DYNAMAP: A LOW-COST WASN FOR REAL-TIME ROAD TRAFFIC NOISE MAPPING

PACS: *43.50.-x, 43.50.+y, *43.60.-c, 43.60.+d.

Alías, Francesc; Alsina-Pagès, Rosa Maria; Socoró, Joan Claudi; Orga, Ferran.
GTM – Grup de Recerca en Tecnologies Mèdia, La Salle – Universitat Ramon Lull
Quatre Camins, 30, 08022, Barcelona, España
Tel: +34 93 290 24 00
E-Mail:{francesc.alias,rosamaria.alsina,joanclaudi.socoro,ferran.orga}@salle.url.edu

Palabras Clave: Wireless acoustic sensor network, environmental noise, acoustic signal processing, noise monitoring, road traffic noise.

ABSTRACT

Several studies have found that noise pollution is a real public health problem, causing severe effects on concentration, sleep and stress in population. The Environmental Noise Directive 2002/49/EC and the CNOSSOS-EU framework are the main European instruments to address noise pollution, requiring Member States to publish noise maps and noise management plans every five years. DYNAMAP is a LIFE+ project aimed at developing a dynamic noise mapping system to represent the acoustic impact of road infrastructures in real-time using a low-cost wireless acoustic sensor network, including the automatic detection and removal of acoustic events unrelated to traffic noise.

RESUMEN

Varios estudios han demostrado que la contaminación acústica es un problema de salud real, teniendo efectos sobre la concentración, el sueño y el estrés entre la población. La Directiva de Ruido Ambiental 2002/49/EC y el marco CNOSSOS-EU son los instrumentos principales a nivel europeo destinados a combatir la polución de ruido, requiriendo a los Estados Miembros la publicación de mapas de ruido y los planos de gestión respectivos cada cinco años. DYNAMAP es un proyecto LIFE+ destinado al desarrollo de un mapa de ruido dinámico para representar el impacto acústico de las infraestructuras viales en tiempo real usando una Red de Sensores Acústicos Inalámbricos, incluyendo la detección y eliminación automática de eventos acústicos no relacionados con el ruido de tráfico.

INTRODUCTION

Noise pollution is a real public health problem, affecting the quality of life of people living in those environments affected by noise [1] in their concentration, sleep and stress. Some years ago, the competent authorities reacted to this situation in Europe, developing the European Noise

Directive 2002/49/EC (END) [2] and the consequent strategic noise mapping assessment CNOSSOS-EU [3], becoming the main European instruments to address noise pollution. Through this legislation, Member States are required to elaborate noise maps every five years for agglomerations with more than 100,000 inhabitants, major roads, major railways and airports [2], together with the design and deployment of the corresponding action plans to mitigate noise pollution. Finally, the END directive also involves making population aware of the effects of noise pollution on their health.

In general terms, the noise measurements required to feed the simulation software used to tailor noise maps in urban areas have been conducted by professionals that record environmental noise samples in representative locations during specific time periods using certified sound level meters. However, this approach, although guaranteeing the quality of the input data used to build the noise maps, only allows obtaining a static and subsampled picture of the noise levels of that environment. The recent outbreak of Internet of Things technologies has led the development of wireless sensor networks specifically designed to monitor and manage noise pollution in Smart Cities, which have been denoted as Wireless Acoustic Sensor Networks (WASNs) [4]. In the last decade, several works dealing with WASNs developed for environmental noise monitoring have been proposed in the literature [4]. Among them, we want to highlight the IDEA project in Belgium [5], the Cense project [6] in France, and the "Barcelona noise monitoring network" in Spain [7]. Moreover, outside Europe it is also worth mentioning the SONYC project [8] in the USA, aimed at monitoring noise pollution in New York City as well as providing an accurate description of the surrounding acoustic environment. Among the different WASN approaches, hybrid networks allow a large-scale deployment of this kind of networks, combining high-capacity (Hi-Cap) with low-capacity (Lo-Cap) nodes [4]. These networks are especially appropriate to sense places where no power supply is available (or it cannot be provided easily). Both nodes compute the A-weighted equivalent noise level (L_{Aeq}) of the monitored acoustic environment [9], being the Hi-Cap nodes also capable of running other signal processing processes, conduct and collect audio recordings when necessary, etc. In [10], the authors present the design of an acoustic sensor network based on this approach, with basic nodes using a low power µController. RUMEUR network [11] is also a hybrid WASN, including high-accuracy equipment for critical places, which is combined with less-precise measuring equipment in other locations.

