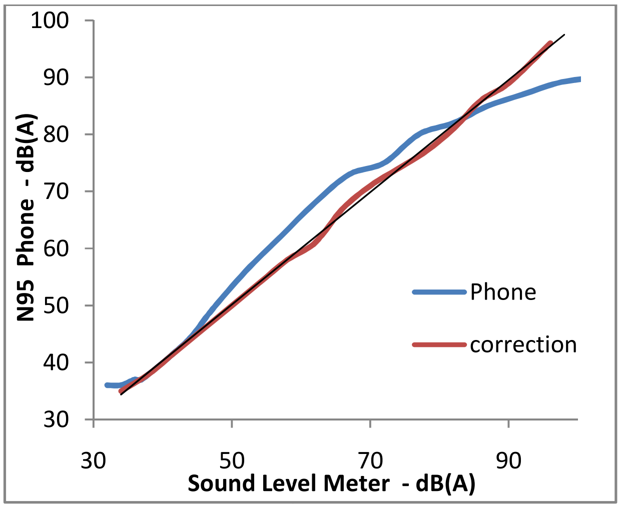

Figure 5. Blue line: loudness (L_{eq}) measured by our algorithm using the built-in microphone of the Nokia N95 8GB compared to a sound level meter in. Red line: results once we applied a post-processing correction function.

Experimentation has been conducted to measure the precision of the measure of the loudness computed with a mobile phone

[3] Initial tests with Sony-Ericsson phones are underway.

[4] To be exact the phone should have support for Java J2ME profile CLDC v1.1 with MIDP v2.0 (or newer), JSR-179 (Location API) and JSR-135 (Mobile Media API).

compared to a sound level meter[5]. We generated a pink noise at different levels of decibels (every 5 dB, from 30 to 105) and measured the results with our implementation on the Nokia N95 8GB handset. The produced curve, the blue line in figure 5 on the previous page, shows the response of the microphone compared to a sound level meter. According to this result this particular handset has the capacity to be used as a sound level meter in the interval [35, 100] due to the bijectivity of the curve. After using the inverse function as a post processing corrector we obtained good results with a final precision of +/- 3 db (red line).

5.2 Positioning accuracy

Using the Nokia N95 8GB with its built-in GPS chip an acceptable level of positioning accuracy in outdoor situations can be achieved. Errors are rarely bigger than 30 meters, which is still good enough to localise noise sources within a specific neighbourhood or street. When using an external GPS receiver[6] positioning accuracy can be slightly improved. Using an external receiver also has the added benefit that the phone's battery life is less effected compared to using a built-in GPS chip. However, in both cases indoor positioning is virtually impossible. This is a general limitation of the GPS system.

6. DISCUSSION AND FUTURE WORK

Democratisation of technologies such as NoiseTube will bring new applications and new questions for the participatory sensing paradigm.

6.1 Roles of citizens

How to sustain a human network at a larger scale and for a longer time than a local and short-term experimentation or campaign? How to design a network mixing humans and machines to monitor environmental resources? As far as we know, these questions have not been tackled yet by the current research on participatory sensing due to the small amount of participants and so the lack of complex structures. No explicit network topology has been used for the experimentation except for the basic ‘star’ topology: each participant collects and sends information to a central point where the data is analyzed by a machine. But further investigation could take advantage of social relationships, shared interests or reputation (expert/scientist) among the participants as a component of the problem of data/analysis credibility by using them not only as sensors but also as filters or regulators.

6.2 Beyond noise evaluation, soundscape assessment

The subjective evaluation of sound in urban environments is a complex fusion of many factors. Therefore, there are many research areas involved in trying to understand noise pollution from a subjective point of view, ranging from (psycho-)acoustics to cognitive research and sociology. Several studies have shown that acoustics alone can only explain part of the subjective evaluation of soundscapes [9, 28]. Besides the widely deployed A-weighted sound pressure levels in noise annoyance research, these studies prove the importance of the meaning of sound in noise annoyance. However, the contributions of the semantics of the sound in its evaluation have been studied in experimental settings mostly. As a consequence, other important aspects in the experience of sound perception, such as the visual contribution, are underexposed. For example, [40] found that environmental factors such as temperature, wind and sunshine influence the evaluation of a soundscape. Democratising noise pollution measurements provides a way to gather a most complete picture of the subjective experience, since it can incorporate acoustic measurements as well as subjective assessments.

6.3 User feedback and awareness

The user experience, especially with the mobile phone application, is crucial to motivate users to contribute. Even though the current version allows users to visualize noise exposure in real-time, we would like to improve the feedback by giving interesting insights coming from the collective experience, e.g. a map to highlight unusual pollution from measured by nearby participants, in order to support local decision-making. Furthermore, we are planning to develop more features related to social translucence to sustain the motivation, the accountability and participation, both are the key aspects of such approach.

6.4 Data credibility at the collective level

Until now we have focussed on the credibility of the measurements made by individual sensors (microphones). However, once a collective collection of noise data is underway we will also need to deal with data credibility among users, e.g. in case of contradictory measurements. This will affect the way aggregate, analyse and filter measurements.

7. CONCLUSION

In this paper we presented NoiseTube, a project aimed at developing a participative noise pollution monitoring network to enable citizens as well as governmental bodies and non-governmental organisations to gain awareness of and insight into the problem of urban noise pollution and its social implications.

We discussed our approach and the supporting rationale as well as a prototype implementation. While this project is still in an early stage we are planning to open up a first public experiment soon to evaluate user experiences and participation, as well as the credibility of the generated noise maps compared to traditional ones.

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