Euronoise 2018
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Adapting an Anomalous Noise Events Detector for Real-Life Operation in the Rome Suburban Pilot Area of the DYNAMAP's Project

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Summary
The DYNAMAP project is aimed at implementing a dynamic noise mapping system able to determine the acoustic impact of road infrastructures in real-time, encouraged by the European Noise Directive 2002/49/EC. The noise maps are updated using the information retrieved from a low-cost Wireless Acoustic Sensor Network (WASN) deployed in two pilot areas: in the city of Milan (urban) and in the A90 motorway around Rome (suburban). For a proper evaluation of the road infrastructure noise level, the anomalous noise events (ANE) unrelated to traffic noise (e.g. sirens, horns, speech, doors,...) should be removed before updating the noise maps. To that effect, an anomalous noise events detector (ANED) has been designed and trained using data from a real-life recording campaign. In this work, the preliminary version of the ANED algorithm designed for Hi-Cap sensors of the network, and its performance is evaluated and adjusted to conform to the requirements of the final 19-node WASN deployed in the suburban environment. The study is focused on the use of acoustic data in real-life operating conditions and the degree of adaptation of the ANED algorithm for each and every sensor of the WASN deployed in the A90 motorway surrounding Rome. To that end, a two-phase process was conducted: firstly, an study of the preliminary ANED version when running with the operative data from the WASN; and secondly, the production of a new labelled audio dataset of 107 hours that reflects more accurately the real-life WASN conditions were the ANED will operate.

PACS no. 43.50.Rq,43.60.Bf 43.60.-c

1. Introduction

Quality of life of people living in urban and suburban areas has been proved to be negatively affected by high traffic noise levels, being one of the main harmful effects on health [1]. The prevention and reduction of the effects of human exposure to this type of annoyance is being addressed by local, national and international authorities through two main initiatives at the European level: i) the European Noise Directive 2002/49/EC (END) [2]; and (ii) the consequent strategic noise mapping assessment CNOSSOS-EU [3]. These two instruments are devoted to reduce noise pollution and to elaborate suitable action plans as well as requesting the responsible authorities to inform and consult the concerned population appropriately. The END requires European member states to prepare and publish both noise maps and the corresponding noise management action plans [2] every 5 years.

Several projects that include WASN deployment in certain European countries have barged in tightly by opening new challenges [4, 5], being those derived from network and hardware platform design, or data collection plus their subsequent audio signal processing (see [6, 7] for further details) the ones that are within the topic of the presented work. However, it must be noticed that most of these proposals do not address the identification of traffic typology (e.g., light or heavy) nor the detection of specific acoustic events of interest (e.g., an air-craft flying over the road, nearby railways, road works, bells, crickets, etc.), as is described in [8]. Nevertheless, this type of actions can be considered very important to cope with the END demands of noise source distinction [2].

The LIFE DYNAMAP project [9] is aimed at designing and implementing a dynamic noise mapping system able to determine the acoustic impact of road infrastructures in real-time on a Geographic Information System (GIS) basis. The GIS-based noise maps are updated using the information obtained from a low-cost Wireless Acoustic Sensor Network (WASN) deployed in two pilot areas located in the city of Milan (urban environment) and in the A90 motorway around Rome (suburban environment), respectively [10, 11]. In order to represent the noise levels related to road infrastructures and to allow the appropriate evaluation of their impact, those anomalous noise events (ANE) unrelated to traffic noise (e.g. sirens, horns, speech, doors, music, etc.) should be removed from the equivalent noise level calculation before updating the road traffic noise (RTN) maps. To that effect, an Anomalous Noise Event Detector (ANED) has been included in the noise map computation pipeline, being designed to run on the high-capacity low-cost acoustic sensors composing the network [12].

After the initial training and evaluation of the ANED using real-life data from a recording campaign conducted on both urban and suburban areas [13, 12], this article describes the main steps followed to evaluate and, if necessary, re-train the ANED to the real operation in suburban pilot for a 19-node WASN deployed along the A90 motorway surrounding Rome [11]. The adaptation of the ANED described in this work has been performed taking into account the final positioning of low-cost acoustic sensors within the suburban acoustic network [11], which potentially implies a larger diversity of anomalous noise occurrences from the observations taken during the preliminary recording campaign in the suburban area, and also different road traffic noise patterns (e.g., from workdays or weekend days). Moreover, the adaptation allows to ensure a proper operation of the re-trained ANED in the acoustic environments where the high-capacity sensors are finally located.