The aforementioned works are focused on the monitoring of the general noise of the environment, obtaining the L_{Aeq} of the locations where the low-cost acoustic sensors are installed. Therefore, no information about the type of traffic (e.g., light or heavy) or about the presence of specific acoustic events in the acoustic environment are obtained; issues that are mandatory for the END directive [2]. Among them, Road Traffic Noise (RTN) has been identified as the main noise pollutant in cities [1]. In order to obtain a RTN map, the events that are unrelated to regular RTN should be removed before building the noise map. To this aim, those events, denoted as Anomalous Noise Events (ANE) should be removed automatically before computing the L_{eq} through specifically designed digital signal processing techniques.

The DYNAMAP LIFE+ project is aimed to develop a dynamic road traffic noise mapping system focused on monitoring the acoustic impact of RTN from road infrastructures in real-time [12]. To do so, a hybrid low-cost WASN including both Hi-Cap and Lo-Cap slave sensors has been designed. The DYNAMAP is currently being tested after been deployed in two Italian pilot areas: in the A90 motorway surrounding Rome as suburban environment, and in the District 9 of Milan as an urban environment [12]. In order to minimize the impact of ANEs from the L_{Aeq} computation [13], the noise map generation system includes an Anomalous Noise Event Detector (ANED) [14]. The ANED algorithm parameterizes the input acoustic data using Mel Frequency Cepstral Coefficients (MFCC) [15] to classify the input data as ANE or RTN (i.e., a two-class classifier) using Gaussian Mixture Models (GMM). The algorithm has been designed and implemented in real-time on the Hi-Cap sensors of the hybrid WASN [14]. However, the Hi-Cap ANED algorithm cannot be implemented as originally designed in the Lo-Cap sensors due to the computational resources it demands. Nevertheless, a Lo-Cap version of ANED for those sensors has been designed in order to provide a homogeneous picture of the RTN, thus, allowing the hybrid WASN to discard ANE from the L_{Aeq} computation also in those locations where the slave sensors will be placed (see [16] for further details).

This paper describes the current status of the development and deployment of the hybrid WASN of the DYNAMAP project together with the key elements of the noise monitoring system. The system includes the ad hoc design of the nodes of the network, the development of the ANED to automatically detect and inform about the presence of ANEs, and the central server that runs the noise map generation and the publication of the processed information through a web site that depicts the data using a GIS platform.

DYNAMAP WIRELESS ACOUSTIC SENSOR NETWORK

System description

The DYNAMAP system is composed of a hybrid network of monitoring devices installed close to the road, in order to detect the noise level, eliminating the anomalous events and transmitting the data to a central unit (see figure 1). The system has involved the design of customized hardware and software components, i.e. the low cost monitoring devices (both low capacity and high capacity), the algorithm to detect and eliminate anomalous noise events (ANED), the application to process and view data (NOISEMOTE) and the web-GIS software platform to update and report noise maps in real time.

The low cost monitoring devices

The project includes the development of a hybrid sensor network, using two sensor types:

- Hi-Cap: a high computation capacity sensor, able to compute a spectral analysis of the detected signals, to be used in complex environmental contexts;
- Lo-Cap: a low computation capacity sensor, customized to perform a limited number of operations, to be used in simple suburban contexts.

