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Participatory noise pollution monitoring using mobile phones

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Abstract. Noise pollution is a major problem in cities around the world. The current methods to assess it neglect to represent the real exposure experienced by the citizens themselves, and therefore could lead to wrong conclusions and a biased representations. In this paper we present a novel approach to monitor noise pollution involving the general public. Using their mobile phones as noise sensors, we provide a low cost solution for the citizens to measure their personal exposure to noise in their everyday environment and participate in the creation of collective noise maps by sharing their geo-localized and annotated measurements with the community. Our prototype, called NoiseTube, can be found online [1].

Keywords: Environmental policy, pollution measurement, participatory sensing, citizen science, mobile phones, Web 2.0

1. Introduction

Noise pollution is a major problem in big cities around the world. It affects human behaviour, well-being, productivity and long-term health [8]. Noise has also a broader environmental impact, by chasing animals out of their habitat or altering their behaviour [41]. According to a publication of the EU [8], *"Environmental noise* (...) *is one of the main local environmental problems in Europe and the source of an increasing number of complaints from the public"*. EU experts estimate that 80 million people suffer from noise levels considered as unacceptable, and 170 million people experience serious annoyance during daytime in the European Union [13]. This problem is also pressing in other parts of the developed world (e.g. in US cities [17]) but also in developing countries (e.g. in Mumbai, India [2]) where regulations and monitoring systems to curb excess noise are often lacking.

Recognising noise pollution as an important issue, the European Commission adopted the European Noise Directive (END) [14], which requires major cities to establish a noise management policy. The END defines environmental noise as *"unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic, and from sites of industrial activity"*. The first step in the establishment of such a policy is to assess the current situation by gathering real-world data and building strategic noise maps. A noise map is a graphic representation of the sound level distribution existing in a given region, for a defined period (see section 2). Based on these maps, local action plans and legislation can then be established to reduce noise pollution and to preserve environmental noise quality where it is good. It should be mentioned that the END deals with strategies and long-term approaches to reduce noise for the majority of the population. It does not

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address individual or accidental cases, complaints and neighbourhood noise nor noise in the working environment.

The establishment of a noise policy is complicated. It cannot be tackled by institutions alone [19] and needs the participation of the general public [30]. Numerous international reports such as the Principle 10 of the Rio Declaration on Environment and Development [38] have expressed the importance of public participation to move towards sustainable development. However, in the case of noise pollution, its assessment neglects to represent the real exposure experienced by the citizens themselves, and therefore could lead to wrong conclusions and a biased representations.

Web 2.0 practices [22] – characterized by user participation, openness and network effect – have transformed the role of the public, from passive consumers of information into active participants due to a democratization of authoring tools (e.g. wikis, blogs, etc.) and social connection tools (e.g. social networks). Recognising this development as an important trend the UK Government recently commissioned a report, titled "Power of Information" [21], which investigates the potential of ICT tools to transform public service information.

The question is then, can we transfer such user-generated content practices from the digital world to the real world and environmental context? How could the practice of pollution monitoring change if every citizen had a personal mobile measurement device?

In this paper we present the NoiseTube project [1] a novel approach to monitor noise pollution involving the general public. The main idea is to turn smart phones into noise sensors enabling every citizen to contribute to a collective effort to map and monitor noise pollution. Taking inspiration from participatory sensing [6] our goal is to investigate how a participatory and people-centric approach to noise monitoring can be used to create a low-cost, open platform to measure, annotate and localize noise pollution.

In Section 2 we discuss the current methods of noise pollution assessment. Next, Section 3 introduces our alternative approach to monitor urban noise pollution. In Section 4 we explain the different components of the NoiseTube platform. Then, in Section 5 we give an overview of some of the scenarios in which NoiseTube could be used. Further discussion and directions for future work are provided in Section 6.

2. Noise assessment challenges

Laws and regulations, such as the END [14] in Europe, have stimulated the development of two approaches to assess noise pollution by governmental agencies: simulated noise maps and real-world data gathering using sensor networks. Alternatively, there have a been many *grassroots* noise measurement campaigns, small citizen-led initiatives focusing on specific local issues to collect evidence to convince authorities without waiting for officials to conduct measurements. We discuss each of these approaches and their limitations.

Method 1: Simulation-based maps

Starting from knowledge about the behaviour of noise sources and by applying physical laws of sound propagation, complex computer models are able to predict noise levels over huge areas. This emission modelling results in simulated noise maps such as the one shown in Fig. 1.

Current limitations

Uncertainty of results Since the basis of such computer models is only validated with a limited amount of measurements, it is hard to estimate their error margins. Secondly, modelling the emission of

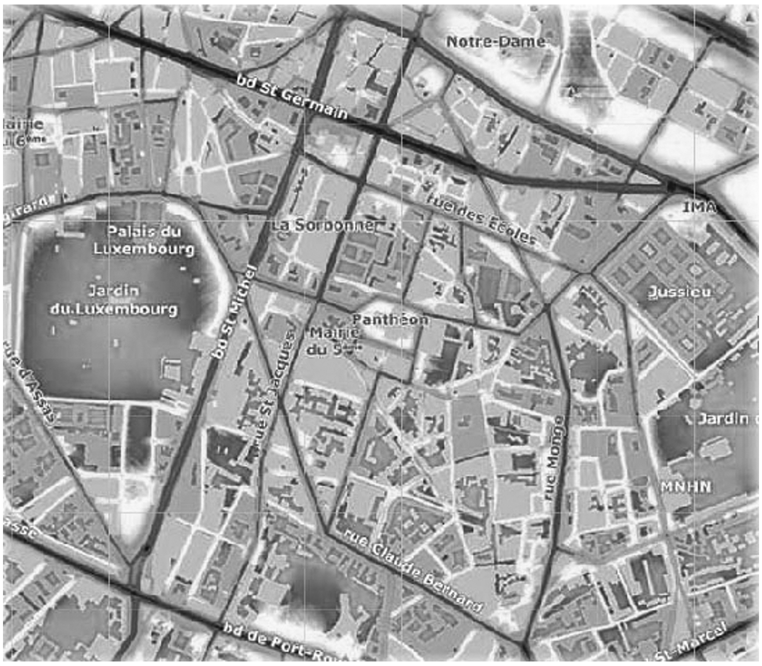

Fig. 1. A part of the official noise map of Paris, generated using a computational model.

noise source requires a large number of difficult to estimate input parameters. For instance, to model road traffic, one needs to account for the frequency of different vehicle types, road surface types, weather conditions and urban topology. Thirdly, noise maps as defined in [14] only cover noise caused by road, rail and air traffic industry. However, the diversity of sources in real scenarios is much broader. Also, indoor situations are rarely modelled despite people spending the majority of their time there. All of these issues may lead to incorrect conclusions regarding the actual discomfort [34] caused. As stated by the EU practice guide [13], real data with fine granularity in both time and space is required.