The paper is structured as follows. In Section 2, the description of the preliminary ANED version using acoustic data from the suburban recording campaign is detailed. Next, Section 3 describes the main steps related to re-train the ANED with the data collected from the entire sensor network data of the 19-node network already deployed in the Rome suburban environment. Finally, Section 4 presents the main conclusions of the process, as well as potential future lines to improve the algorithm.

2. ANED trained with real-life acoustic data from a recording campaign

This section reviews the development of the preliminary version of the ANED trained with acoustic data from the recording campaign. The purpose of this work was focused on training the algorithm using real-life measurements from the acoustic scenario of application [13], in a similar context but not exactly in the final sensor locations due to the timings of the project. This ANED proposal designed to run on the high-capacity sensors of the low-cost WASN is presented in [12]. In order to discriminate between ANE and RTN, it considers standard Mel Cepstral Coefficients [14] to parametric the input acoustic data, and Gaussian Mixture Models (GMM) to build the two-class classification system. The ANED was assessed using an audio database specifically designed for this purpose, showing the feasibility of the proposal both in terms of computational cost and classification performance. The system was initially designed using real-life audio database [13] gathered during a recording campaign, specifically produced for training and validation purposes before the WASN was operative. Once the network was deployed, the previously designed algorithm had to be tested and re-trained if necessary with audio data from the definitive sensors locations.

The recording campaign to collect real-life acoustic data was conducted between the 18^{th} and the 21^{st} May 2015 in specific locations of the two pilot areas of the DYNAMAP project, covering both urban (Milan) and suburban (Rome) scenarios. In order to train the ANED with the same data characteristics of future operating conditions, the recordings were conducted using the low-cost sensor [15] (ARM-based acoustic sensor that integrates a low-cost class 2 microphone) connected to a ZOOM H4n digital recorder.

For the suburban area, the recordings were conducted in six sites along the A90 highway surrounding Rome during daytime (specifically, placing the recording equipment on the highway portals, where the final sensors would be located). The recordings performed in the Rome suburban resulted in 16493 seconds of road traffic noise and 543 seconds of anomalous noise events, endowing up to 4 hours and 44 minutes of processed audio. Most of the collected ANEs were sirens, noise of portals structure derived from its vibration (typically caused by the passing-by of very large trucks), noise of trucks or heavy vehicles passing over a bump, and vehicle horns. Although the acoustic salience of these events were usually low (e.g., the mean value of their SNR was 1.3 dB [13]), some of them (mainly sirens and horns) produced a significant impact on the measured equivalent sound level curve [16].

3. Adapting the ANED to run on real-life operating conditions

In this section, the work conducted towards adapting the anomalous noise event detector to properly run with acoustic data obtained from the deployed WASN in the suburban scenario is explained.

After the positioning of the low-cost sensors along the A90 motorway surrounding Rome [11, 17], the ANED algorithm could be re-trained by considering acoustic data from the final location collected from the 19 nodes of the WASN. The preliminary ANED version was generated using only a limited sample of the acoustic soundscapes (five locations out of 19 final sensor locations) and only during certain times of the

Figure 1. Example of the sensors positioning during the recording campaign (top) and in the definitive installation (bottom) within the WASN.

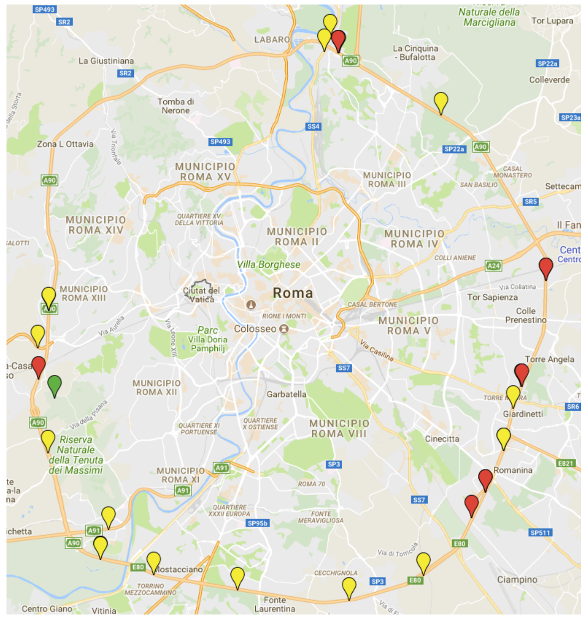

Figure 2. Map with sensors location information within the WASN of DYNAMAP project.

day (not the entire day, or not even different days of the week).