Both sensor categories were designed to collect, clean and send data to a central server, where they are analysed, processed and used to scale the basic noise maps. The raw signal clean-up function is achieved by means of the ANED algorithm especially developed for the project. The algorithm is embedded in the monitoring device, in order to obtain a more scalable system.

The Hi-Cap nodes are composed of low cost microphones and inexpensive embedded electronic boards, with high sound quality equipped with 3G modems. The main advantage of this system configuration relies in the possibility of being remotely reprogrammed. The main disadvantage of this solution stands in its high power consumption (over 2 W), which entails a physical connection to the electric power grid, limiting its application as a stand-alone system in remote places. A simpler solution was developed for the Lo-Cap, in order to reduce costs and make them operating also off-line with solar panels and batteries, assuming less consumption and very limited processing capabilities.

The data gathered by the monitoring devices are processed and published on the web through the NoiseMote Application (see the description below).

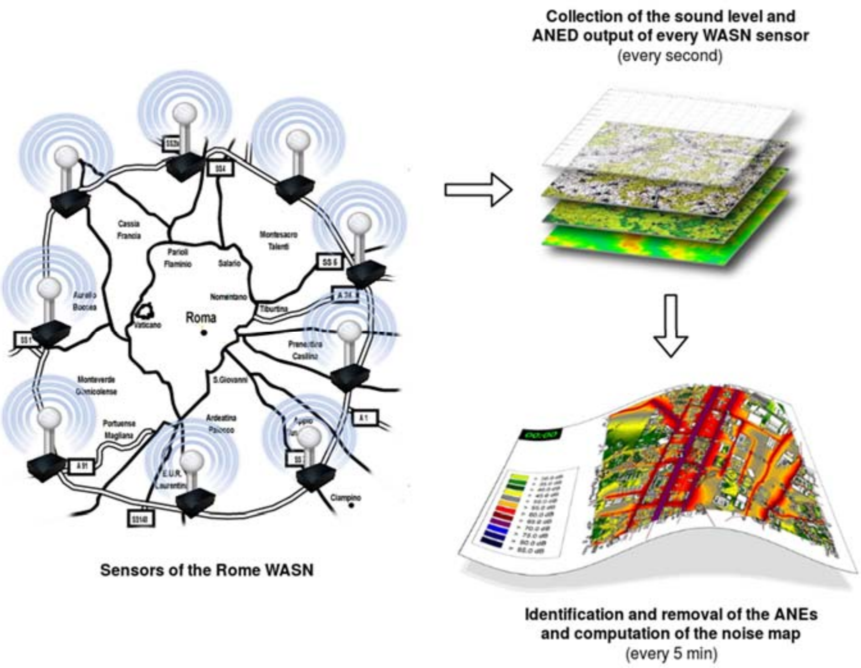

Figure 1: Description of the DYNAMAP System.

The ANED algorithm

Automating the update of noise maps through the DYNAMAP system entails several consequences. One of them deals with the content of the evaluated L_{Aeq} that can include, in addition to the main noise source, which is road traffic, the contribution of other urban noise sources. Therefore, the resulting maps would not constitute a reliable picture of the acoustic impact of road infrastructures. Then, it is necessary to enrich the DYNAMAP system with the ability to discern between road traffic noise and other types of acoustic events (e.g., sirens, aircrafts, industries, works on the road), to exclude the non-traffic related noise from the noise level computation. The ANED algorithm was developed using real-life data from a recording campaign [14]; it operates on the audio stream captured by the acoustic sensors and identifies the presence of ANEs automatically, activating an alert signal every second to exclude the corresponding audio segments from the computation of noise levels.

The NOISEMOTE application

The data gathered by the monitoring devices is managed and published by a software application developed ad hoc for the project, named Noisemote. Noisemote is able to show in real time, historical and statistical acoustic data within a time frame defined by the user. Real time data are updated with a time frequency of 1s within a time interval varying from 5 to 30 minutes.