"Hot spot" detection Strategic noise maps can only inform about expected noise levels generated by predefined sources of noise and are only updated every 5 years (END requirement). This makes it impossible to cover local variations, let alone accidental or short-term pollution peaks, for instance caused by construction sites, road works, traffic deviations, festivals, etc.

High cost Creating strategic noise maps requires the use of expensive simulation software (and powerful computers to run it) as well as human expertise. This restricts cities with limited budgets from conducting such assessments.

Emission vs. exposure The EU practice guide [13] recommends detailed assessment of the level of noise citizens are actually exposed to. However, few efforts have been done to combine emission modelling and population data to estimate the actual noise exposure of citizens in an accurate way [35].

Method 2: Sensor networks

Recent years have seen an increasing interest in sensor networks for environmental monitoring [31] and urban sensing [10]. A sensor network consists of distributed sensor devices cooperatively monitoring in

Fig. 2. One of the few sensors measuring noise in Paris.

real-time environmental phenomena (e.g. temperature, sound, air pressure, air quality, etc.) at different locations. Figure 2 shows a noise sensor in Paris. Some experiences using sensor network for noise monitoring is discussed in [33]. In this project noise sensors were placed at fixed locations to measure traffic noise.

Current limitations

Network sparsity Even though a number of EU cities have deployed sensor networks, the number of sensors is usually very limited. For instance, in Paris the network of noise sensors currently consists of only 5 sensors [4]. Data collection at sparse locations hardly scales to meet the high spacial and temporal granularity recommended by [13].

High cost Deploying large number of sensors to cover the city is expensive, restricting cities with limited budgets from applying this method.

Source identification Using this method, as opposed to emission modelling in which simulated sources are predefined and can be mapped separately, identifying the (mixed) sources of pollution from raw measurements is a difficult and hard to automate task.

Places vs. people Sensors are usually placed on fixed locations, which means they are inherently measuring pollution at given places and not the exposure of actual people during their daily lives and mobility. The assessment of the exposure to pollution of the population is a real problem due to the complexity to measure it. For officials, measuring personal exposure for a citywide population is currently viewed as impractical.

Method 3: Grassroots campaigns

Participatory GIS [9] and participatory mapping are new methodologies are being researched to better support the 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 projects in the context of noise pollution monitoring are [16] and [12,18]. In the latter project researchers reached out to citizens concerned with noise pollution in their London neighbourhood. The citizens were trained, coached and equipped with noise level meters to measure noise in their neighbourhood and visualise it through an online GIS.

Current limitations

Cost/availability of instruments One of the obstacles is that participants need to be equipped with expensive equipment (sound level meters, GPS devices, etc.). Because the budgets for such campaigns are usually limited this restricts the number of participants, which in turn can lead to a biased representation of the environmental conditions of the local population.

Credibility To achieve credible results it is necessary to gather as much data as possible and thus mobilise large groups of participants. Also, average citizens are not trained experts. Without the support of professionals, campaigners have a hard time providing scientific evidence to back their claims.

Lack of a knowledge infrastructure Such campaigns are usually short-term efforts to raise awareness about local issues and thus lack the continuity required for a long-term view on and management of the situation. There is a lack of an infrastructure to gathering knowledge in a more sustainable way and re-diffusing this knowledge to the public.

3. Approach

Under the name *NoiseTube*, we propose a low-cost approach involving the general public to monitor noise pollution using their mobile phones as noise sensors. Our approach is based on the idea of community memories. In [36] community memories are defined as ICT resources (usually Web-based) that enables communities to record and archive information relevant to the management of a commons. In the case of noise pollution the commons at stake is silence and thus quality of life in urban areas.

3.1. Crowd-sourcing noise pollution

3.1.1. Phones as personal measurement instruments

Participatory sensing [6] advocates the use of mobile devices to form sensor networks that enable public and professional users to gather, analyse and share local knowledge. The growing popularity of *smartphones*, with significant computational power, Internet connectivity and integrated sensors (e.g. microphones, cameras, GPS, motion sensors) opens the door to a wide range of such new applications. Firstly, these devices represent a cheap but powerful sensor network that is readily available and widely deployed. Secondly, in this perspective phones can serve as mobile sensors which are carried by humans rather than placed at static locations.

3.1.2. Measuring noise as experienced by people

People can use this instrument in the context of grassroots campaigns to collect pollution measurements at specific locations outside their daily environment. But the cellphone is mostly co-located with the user. As a consequence, it can be also used as a tool to monitor their individual exposure in the short or longer term. A sensor network consisting of these phones would match the rich diversity of the lives and mobility patterns of citizens and could thus supply real data on their exposure. Moreover, the approach could provide a new social perspective to support the understanding of this urban problem. This opens potential links with epidemiological studies at a larger scale. The usefulness of such people-centric data has been demonstrated at a small-scale level in medical projects such as [40], in which children were equipped with sensors for air pollution to understand the factors affecting asthma.

3.1.3. Adding contextual information

Noise maps created by officials only provide very limited information regarding the source or context of noise. This sort of semantic information is vital to make maps more useful and meaningful for end-users, particularly citizens. The problem is even worse for current sensor networks, which are unable to automatically identify sources of noise from raw measurements. Furthermore, navigating and searching through large amounts of numerical data is a difficult task. When thinking of pollution people do not reason in quantitative terms but rather in qualitative ones, therefore expertise is required to interpret numerical values.

To tackle these issues, we enrich measurement data with semantic annotations by relying on the *collective intelligence* of both people (via social tagging) and machines (using automatic classifiers). Through social tagging [36], people can for supply all kinds of qualitative meta-data such as the source of noise (“airplane”), the location (“7, av. Fontarabie”), the time (“morning”) or even subjective comments (“annoying”). Additionally, because participants cannot be expected to tag all the time, automatic contextual tagging done by the machine complements the human effort. The contextual information that is thus supplied adds a semantic layer on top of the map and allows us able to aggregate measurements in more meaningful ways for end-users. See 4.1.3 and 4.2.4 for more details.