Regarding the final sensor installation, also its exact location within a certain motorway portal was different in comparison with the configuration used for the recording campaign. In the recording campaign, a tripod placed over the portal floor with an oblique orientation was used (see Figure 1). These changes can provide some spectral variations due to the presence of different multipath profiles of the acoustic waves that approach the sensor, as well as some differences of the noise levels obtained for each configuration, because the distance to the noise sources in both configurations can be clearly different. Due to all these changes in the measurements, there are enough evidences to foresee that the preliminary version of the ANED could not operate properly in the entire WASN. Nevertheless, the methodology used for the ANED adaptation has been focused on the analysis of the results of this preliminary version [12] together with an upgrade of the collected data for the subsequent possible re-training of the algorithm.

The work conducted to obtain the updated version of the ANED has consisted of two main phases:

- **Phase I**: Verification and update of the ANED with new acoustic data obtained from sensors that coincide with locations already explored during the construction of the audio database used for the preliminary version of the ANED. Two days of data were chosen, one weekday and one in the weekend, due to the fact that the type and distribution of the traffic is slightly different [11].
- **Phase II**: Data collection from the 19 sensors of the WASN on real-life operation. Labelling of new audio samples obtained from the 19 sensors of the WASN for 2 days (also one weekday and one in the weekend) and samples gathered from all the 24 hours per day.

Phase I was mainly focused on exploring the usefulness of the acoustic models considered to train the preliminary ANED version for the final WASN, that is, evaluating to what extent the acoustic information used for its training was good enough to represent ANED real-life operation (i.e., 24 hours/day x 7 days/week). Once this analysis was completed, phase II was carried out to allow the construction of the acoustic models specifically representing the new real-life operation acoustic environment.

Figure 2 shows the locations where the sensors of the WASN are located in the Rome's suburban pilot area. For the phase I, sensors marked in red where used as reference at the same locations where the audio dataset from the recording campaign was obtained (see section 2). Table I presents the complete list of sensors that compose the WASN, showing their ID, their geographical localization and which of their sites where also sensed during the recording campaign.

3.1. Phase I

In order to validate the performance of the preliminary ANED version [12] with the acoustic data coming from the sensors of the already deployed WASN, we considered that the testing should start in those node locations that were also recorded during the first database design. For the test, all day and night time sampling periods have been into account, at a regular basis of 20 minutes per hour recording and using the 24 hours per day. Also two days were explored, one as a labour day and another during the weekend, in order to check the ANED operation in different type of road traffic conditions.

The analysis presented in this section is based on the % of ANEs labelled by the ANED when evaluating the 19-node network data, and not in the accuracy of the algorithm. Previous studies about the dataset from the recording campaign [13] and describing the preliminary ANED performance on it [12] give us the statistics of ANEs occurrence depending on the location and even on the hour of the day. Therefore, any significantly different pattern from the preliminary ANED results should be analyzed in detail. As a first approximation, we discarded the subjective labelling of all data since it is prohibitive in terms of resources and time. Nevertheless, we do not discard conducting a deeper analysis and labelling of the data will be conducted to improve the training of the algorithm In further steps of this investigation.

During the preliminary design phase of the ANED, the performance obtained in terms of the macro-averaged F1 measure (F1-macro) in the Rome scenario was about 71% for the optimal classifier. Assuming that the number of noise events in the suburban scenario was really low (around 3% in the audio database of the recording campaign), this could lead to a ratio of detected ANEs that can be as high as 32%, which represents about 380 seconds of ANE every 20 minutes of analyzed audio, in the worst possible situation with the statistics we had available.

Then, an objective analysis of the ANED performance was conducted through studying the ratio of detected ANEs for all sensors every hour, taking into account the aforementioned upper bound. In Figures 3 and 4 the total time of ANEs obtained using the ANED [12] for one of the sensors of the network (sensor hb105) with the preliminary trained version of the ANED are shown for a working day and during the weekend, respectively. The total ANE time duration is computed for each hour, taking into account that only 20 minutes of audio per hour are recorded. Floor values keep below 50 s, but in night periods (between 0 a.m. and 5 a.m.) the total estimated ANE duration grows to 400 or 500 seconds.