The web-GIS software application

The role of the GIS software application is to re-scale pre-computed partial noise maps (basic noise maps), related to each noise source, using the noise levels detected by the monitoring devices. These L_{Aeq}'s are added together in order to update the noise map of the whole area under monitoring before publishing the results online (see figure 2). In fact, the system performs several tasks simultaneously: data collection and storage, maps scaling and addition of real-time data, and the publication of the information on the web. As noise maps should comply with the END and also with national legislation, in addition to dynamic noise maps, the software also provides a series of statistical information, such as day, evening and night data, L_{den} data, people and dwellings exposed to noise level intervals, etc. Moreover, the application reports information on the actions planned to mitigate noise levels. As for public information and communication, two levels for accessing the information of the system are available. A high privilege access level, reserved to authorized stakeholders, which provides detailed information (time histories and statistics), but also a low privilege access level, fully open, to inform about noise levels impacting the mapped areas and ease the participation of the public in the preparation of action plans.

Since L_{Aeq} and L_{den} values, representing the average noise level over a given period on a logarithmic scale, are indicators not easy to understand by the public and authorities responsible to take ownership of noise related issues, the Harmonica [17] index was applied in order to investigate its suitability to real time noise maps.

Figure 3: Portion of the dynamic noise map in the suburban area of Rome (left) and in the urban scenario of Milan (right)

The pilot area of Milan is located in the northern part of the town in a highly urbanized zone of the town. Because a large number of roads is present in that area, a statistical approach was evaluated to size the monitoring network. Thus, roads having similar traffic flow conditions and, consequently, similar noise trends were grouped together after an extensive measurement campaign that involved the acquisition of noise levels from 93 monitoring stations distributed all over the city [18]. Due to the statistical approach used, dynamic noise maps are updated with a time frequency that depends on the time of the day: 5 minutes from 7 a.m. to 9 pm; 15 minutes from 9 p.m. to 1 a.m. and 60 minutes at night, from 1 a.m. to 7 a.m. This solution was adopted in order to achieve more or less the same error in the estimate of the noise level, that it is around 2 dB.

Figure 3: View of the Hi-Cap sensor installed in a portal of the A90 motorway in Rome

Rome Pilot Area

The pilot area of Rome is located along the motorway A90 that surrounds the city [19]. In this case the road network was divided into 19 noise measuring points, corresponding to as many road stretches with invariant traffic trends. Nineteen Hi-Cap sensors were consequently installed at the top of portals located along the motorway (see figure 3). Four Lo-Cap sensors were also placed in parallel with the Hi-Cap to check their ability in the detection and removal of anomalous noise events. The noise levels detected by these monitoring devices are used to update the most appropriate basic noise maps among those prepared for the area as a function of traffic and weather conditions. In order to improve the selection of the basic noise maps and to take into account their dependence on the time of the day (traffic distribution) and meteorological conditions, four weather stations were also installed to complete the system configuration. The weather stations were placed in positions corresponding to the main four wind sectors (north, south, east and west). In the pilot area of Rome noise maps are updated with a time frequency of 30 seconds from 6:00 a.m. to 10:00 p.m. At night, when traffic flow is less continuous, noise maps are updated every 5 minutes.

Anomalous Noise Event Detector

In order to identify and subsequently remove the impact of ANEs on the road traffic noise computation real-time with an automated method, an algorithm named ANED has been designed, developed and implemented to run on low-cost acoustic sensors of a WASN. The algorithm has been conceived as a two class GMM-based classifier that uses Mel Frequency Cepstral Coefficients (MFCC) as input parameters, and that has been shown to improve a classic One-Class approach in both suburban and urban scenarios and to reach real-time requirements within a WASN [14]. In figure 4 the block diagram of ANED system embedded in a low-cost acoustic sensor within a WASN is depicted. The sensor provides computation of equivalent noise levels at intervals of 300 s, as shown in the lower part of figure 4.