3.1.4. Community Memories: Managing and diffusing data

To manage and diffuse the data among the community our goal is to create a “data commons” [10], a repository gathering the measurements, that is legally and physically accessible for the community. To manage this commons a platform was developed to support the organization and exploitation of the data with different aspects: visualization, semantic exploration and access to raw data.

Furthermore, rise of social media and the power shift it represents allows to envision the distribution and diffusion of data in a new way. People can use social networks and micro-blogging platforms (e.g. Facebook and Twitter) to spread their exposure measurements, especially when values are considered abnormal or dangerous, to their contacts living in the same area. Compared to traditional environmental agencies using only a static websites (*pull* system), citizens can spread the latest evidence of local noise pollution through social media to increase visibility and reach more stakeholders in a more direct way (*push* system; e.g. via SMS or e-mail alerts). By moving the information from traditional Web platforms to a social media ecosystem we also facilitate public debate and thus collective action: aware of local pollution via messages from peers, people can make their own measurements to support or counter the credibility of the case being made.

3.2. Empowering Citizens

3.2.1. Enabling low cost measurements

“How much decibel am I exposed to now?” This kind of information is currently hard to obtain for a citizen. One of the principles of the governance of commons, as introduced by Nobel price for Economics winner Elinor Ostrom [25], states that it is necessary that “resources can be monitored, and information can be verified and understood at relatively low cost”. By turning smart phones into personal environmental instruments, we strongly lower the barrier to environmental measurement technology to achieve a democratisation of the monitoring process.

3.2.2. Individual level: Supporting behaviour change

Citizens are often partially responsible (at least indirectly) for some of the noise pollution they experience. Changing collective behaviour could thus solve a part of the problem. At an individual level, giving the possibility to any citizen to measure their personal noise exposure in their daily environment could influence their perceptions and potentially raise awareness about environmental issues, the first stage in the adoption of new behaviour in the long term [32]. Indeed, personalized information has a bigger impact than general statistics provided by governmental agencies. Thanks to its ubiquity, the mobile phone has already demonstrated its value as a persuasion tool in several cases (e.g. education, health and marketing [15]).

3.2.3. Collective level: 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 and tools for citizens to collect data and build collaborative exposure maps to convince authorities and influence decision making on local issues, without waiting for officials to gather data [26]. This approach enables the production of local environmental information for the community and empowers citizens in the debate on environmental management by raising awareness about their living conditions. This new paradigm could also render noise management polities more transparent, since the citizens can participate in the data collection, make counter-measurements, validate, annotate, structure and share information.

3.2.4. From sharing to cooperation to collective action

Even though the ubiquity of mobile phones makes mass participation feasible, as attempted in [28], it remains questionable how the general public can be motivated to participate voluntarily. However, well known Web 2.0 success stories such as Flickr, YouTube or Wikipedia prove that it is possible.

As pointed out in [3] the Web 2.0 phenomenon contradicts many predictions regarding the form of cooperation and community that were encouraged by the founders of the Web. As shown in studies of bloggers or Wikipedia [5], the motivations of contributors do not fit into a single category, apart from the utilitarian maximising of personal interest they are just as well motivated by a desire to volunteer and be part of a community. Users generally first have individualistic motivations when they begin to publish personal production (e.g. blog posts). But doing so appears to develop a greater number of interpersonal relations than expected, although the links between individuals are 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 sharing of personal exposure measurements on a public profile is an opportunity to test this 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 emerge and collective action could be facilitated to overcome the cold start effect.

3.3. Summary

To summarise, Table 1 provides a comparison of our approach with the three more traditional approaches which were discussed in Section 2.

Table 1
Summarising comparison of NoiseTube with 3 more traditional noise assessment approaches

	Simulation-based maps	**Sensor networks**	**Grassroots campaigns**	**NoiseTube**
Inputs	Complex parameters for each considered noise source	Limited number of geographically distributed high quality sound level sensors	Short term measurement campaign in specific area or sparse locations + qualitative information	Raw measurements with limited accuracy + contextual/semantic information, combined with publicly available geographical data (Google Maps/ Earth, OpenStreetMap, . . .)
Operators	**Authorities, public institutions, environmental agencies**		**NGOs, small citizen groups**	**Potentially everybody, initiative can be citizen- or authority-led**
Outputs	END [14] noise maps: showing (simulated) impact of industry and road, rail and air transport on an average day and night, to be updated every 5 years. Difficult to interpret by citizens.	Daily indicators (+ annual reports) based on measurements at a limited number of locations	Reports about local issues	Actual noise measurements, enriched through tagging, collective noise exposure maps with semantic layers, aggregation per administrative boundary, noise exposure profile for individual users or communities, semantic exploration feature, . . .
Deployment cost	**High** Requires access to private and up-to-date data, simulation software, expertise	**High** Expensive sensors and infrastructure to deploy the network	**Moderate** Requires costly professional devices, sufficient participants, coaching	**Low** Requires participation of (sufficiently large) number of people (possibly volunteers) limited only by availability compatible phones
Diffusion	Often maps are published online but in some cases they remain inaccessible for the public	Indicators, usually published online (no public access to raw data)	Public reports but no access to raw data	Community memory website, downloadable maps, access to raw data, sharing through social networks (e.g. Facebook or Twitter), . . .

4. NoiseTube platform

The main components of the NoiseTube platform are a mobile application that people have to install on their smart phones and a Web-based community memory system running on a central server.

4.1. Mobile application

The mobile application can be freely downloaded via the NoiseTube website [1] and installed on a variety of compatible smart phones[1] to turn them into mobile noise sensors. It collects information from different sensors (noise level, GPS coordinates, time, user input) and sends it to NoiseTube community memory server. The photo in Fig. 3 shows this application being used in a busy street. Below we will discuss the principal features of the application.

[1]Phones should support the Java J2ME platform, with the CLDC v1.1 profile and with MIDP v2.0 or newer (the most common J2ME variety) and implement the JSR-179 Location API, preferably with a built-in GPS receiver, and the JSR-135 Mobile Media API, with the capability to record sound in an uncompressed format (PCM, WAVE, AIFF). More details on these requirements can be found in the NoiseTube User Guide [37].