This result shows that the preliminary ANED version does not work properly within the night passages, probably by the fact that the original recordings used to built the acoustic models did not contain these type of data, which are mainly composed of background noise and few vehicles or ANEs. During the night, road traffic noise presents a significantly different pattern from that during day, with some individual vehicle pass-bys separated by long silent passages with background city noise. Figure 5 depicts a L_{Aeq} level

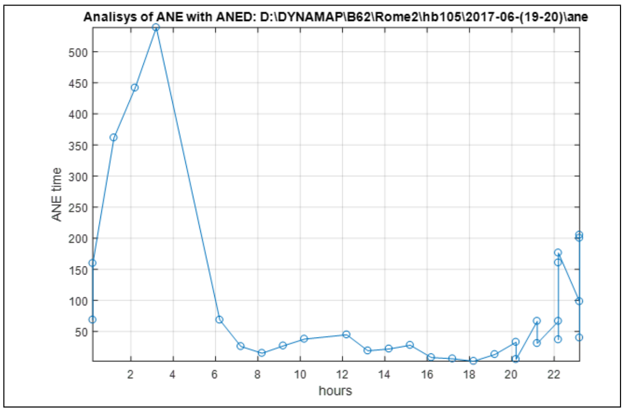

Figure 3. Analysis of the ANED performance in terms of total ANE time estimation for the sensor hb105 during a working day (02-11-2017).

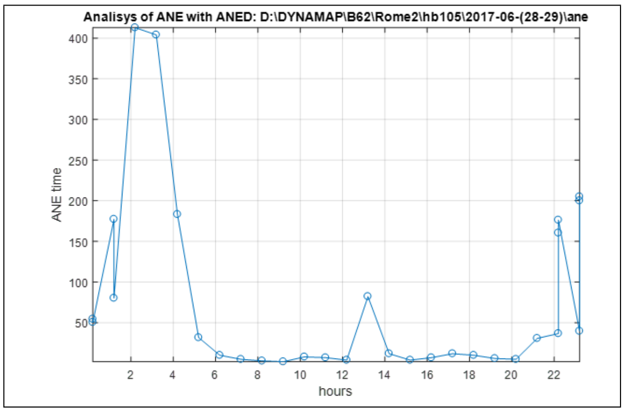

Figure 4. Analysis of the ANED performance in terms of total ANE time for the sensor hb105 during the weekend (05-11-2017).

curve for a two day period of the sensor hb154. Moreover, the equivalent noise level values during night period are clearly lower than those obtained during daytime.

Moreover, in Figure 4 a peak value of detected ANEs can be seen at 1 p.m. (between 50 and 100 seconds of detected ANE), which it was identified as a short rain period with some thunder after informal listening of the corresponding audio signal. The ANED detected as ANE some pass-bys of vehicles that were recorded in rainy conditions, a weather condition that changed the spectral profile of the road traffic noise dramatically.

Figures 6 and 7 show the total ANE time estimated by the preliminary ANED for the weekday and during the weekend for another sensor of the set analyzed during phase I (specifically, sensor hb154). Night periods seem to be also underestimated, obtaining such high number of ANE labels, specially for the weekday in this sensor. However, there is another peak during the weekend day at 1 a.m., which is more prominent on sensor hb154 (see Figure 7) than on sensor hb105 (see Figure 4). In this case, also road traffic noise in

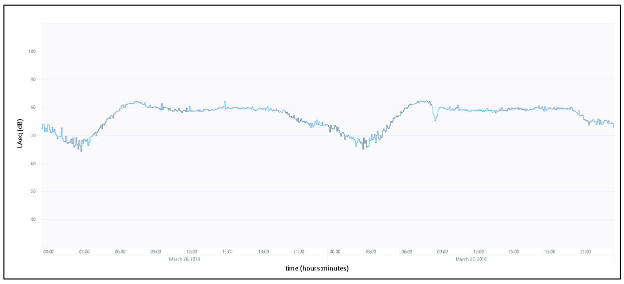

Figure 5. Example of two day L_{Aeq} curve for the sensor hb141 of the deployed WASN.