ANED is asked to provide a binary decision between ANE and RTN every second through a four-step process (see figure 4). Firstly, a short-term windowing of the acoustic signal is performed using Hamming window of length T_a, delimiting the time region where the analysis take place. Then a feature extraction is conducted using MFCC to capture meaningful spectral envelope information of the analysed acoustic signal frame.

ANED performs classification at two decision levels, as can be seen in figure 4:

i. frame-level classification, where the algorithm obtains one binary decision (RTN or ANE) every signal frame of length T_a

ii. high-level decision stage, that takes N consecutive frame-level decisions and fuses them to obtain a global decision with higher reliability.

The frame-level decision stage is implemented training two GMMs (one for each acoustic class, ANE and RTN) using samples from a real-life acoustic dataset; the two acoustic models generated are then used to perform the binary decision in real-time. If the training of GMM models takes into account the full amount of available labelled audio data, the majority class (RTN) can be overtrained, so the training is conducted using a balanced audio database, which demands for further pre-processing of the data.

High-level output decision is performed using a majority vote of the last N binary decisions given by the frame-level classifier.

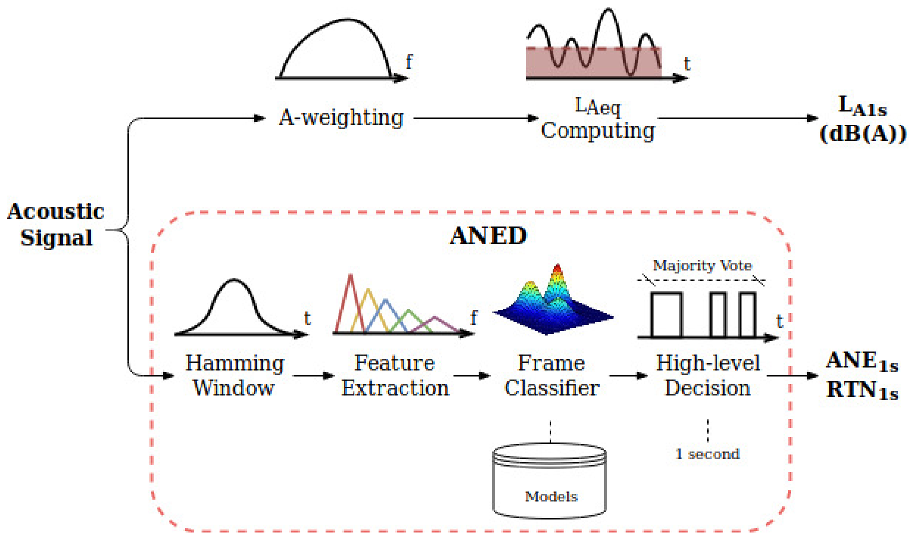

Figure 4: ANED diagram.

CONCLUSIONS

The DYNAMAP hybrid WASN is currently being tested after being deployed in the two pilot areas considered in the project. Specifically, the adjustment and improvement of the GIS and in-situ validation of the acoustic measurements provided by the low-cost sensors will be conducted during several months. The web interface includes several explanatory terms and measurements, as the Harmonica index, focused on the non-expert public. The software running on both Hi-Cap and Lo-Cap the sensors is being evaluated and upgraded where necessary with improved versions of the ANED algorithm. In particular, the ANED is being updated to improve its performance to operate in all the node locations of the network in Rome, and especially in Milan, where the variability of anomalous noise events is larger. To conclude the project, a guide of good practices for the deployment of WASN will be written as reference for future deployment of this kind of acoustic sensor networks in other locations. In the future, we will also study how to aggregate acoustic information with other data collected in the sensor nodes in order to obtain more information for noise management in smart cities.