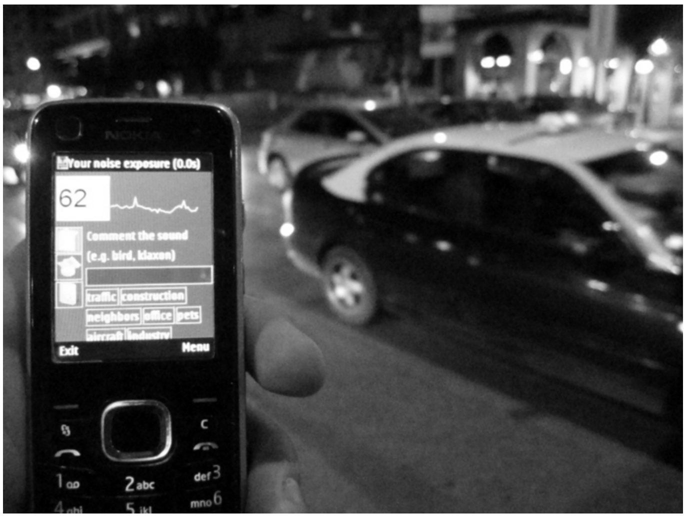

Fig. 3. The NoiseTube Mobile application in use in a busy street.

4.1.1. Measuring noise exposure

The mobile application contains a real-time signal processing algorithm which measures the level of the environmental sound. The algorithm takes 1 second-long samples, recorded using the phone's microphone, applies an A-weighting filter – to mimic the frequency response of human hearing – and computes the equivalent sound level (L_{eq})[2] measured in dB(A). This process is repeated constantly while the application is running, resulting in a stream of measurements which are displayed on the screen of the phone as numeric values and on a histogram (as shown on Fig. 4) to offer real-time feedback. To provide additional short-term feedback each measurement is placed on a simple colour scale, representing the level of annoyance the sound level is likely to cause as well as the health risk of prolonged exposure at that level: $<$ 70 dB: green (no risk); [70, 80] dB: yellow (be careful); $>$ 80 dB: red (risky).

Each decibel measurement is sent to the NoiseTube server in real-time or saved to a file to be uploaded later. To avoid privacy concerns no actual audio recordings are stored.

Because different mobile phones have different microphones the algorithm needs to be calibrated for particular models. Currently the application ships with calibration settings (established in our audio lab) for 7 different models and it detects the phone model to apply the right ones. Furthermore, if they have access to a sound level meter users can calibrate the algorithm themselves from within the program. To evaluate the precision of our solution we have conducted a number of experiments in collaboration with BruitParif, the official observatory for noise in the Paris region. The conclusion of this evaluation was that our solution achieves an average precision of $\pm$ 2.5 dB when the phone is held in the hand, which we consider acceptable for our goals. More information about calibration and accuracy issues can be found in [20].

To be useful in the context of hearing loss prevention the mobile application also provides a mid-term feedback in the form of a personal *noise exposure dose* meter. Discrete noise level measurements are insufficient to be used as an accurate indicator to quantify the risk of hearing loss because the notion of duration is missing. Therefore we implemented an indicator of the cumulative exposure during a

[2] L_{eq} is the standard indicator required by the END [14].

Fig. 4. The NoiseTube Mobile application interface includes the following main components: the measured sound level (visualised with a histogram and a color scale), complemented by a dose indicator (on top), the tagging component and the location tagging component (for indoor locations for instance).

single day. This D-value (shown on top of the interface shown in Fig. 4) represents a percentage of the recommended maximum daily exposure to high noise levels, based on recommendations of the American National Institute for Occupational Safety and Health [23]. We consider the exposure dose calculation a useful addition to the application to enable users to easily estimate when prolonged exposure to high noise levels becomes dangerous and support motivation to measure.

4.1.2. Geographic localisation

The mobile application uses a GPS receiver (built-in the phone or external) to add geographical coordinates (WGS84) to each measurement so they can be projected on a map afterwards. Alternatively, the application supports manual geo-tagging that enables users to enter a street address or a pre-defined place tags (e.g. "home", "work") which can later be turned into geographical coordinates.

4.1.3. Social tagging

Taking inspiration from [36], we enable users to directly annotate or tag sound level measurements using the mobile application. As people are excellent at recognizing noise sources, the mobile application allows them to annotate measurements in real-time regarding the cause or context of their exposure (e.g.: cars, aircraft, neighbours). These *tags* are sent along with the measurements to the server where they are used to enrich visualisations and maps as well as to facilitate organisation and exploration of data (see 4.2.4).

4.2. Web-based Community Memory

The Web-based community memory [1] is the second component of the NoiseTube platform. Here we collect all gathered noise pollution data while offering user-friendly tools to explore, visualise, analyse and search through it.

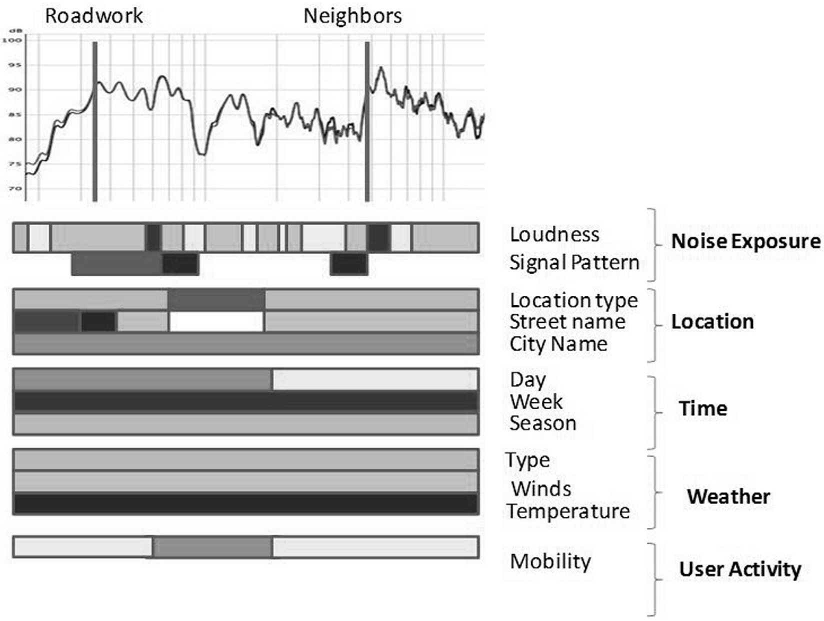

Fig. 5. Automatic contextual tagging: each measurement (a point in the curve) is tagged by a set of classifiers (each line) grouped in different contextual dimensions (e.g. Time, Location, User Activity). For instance, the classifier "Day" tags each measurement according to its timestamp, using for example the tags "morning" and "afternoon".