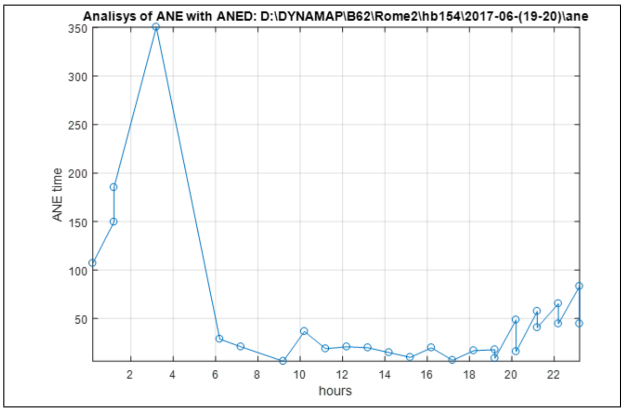

Figure 6. Analysis of the ANED performance in terms of total ANE time for the sensor hb154 during a working day (02-11-2017).

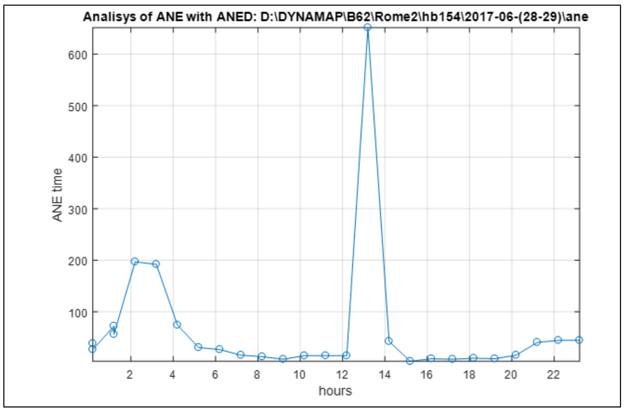

Figure 7. Analysis of the ANED performance in terms of total ANE time for the sensor hb154 during the weekend (05-11-2017).

rainy conditions was found, which in this sensor was due to heavier rain than the one observed in the first one analyzed. ANED here gave a higher percentage of ANE labels due to the clearly different acoustic pattern due to the rain presence, which can be appreciated in the spectrograms shown in figure 8.

After finishing the first analysis, new samples from nodes considered in phase I were added to the original database for the RTN acoustic model training, including night and rain audio samples. The purpose of this proof-of-concept was to validate to what extent the acoustic models for the ANED trained with the nodes that were sensed during the recording campaign were able to be completed with audio samples corresponding to the time periods that were not observed. The procedure consisted in re-training the ANED including new audio data from two sensors (hb141 and hb154) and testing the ANED with the other three acoustic nodes (hb105, hb119 and hb141). As a result, the ANED performance improved during night and rain, and the mean % of ANE was reduced up to 19% in average.

3.2. Phase II

The second phase towards obtaining an adapted version of the ANED ready to operate in the 19-sensor WASN was the recording and labelling of new audio samples coming from the sensors placed at their final locations. To that end, the same amount of data used during the previous phase for some sensors of the network was obtained for the complete set of available acoustic nodes. In this case, also two complete days were recorded (one weekday - on Thursday - and one weekend day - on Sunday) gathering 20 minutes of audio data each hour. In Figure 9 an schematic diagram shows the methodology used for the new recordings used for the ANED re-train within the WASN context.

For the acoustic data gathering, Bluewave, the partner of the DYNAMAP project that handles sensors hardware design and maintenance, provided us an access to the recorded data files in the cloud, which were subsequently downloaded. For each 20 min recording an audio datafile (using FLAC format) specifically named with the sensor identifier and the initial recording time and date, together with the ANED decisions were obtained. Automatic decision labels were used for an initial checking (phase I) but also served as a reference for the labelling in phase II.

The next step was labelling by subjective listening of half of the available audios (all odd hours of the 20 min recorded: 1h, 3h, 5h, .., 23h), which was performed by 5 trained listeners. As in [18], the labelling process was produced using Audacity with the visual support of the audio signals spectrogram (see example in Figure 10). The preliminary ANED output decision labels provided every 1 s long audio segment [12] were used as a reference to reduce the labeling time, taking advantage of the fact that most of RTN passages were correctly detected by the algorithm. Apart from the labels used during the labelling of the first recording campaign for the ANE passages (which include sounds of horns, sirens, noise impact of trucks of when passing over a bump, or sound of brake vehicles, among others), new ANE typologies were observed, and thus, labelled:

- **bird**: singing of birds, more prominent during early morning hours and sometimes with deep impact when they are placed near the acoustic sensors.