REFERENCES

1. Babisch, W. Transportation noise and cardiovascular risk. *Noise Health* 2008, *10*, 27–33.
2. E.U. EU Directive: Directive 2002/49/EC of the European Parliament and the Council of 25 June 2002 relating to the assessment and management of environmental noise. In *Official Journal of the European Communities*; L 189/12; European Union: Maastricht, The Netherlands, 2002.
3. Kephalopoulos, S.; Paviotti, M.; Ledee, F.A. *Common Noise Assessment Methods in Europe (CNOSSOS-EU)*; European Union: Maastricht, The Netherlands, 2012.
4. Basten, T.; Wessels, P. An overview of sensor networks for environmental noise monitoring. In Proceedings of the ICSV21, Beijing China, 13–17 July 2014.
5. Botteldooren, D.; De Coensel, B.; Oldoni, D.; Van Renterghem, T.; Dauwe, S. Sound monitoring networks new style. In Proceedings of the Acoustics 2011: Breaking New Ground: Annual Conference of the Australian Acoustical Society, Gold Coast, Australia, 2–4 November 2011; pp. 1–5.
6. Cense—Characterization of Urban Sound Environments. Av. online: http://cense.ifsttar.fr/
7. Farrés, Júlia Camps, and Javier Casado Novas. "Issues and challenges to improve the Barcelona Noise Monitoring Network." (2018).
8. SonYC–Sounds of New York City. Available online: https://wp.nyu.edu/sonyc/
9. Pierre, R.L.S., Jr.; Maguire, D.J.; Automotive, C.S. The impact of A-weighting sound pressure level measurements during the evaluation of noise exposure. In Proceedings of the Conference NOISE-CON, Baltmore, Maryland, 12–14 July 2004; pp. 12–14.
10. Wessels, P.W.; Basten, T.G. Design aspects of acoustic sensor networks for environmental noise monitoring. *Appl. Acoust.* 2016, *110*, 227–234.
11. Mietlicki, F.; Mietlicki, C.; Sineau, M. An innovative approach for long-term environmental noise measurement: RUMEUR network. In Proceedings of the EuroNoise 2015, Maastrich, The Netherlands, 31 May–3 June 2015; EAA-NAG-ABAV: Maastrich, The Netherlands, 2015; pp. 2309–2314.
12. Sevillano, X.; Socoró, J.C.; Alías, F.; Bellucci, P.; Peruzzi, L.; Radaelli, S.; Coppi, P.; Nencini, L.; Cerniglia, A.; Bisceglie, A.; Benocci, R.; Zambon, G. DYNAMAP—Development of low cost sensors networks for real time noise mapping. *Noise Mapp.* 2016, *3*, 172–189.
13. Orga, F.; Alías, F.; Alsina-Pagès, R.M. On the Impact of Anomalous Noise Events on Road Traffic Noise Mapping in Urban and Suburban Environments. *Int. J. Environ. Res. Public Health* 2018, *15*, 13.
14. Socoró, J.C.; Alías, F.; Alsina-Pagès, R.M. An Anomalous Noise Events Detector for Dynamic Road Traffic Noise Mapping in Real-Life Urban and Suburban Environments. *Sensors* 2017, *17*, 2323.
15. Mermelstein, P. Distance measures for speech recognition, psychological and instrumental. *Pattern Recogn. Artif. Intell.* 1976, *116*, 374–388.
16. Alsina-Pagès, R.M.; Socoró, J.C.; Alías, F. Detecting Anomalous Noise Events on Low-Capacity Acoustic Sensor in Dynamic Road Traffic Noise Mapping. *Multidiscip. Digit. Publ. Inst. Proc.* 2018, *2*, 136.
17. Mietlicki, Christophe, et al. "The HARMONICA project, new tools to assess environmental noise and better inform the public." *Proceedings of the Forum Acusticum Conference, Krakow, Poland*. 2014.
18. Zambon, Giovanni, et al. "The LIFE DYNAMAP project: Towards a procedure for dynamic noise mapping in urban areas." *Applied Acoustics* 124 (2017): 52-60.
19. Bellucci, Patrizia, Laura Peruzzi, and Giovanni Zambon. "LIFE DYNAMAP project: The case study of Rome." *Applied Acoustics* 117 (2017): 193-206.