4.2.1. Collecting and post-processing measurements

Once the measurements are sent to the server, post-processing algorithms are applied to correct and/or enrich them.

Automatic contextual tagging: As explained above, people can tag their measurements, for instance to identify sources of noise, a very hard task for machines. But because tagging takes time participants may not do it frequently enough to provide sufficient meta-data to fully understand the context in which measurements were made. Therefore we rely on an automatic post-processing algorithm to complement the efforts of the users. The algorithm uses a set of classifiers to add additional tags describing different contextual dimensions such as time, location, weather conditions and user activity, as illustrated by Fig. 5. For instance, the location-related classifiers take WGS84 coordinates as input and use reverse geo-coding to add tags such as city and street names. Another example are the time-related classifiers that tag each measurement according to the moment of the day (e.g. "afternoon"), type of day ("weekend", "workingday"), season, etc.

GPS correction: To partially make up for GPS positioning errors we apply a *map matching* algorithm. By making the assumption that all outdoor measurements are made in streets (i.e. not on roofs, in gardens or parks) and relying on a GIS database which stores digital street maps [3] the algorithm basically "pulls" all points that do not lay on a street to the nearest position that does. Figures 6 and 7 illustrate the process. Of course the assumption being made can be too restrictive in some cases, so in the future we may add a feature that allows users to switch off the correction (e.g. when they *are* in a garden or a park).

[3]Using data provided by city councils or obtained through free services like OpenStreetMap (http://openstreetmap.org).

Fig. 6. A measurements series before applying GPS correction.

Fig. 7. The same measurements series as in Fig. 6 after applying GPS correction.

4.2.2. User profile: Elog

After post-processing measurement sessions (or *tracks*) are added to the board of activity of the user, called the *Elog*, or “Exposure Log” as shown on Fig. 8. Inspired by the concept of blogs, an Elog represents the digital trace of the environmental dimension of a user’s daily activity by making their measurements public to the community. Measurement series (called *tracks*) also can be visualised on a map using Google Earth[4]. Complementing the Elog, the user’s semantic profile, in the form of a tag cloud, is displayed. With this public profile we also attempt to support opportunistic connection and interaction among people facing similar problems and environments or leading similar lives.

4.2.3. Collective exposure maps

Per city a collective noise map is available which shows all shared measurements made in that particular place. To add context and meaning to the data, the maps include a semantic layer (consisting of the social

[4]Google Earth is available for free at http://earth.google.com.

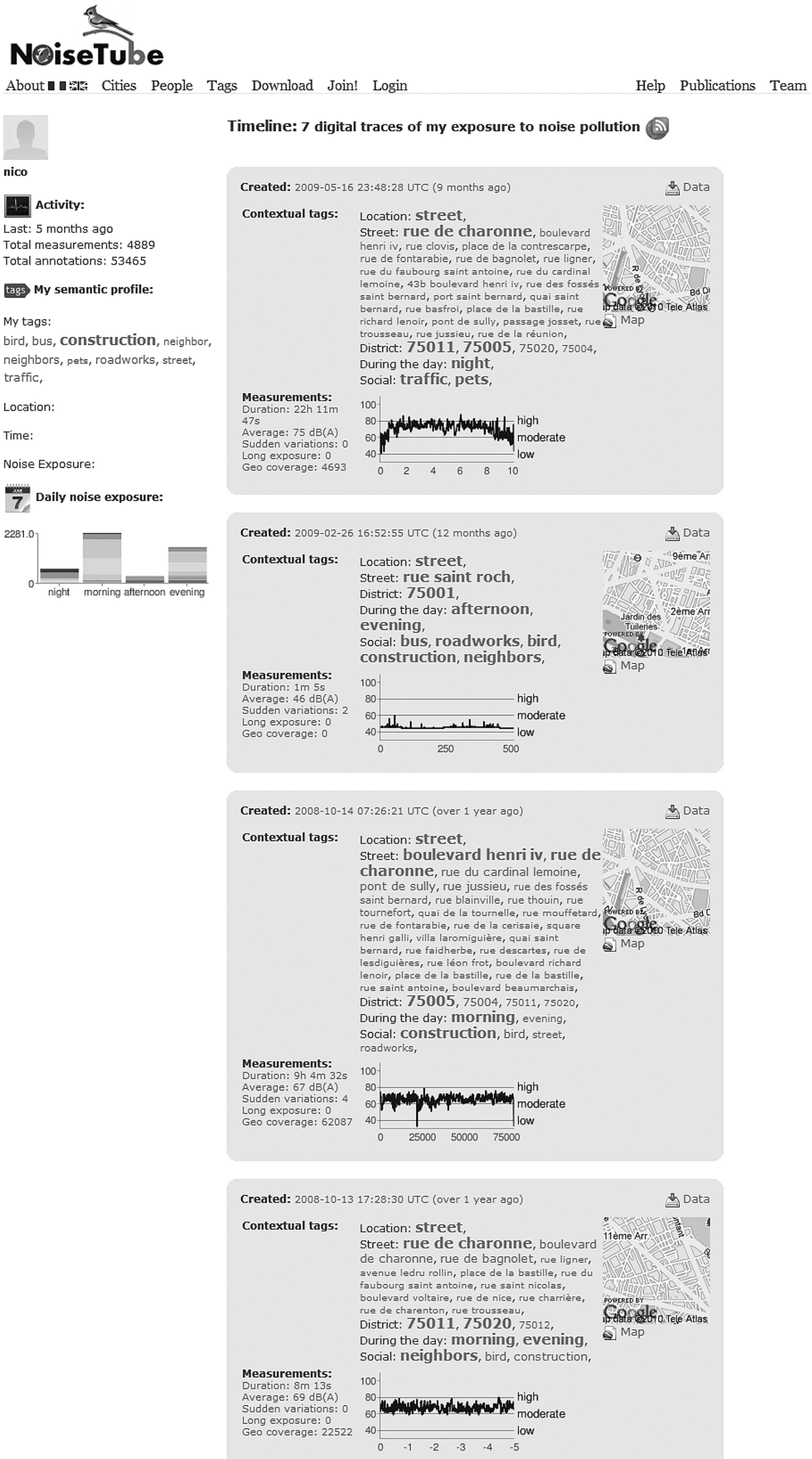

Fig. 8. *Elog* page of a NoiseTube contributor.