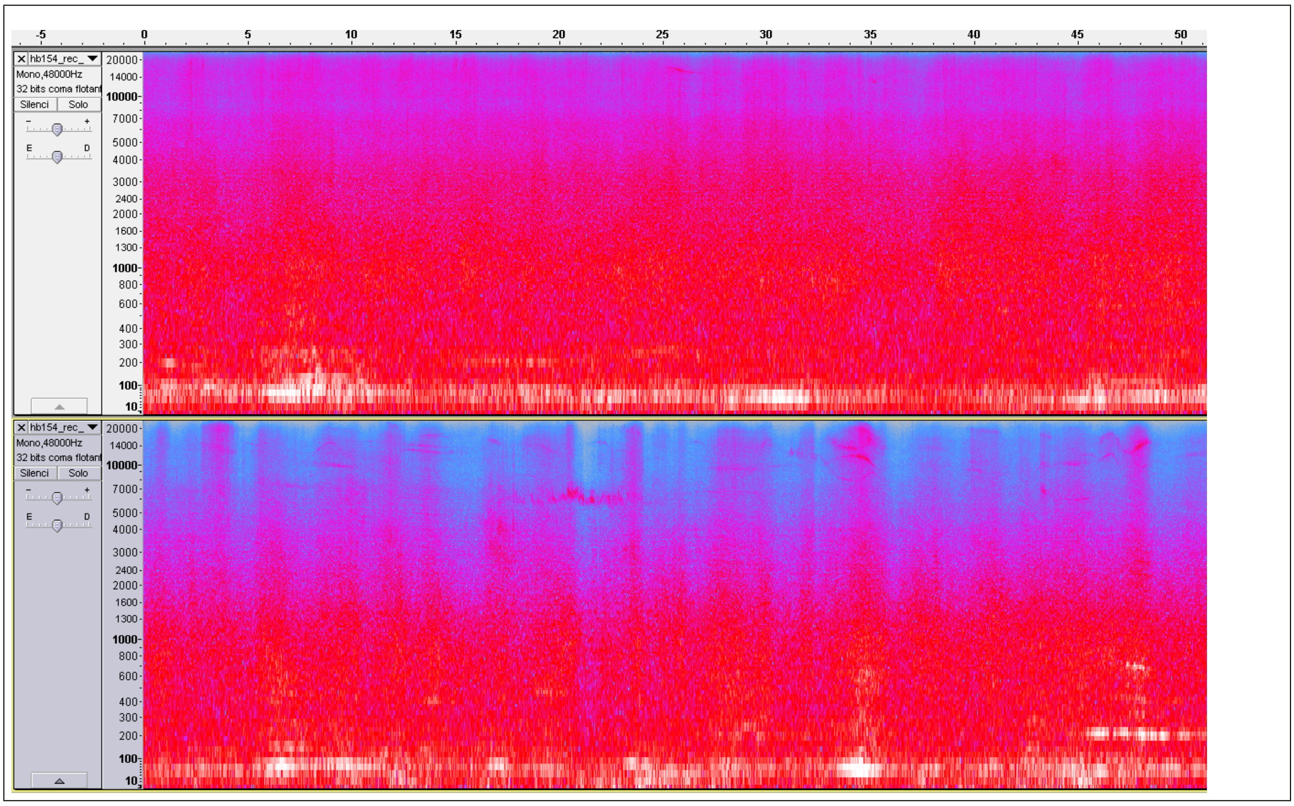

Figure 8. Comparison of spectrograms computed with Audacity for two audios obtained for the sensor hb154 during a rain (top) and without rain (bottom).