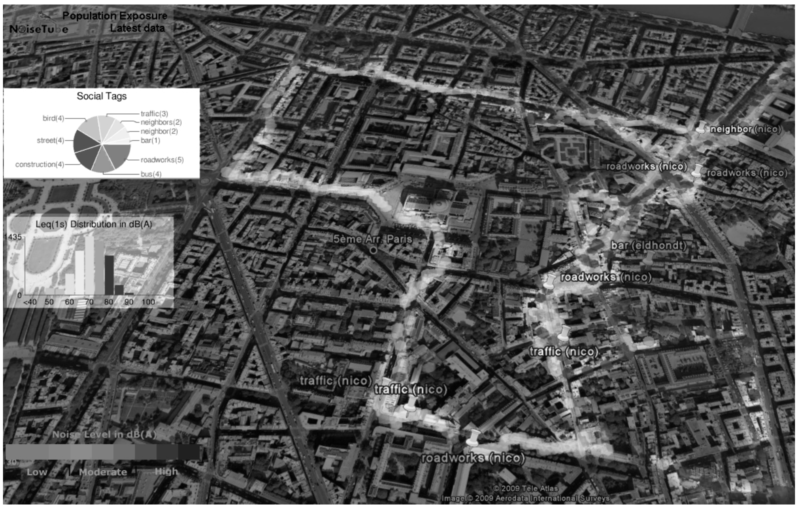

Fig. 9. The collective noise map for Paris, displayed using Google Earth. The legends on the left (pie chart of the social tag cloud and the sound level distribution) are dynamically updated with respect to the area in view.

Fig. 10. A noise map of an area of Paris, without applying aggregation.

tags) and legends (e.g. distribution of the sound level, and distribution of the social tags) that change dynamically according to the area displayed. Figure 9 shows an example of such a map.

Furthermore we created a semantic clustering feature to aggregate measurements per administrative boundary (e.g. street segment or district), as illustrated by Figs 10 and 11. Such representations are rarely seen on public noise maps despite the fact that it could be useful to support local decision making. [5]

4.2.4. Semantic exploration

To support interpretation on a higher semantic level we developed a feature that projects annotated noise exposure data in a semantic space, contextualizing information and thus facilitating exploration

[5] We must note however that this aggregation currently does not account for the spatial distribution of measurements *within* the boundaries and the physical propagation of the measured noise. Using existing sound propagation models it should be possible to make these aggregations more representative.

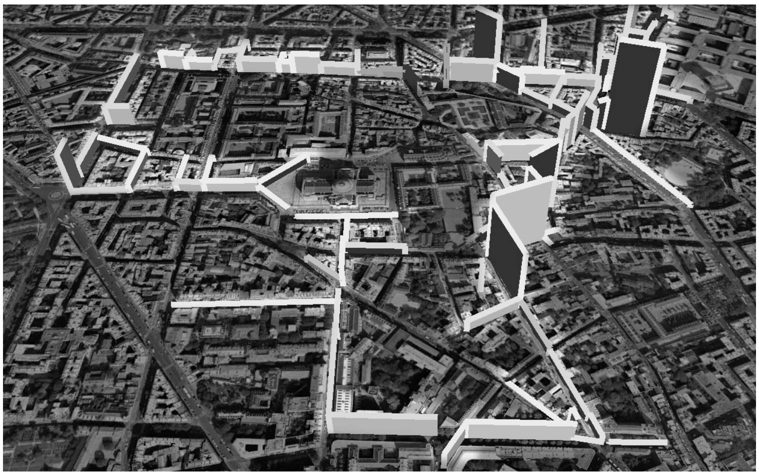

Fig. 11. A noise map generated from the same data as Fig. 10 but aggregated by street segment.

for contributors and stakeholders. Once tagged by people or by the machine, the data can be explored by anyone using the Tag-based or Semantic Exploration feature. As shown on Fig. 12, the dataset is represented semantically using a set of tag clouds, one per contextual dimension, e.g. location, time or user activity. Users can explore the dataset by iteratively selecting tags to zoom in on the dataset to retrieve particular information they are looking for (e.g. traffic noise on Monday mornings in the 5th arrondissement of Paris). In each iteration the semantic representation (i.e. the tag clouds) are recomputed according to the selected subset, which can also be projected in the geographical space by downloading a dynamically generated map.

5. Scenarios

We expect NoiseTube, or similar participatory sensing solutions, to be useful in a number of different situations. In an effort to categorise the possibilities we differentiate them according to the party who takes the initiative.

5.1. Citizen-led initiatives

Because of the low barrier, in terms of both cost and complexity, concerned individuals can use the platform to study noise pollution in their neighbourhood. The participants can be self-organised citizens with varying levels of organisational involvement: ranging from total strangers that happen to live in the same area; over loosely organised groups of neighbours facing a shared problem; to well-organised previously existing activism groups.

The motivation for such initiatives can be diverse: from curiosity about one's daily environment to the gathering of evidence on concrete local issues. These can be long-term issues (such as the problems faced by people living close to airports, highways, factories or nightclubs); short-term ones (such as roadworks or nearby construction sites); or accidental annoyances (such as manifestations). NoiseTube can be applied by citizens to complement (e.g. in terms of spatial and temporal granularity) the work of authorities or it can be used in places that are not covered by any official initiative. Examples of the latter case can be cities in developing countries or specific environments for which data may be lacking.