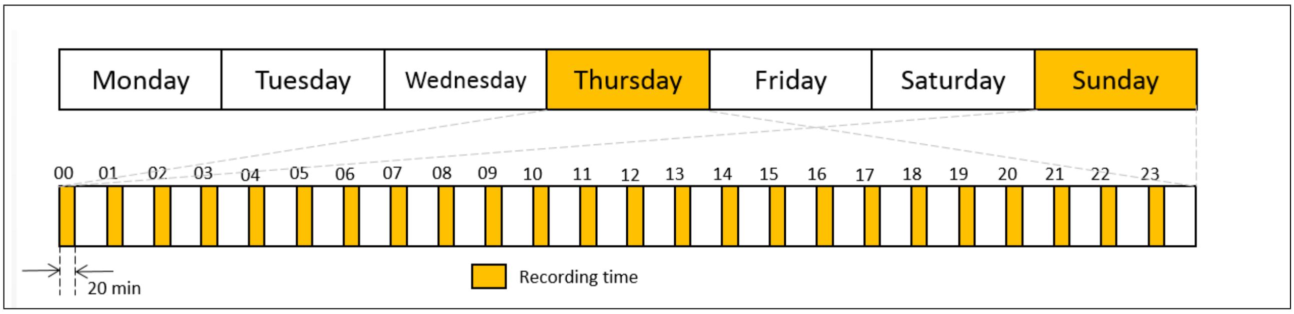

Figure 9. Schematic diagram of the methodology used for the new recordings of audio WASN sensors for the ANED re-train.

- **machine**: sound of machinery from neighbouring industries, which were more prominent during night.
- **rain**: includes sound of heavy rain, occurred during one of the recording days, but only when rain surpasses the level of road traffic noise.

As in [18], when an acoustic event has been perceived but with high difficulty and mixed with the background traffic noise (or other types of noise) a "cmplx" label has been used to prevent from using it as a sample for ANE or RTN.

Hence, those complex passages were next discarded for the subsequent adaptation of the ANED algorithm. The rest of the audio regions that were not labelled as ANEs or as "cmplx" were considered as RTN, which conforms clearly the majority class.

In Figure 10, an example of the labelling of an audio coming from a low-cost sensor of the deployed WASN in Rome is shown. Two ANE passages are shown, one from a train sound and another from a vehicle horn. In both cases, some neighboring time regions of the ANE are labelled as "complx", during which is difficult to define a clearly unique acoustic category. For the labelling, both the spectrogram and the audio waveform were visual stimuli that reinforced the perceptual one in order to detect subjectively the presence of anomalous noise events.

As a result of the new data collection and labelling performed to adapt the ANED algorithm to real-life operation, a total of 2 hours 38 minutes and 10 seconds of ANE (or 9490 seconds altogether) and 104 hours 16 minutes and 34 seconds of RTN (or

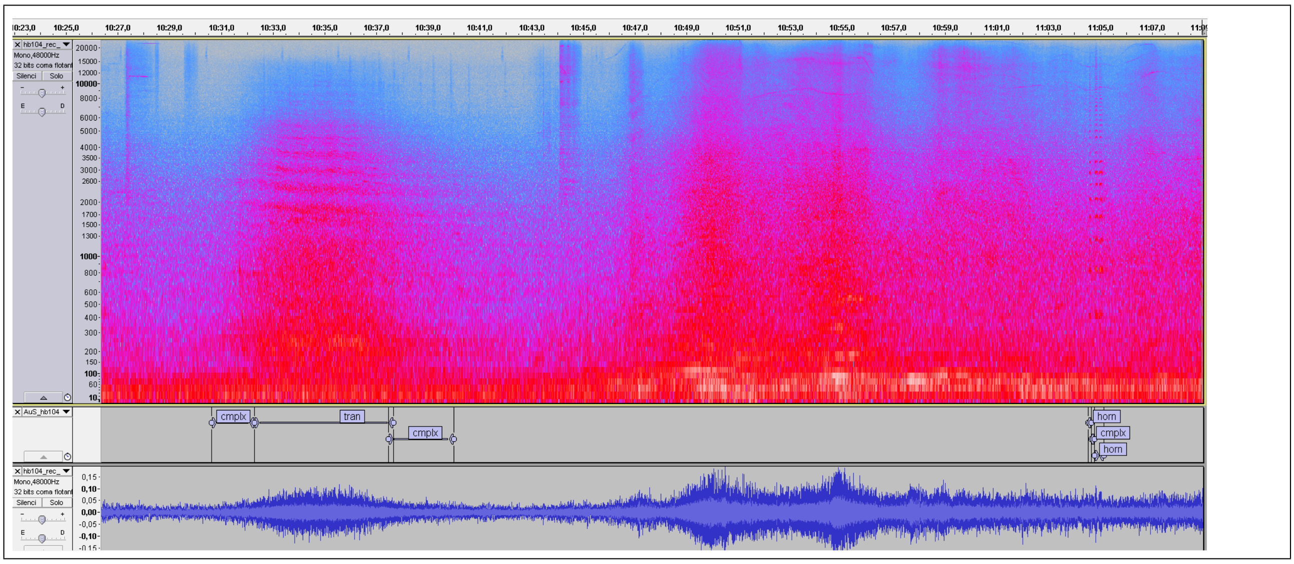

Figure 10. Example of labelling of an audio file from the WASN using Audacity. It is show the spectrogram (top), the audio labels (center), and the audio waveform (bottom).