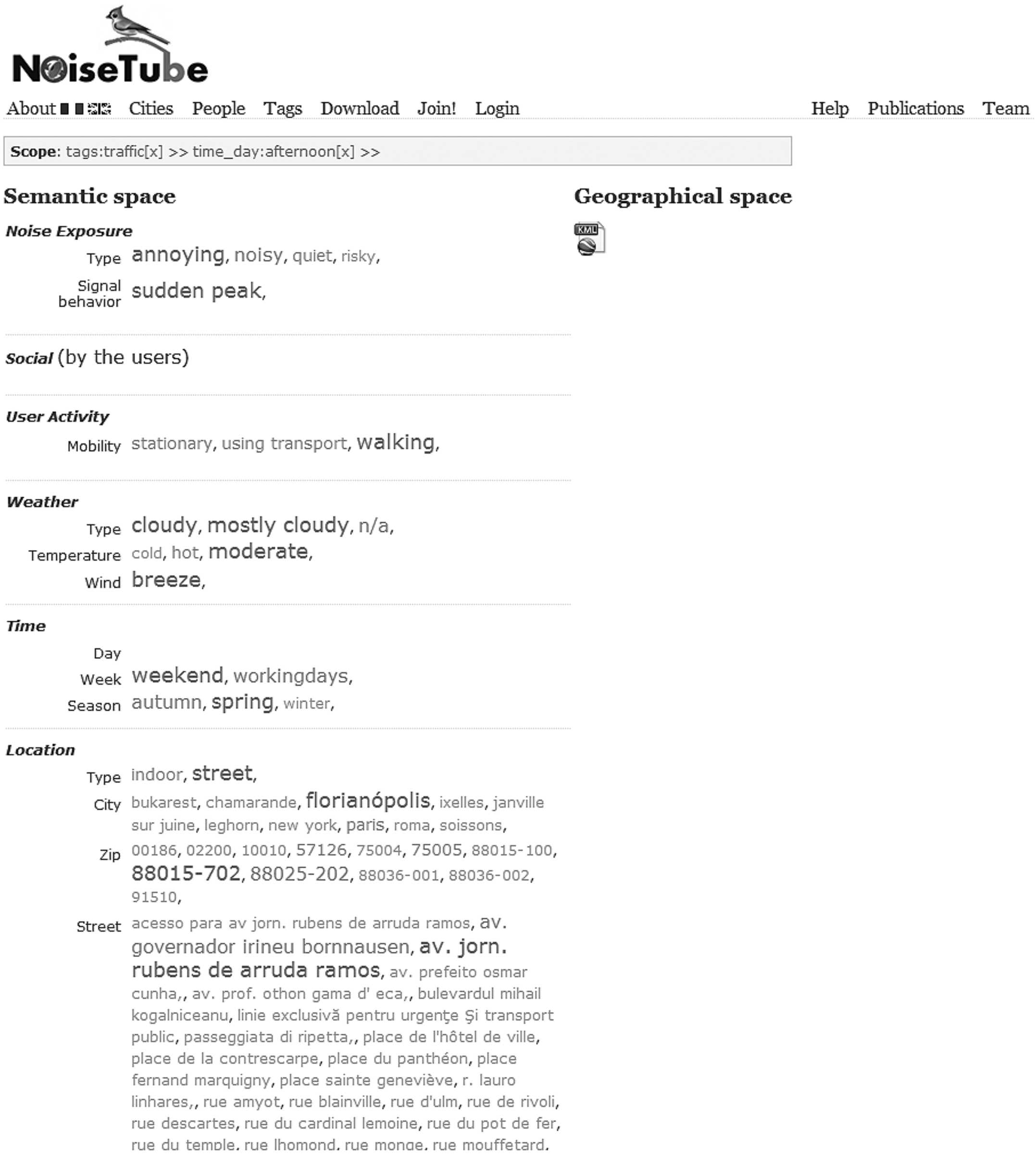

Fig. 12. The semantic exploration feature of the NoiseTube community memory server allows users to explore the database by iteratively selecting tags.

Figure 13 shows a NoiseTube map of a subway network, a noisy environment [24] for which little or no data on noise exposure is available.

5.2. Authority-led initiatives

NoiseTube can also be used by authorities and public institutions – typically, but not exclusively, on municipal or regional levels – to gather data on noise exposure and pollution. This data can be

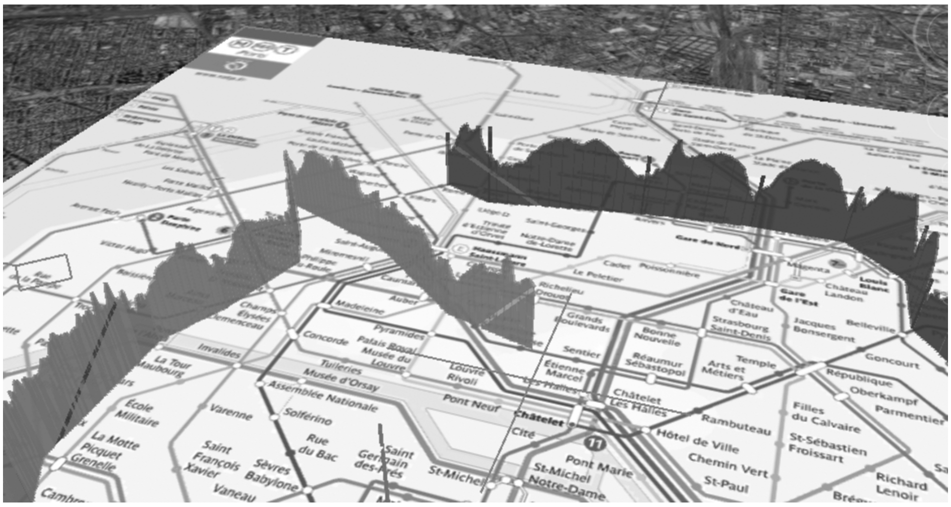

Fig. 13. Visualization of the measured noise exposure along several Parisian subway lines.

used to support decision and policy making in different domains such as public health, urban planning, environmental protection and mobility. Applying a system like NoiseTube can complement or be integrated with existing (traditional) environmental monitoring initiatives. However, the low cost of deployment also enables authorities that currently have no monitoring system in place due to limited budgets (e.g. small cities or authorities in developing countries) to start gathering data on the pollution their citizens are exposed to. When used alongside an existing monitoring system a participatory sensing platform could make up for missing data, help to estimate error margins of simulation models, add semantics (e.g. identification of pollution sources), etc.