Table I. List of sensors IDs (first column), their localization (second column) and if their localization was sensed during the preliminary recording campaign (third column).

ID	Longitude/Latitude	RC
hb103	41° 48'34.78"N/12°24'22.09"E	-
hb104	41° 59'14.11"N/12°30'41.41"E	-
hb105	41°49'58.69"N/12°35'13.94"E	Yes
hb110	41°57'54.09"N/12°33'58.06"E	-
hb111	41°48'15.13"N/12°25'51.27"E	-
hb112	41°51'44.70"N/12°36'1.39"E	-
hb119	41°52'12.02"N/12°36'15.08"E	Yes
hb128	41°52'19.71"N/12°22'35.32"E	Yes
hb134	41°50'51.60"N/12°35'44.49"E	-
hb141	41°59'12.35"N/12°31'04.71"E	Yes
hb143	41°49'12.16"N/12°24'34.89"E	-
hb147	41°47'55.78"N/12°28'14.04"E	-
hb148	41°47'42.23"N/12°31'23.17"E	-
hb149	41°48'13.93"N/12°33'28.91"E	-
hb153	41°59'32.63"N/12°30'50.74"E	-
hb154	41°54'25.77"N/12°36'56.07"E	Yes
hb155	41°53'01.02"N/12°22'35.12"E	-
hb156	41°53'48.33"N/12°22'54.34"E	-
hb157	41°50'48.82"N/12°22'51.95"E	-

375394 seconds altogether) were obtained. This audio database will be used to re-train the ANED and perform the adaptation to the operative WASN in the near future.

4. Conclusions

In this paper, we have described the main steps to adapt the preliminary version of an Anomalous Noise Events Detector to run in real-life operation conditions, after being trained and evaluated using acoustic data from similar, but not the final exact locations by means of a recording campaign. The experiments have been conducted on the 19-nodes WASN deployed in a suburban scenario within one of the pilots of the DYNAMAP project (Rome ring). The analysis has been divided in two phases. The first one focused on the validation of the preliminary ANED version runinning on real-life operation data, and the second one designed to collect new data from the sensors of the already deployed WASN.

The results from the first phase show that the ANED presents significantly poorer results than those previously observed in terms of % of labelled ANE by the algorithm, specially at night and during rainy conditions, obtaining very high periods of ANE classification. These results reflect the misrepresentation of night data and rainy conditions in the previously built acoustic dataset. However, the lack of data contained in the original audio database for the proper ANED operation within the final WASN configuration is not only limited to those two concrete situations. Original data did not include audio samples from all final sensors locations (only 5 nodes from the 19 included in the designed network), nor samples from all time periods within a day were not included.

At the second phase, a new set of recordings were collected from the WASN operation in the final real-life context from the full set of 19 acoustic nodes. To do so, two different type of days in terms of traffic density (one labour and one weekend day) were sensed by recording 20 consecutive minutes every hour. After that, a subjective labelling of a representative subset of the recorded data has been performed, obtaining a significantly larger and richer dataset (i.e., new ANE categories are included) than after the recording campaign composed of around 107h of audio samples.

It is worth mentioning that the dataset presents a highly unbalanced nature, since ANE only represents about 2.5% of the available RTN, which in turn, is a logical result due to the intrinsic characteristics of the anomalous noise events, which are highly local, occasional, diverse and unpredictable. Nevertheless, the ANE class is composed of about 2.5 hours of audio data, which is a representative sample of the type of typical ANEs that can be found in the suburban environment at hand. Future work will be focused on the re-training of the ANED algorithm with this new database tackling the challenges of moving from around 4h to more than 100h of acoustic unbalanced data to perform a proper training for the ANED algorithm.

Acknowledgement

This research has been partially funded by the European Commission under project LIFE DYNAMAP LIFE13 ENV/IT/001254 and the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement (Generalitat de Catalunya) under grant ref. 2017-SGR-966. Ferran Orga thanks the support of the European Social Fund and the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement of the Catalan Government for the predoctoral FI grant No. 2017FI_B00243.

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