Of course deploying a participatory sensing network on a wide scale requires a large number of participants. While authorities can choose to work exclusively with volunteers (i.e. concerned citizens), it may take big publicity, communication and coaching efforts to keep these people motivated and active. Therefore it is probably wise to look for schemes that provide (financial or other) incentives to contributors. A possibility could be to offer free calling minutes in return for measurement data or a leasing system in which volunteers are given a fancy mobile phone that they can come to own if they remain active during a predefined period of time. Other schemes could involve publicity deals with advertisers or network operators.

6. Discussion and Future work

6.1. The roles of citizens and machines

How to sustain a human network at a larger scale and for a longer time to go beyond local and short-term experimentation or campaigns? How to design a network mixing humans and machines to monitor environmental resources? As far as we know, these questions have not yet been solved by the current research on participatory sensing due to the small amounts of participants in campaigns and a 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 analysed by a machine. Further research could take advantage of social relationships, shared interests or reputation (beginner/citizen vs. expert/scientist) among the participants to tackle the problem of data/analysis credibility by using people not only as sensors but also as filters or regulators.

6.2. Supporting the debate

How to design and represent knowledge in a way that engages debate and encourages action is still an open question. In [27] Paulos highlights a set of challenges related to such issues and proposes a design that favours raising doubt rather than promoting blind acceptance of fact. Knowing the underlying issues related to such social production (e.g. data credibility), how will people use data to argue for or against various hypotheses? Which approach could encourage the development of solutions to environmental problems using these data commons?

A possible track could be to take inspiration from the qualitative work on controversy mapping [39], initiated by Latour. Controversy is used as a general term to describe a shared uncertainty and confront the user with forms of knowledge that are still unstable or complex situations of conflict. It was developed for the investigation of contemporary socio-technical debate but could be used in a context of local environmental issues due to their complexity. Such mapping does not find the most appropriate or optimized technical solution, but aims at assist stakeholders in identifying all possible scenarios and links.

Finally another approach is the use of a narrative model as a complex form to explain a situation from multiple stakeholders' points of view. In [29] the narrative is presented as a type of output from a environmental model, a more useful way for the non-expert than statistics or maps due to a richer contextualization and causality of issues. Narratives provide a rich medium for expressing causal chains of events that form the basis for explanation and its future use in policy and decision making. By extending data models to support such a narrative unit the author argues that some aspects could be automated to generate scientific explanations in narrative form.

6.3. Lessons learned

The NoiseTube prototype has been publicly released in the summer 2009 and has been demonstrated at a number of events such as the Sony CSL Open House which was held in October 2009 in Paris. Until now, more than 200 users from 20 cities from all over the world have individually participated to collect noise pollution measurements using their mobile phones. Several communities and NGOs (e.g. the Awaaz foundation in Mumbai) contacted us to use the platform but so far there has been no pilot deployment in a real world situation with a group of participants working together in a specific area. The main reason for this is has been a lack of time and resources – from our side – to organize, finance and coordinate such a pilot. Furthermore there are a number of other obstacles that impede the deployment of a NoiseTube based noise assessment initiative:

Accessibility of technology Users need powerful, relatively expensive smartphones, compatible with the application. We chose to target the mobile application at the most widely spread mobile software platform (Java J2ME)[6], but the downside of this is that there are a huge number of different phone models to support and calibrate for. Currently just 7 phone models are compatible. While we

[6]To give an idea of the ubiquity of J2ME: in Q2 2009 over 50% of all sold smart phones run Symbian [7], which is just one of the mobile phone operating systems that support J2ME.

made it possible for users to do the calibration themselves (see 4.1.1) this only partially solves the problem because they need to have access to a sound level meter (and preferably also a sound proof room) to do so. This makes it difficult for local communities or NGOs to evaluate the technology because they do not just need to find volunteers but volunteers with compatible phones. Especially for organisations with limited financial resources, such as in developing countries, who cannot equip participants themselves, this is a major showstopper. We must note however that this constraint is likely to become less problematic in the future as today's powerful smartphones become cheaper and begin to spread in developing countries.

Social- and policy-related issues While we believe our platform is well suited to power small- to medium-sized campaigns more research is necessary to come up with strategies to truly foster cooperation between participants, local authorities and experts and to enable the transformation of collected data into to policy-relevant, actionable knowledge. Only then will it be possible to fully integrate participatory sensing assessments into environmental polities. In fact, the motivation of participants depends directly on the acceptance and legitimacy of their actions. Knowing that their collective work will not be rejected by local government or experts is a primary factor in the motivation process of participants.

Computer Science and ICT-related issues The NoiseTube platform is still a prototype and not a finished product. This means it should be seen as a proof of concept and a partial solution to a set of research challenges. Citizen science brings many new challenges like coordination of collective action, evaluation and management of data quality and uncertainty, aggregation and routing of information to concerned actors/stakeholders, etc. NoiseTube already contains partial solutions to some of these challenges – for example the latter one is touched upon by the aggregation of data by urban elements (e.g. streets) – but further research needs to be undertaken to complement and improve upon our work.

6.4. Future plans

To open up the technology that has been developed and enable others to reuse, extend and improve it we are currently considering to release (part of) the source code under an open source license.

Within BrusSense [11], a new research project funded by the Brussels regional government, we aim to continue research into participatory sensing and community memories. This project will build upon the NoiseTube technology and apply it in pilot studies in Belgium. To avoid the mentioned problems related to overly diverse devices the goal is to limit ourselves to specific devices.

7. Conclusion

In this paper, we presented NoiseTube, a project aimed at developing a participative noise pollution monitoring platform to enable citizens as well as governmental bodies and non-governmental organisations to gain awareness and insight into the problem of urban noise pollution. This Web 2.0-inspired approach allows the empowerment of citizens in the pollution assessment by raising awareness about their environmental conditions through the use of their mobile phones. As a new source of information, we illustrated how NoiseTube goes beyond traditional noise maps due to the new nature of the collected data – real, local and personal exposure measurements with additional semantic information – and thus goes well beyond the requirements of the EU Noise Directive [14] by highlighting factors outside the scope of a simulation-based noise map. Finally we emphasized our difficulties to evaluate and deploy this approach in real world situations, due to technological, social and open research challenges that need to be resolved before the democratization of environmental sensing through citizen science can succeed.

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