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Acoustic Categorization of the urban Multi-Sensor Network of the DYNAMAP LIFE project developed for Road Traffic Noise Mapping

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ABSTRACT

The DYNAMAP LIFE project proposes the implementation of a dynamic noise mapping system able to determine the acoustic impact of road infrastructures in real-time, following the European Noise Directive 2002/49/EC. A Multi-Sensor Network collects the noise level measurements in two pilot areas: in the city of Milan and in the A90 motorway around Rome. For a proper evaluation of the equivalent noise level of road infrastructures, the anomalous noise events (ANE) unrelated to traffic noise (e.g. sirens, horns, speech, doors. . .) should be removed automatically. For this purpose, an anomalous noise events detector (ANED) has been designed using Mel-Frequency Cepstral Coefficients (MFCC) and Gaussian Mixture Models (GMM). This work focuses on the analysis of the spectral characteristics of the acoustic data from the 24-nodes of the Milan urban area network in order to determine whether a single adjustment of the ANED can cope with the particularities of each sensor location. To that effect, representative acoustic data has been collected through the Multi-Sensor network in real-operation conditions. These data have been subsequently analyzed in terms of their spectro-temporal distribution as a first step of the generalization of the ANED algorithm for all the nodes in the WASN.

Keywords: Noise, Environment, WASN, Noise Maps, ANED
I-INCE Classification of Subject Number: 74
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1. INTRODUCTION

Environmental noise has become one of the major pollutants in urban areas in recent years, causing important negative effects on the quality of life of their inhabitants [1–3]. The European competent authorities reacted to this fact by developing the European Noise

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Directive 2002/49/EC (END) [4], and the subsequent strategic noise mapping assessment denoted as CNOSSOS-EU [5]. These regulations have been defined to address the effects of the environmental noise by requiring the European Member States to determine noise exposure, inform the affected citizens and prevent and reduce the environmental noise if necessary.

To this aim, noise maps and action plans have to be developed every five years for large urban agglomerations, according to the END legislation. Traditionally, noise maps have been tailored using representative measurements (in terms of time and location) conducted by experts, which are input to specifically designed software [6]. This process provides a static picture of the environmental noise of urban areas. However, recently, the development of Wireless Acoustic Sensor Networks (WASNs) has allowed providing a dynamic information of urban noise collected and measured through multi-sensor networks deployed in smart cities (see [7] and references therein).

In this context, the LIFE+ DYNAMAP project [8], aimed to develop a dynamic noise mapping system devoted to represent the acoustic impact of road infrastructures in real time in two pilot areas [9, 10]: in the city of Milan and in the A90 motorway around Rome. To that effect, two hybrid low-cost WASNs have been deployed in these areas. For a proper computation of the equivalent noise level of road infrastructures, the Anomalous Noise Events (ANEs) unrelated to regular Road Traffic Noise (RTN) (e.g., sirens, horns, speech, doors) should be removed automatically before tailoring the noise map. For this purpose, an Anomalous Noise Events Detector (ANED) has been designed as a two-class classifier (ANE vs. RTN) using Mel-Frequency Cepstral Coefficients (MFCC) and Gaussian Mixture Models (GMM) [11, 12].

Specifically, the urban WASN is composed of 24 acoustic nodes installed across the District 9 of Milan. The ANED was initially trained with real-life data collected after a recording campaign [13]. Nevertheless, nor the recording locations and neither the periods of time of the recordings fit perfectly the final location of the nodes of the WASN. As a consequence, it becomes necessary to adapt the ANED to cope with the real-operation final context (i.e., working 24 hours/day during months).

In previous works, the acoustic characteristics of all the nodes in Rome pilot area were considered in the ANED adaptation process [14]. This work focuses on the spectral analysis of the acoustic environments of the Milan pilot area following a similar scheme. First, a recording campaign has been conducted in order to collect representative acoustic data from the 24-nodes of the Milan WASN in real-operation conditions. Second, the collected data have been subsequently analyzed to detect similarities or differences among the sampled acoustic environments in order to determine if they can be grouped or not to train the ANED optimally; a process that is left for future work.

The remaining sections of the paper are organized as follows. Section 2 describes the key elements of the ANED algorithm and its performance in previous works. Next, Section 3 describes the proposed methodology defined and followed to face the ulterior ANED adaptation to the WASN: a recording campaign through the nodes of the network in real-operation conditions (producing a new database containing 372 hours of raw audio), and the subsequent analysis of the sensed acoustic environments in terms of their spectral content and its time variability along a entire day. Finally, Section 4 presents the main conclusions and future research goals derived from this work.

2. ANED DESIGN AND PREVIOUS WORK WITHIN THE DYNAMAP LIFE PROJECT

The goal of the DYNAMAP WASN is to tailor a reliable RTN map, thus, those events non-related to regular traffic should be removed from the equivalent noise level (L_{eq}) computation. For this purpose, an Acoustic Event Detector is implemented to classify the input audio frames into RTN or ANE. As aforementioned, the ANED is the algorithm in charge of doing this task in the DYNAMAP sensor network.

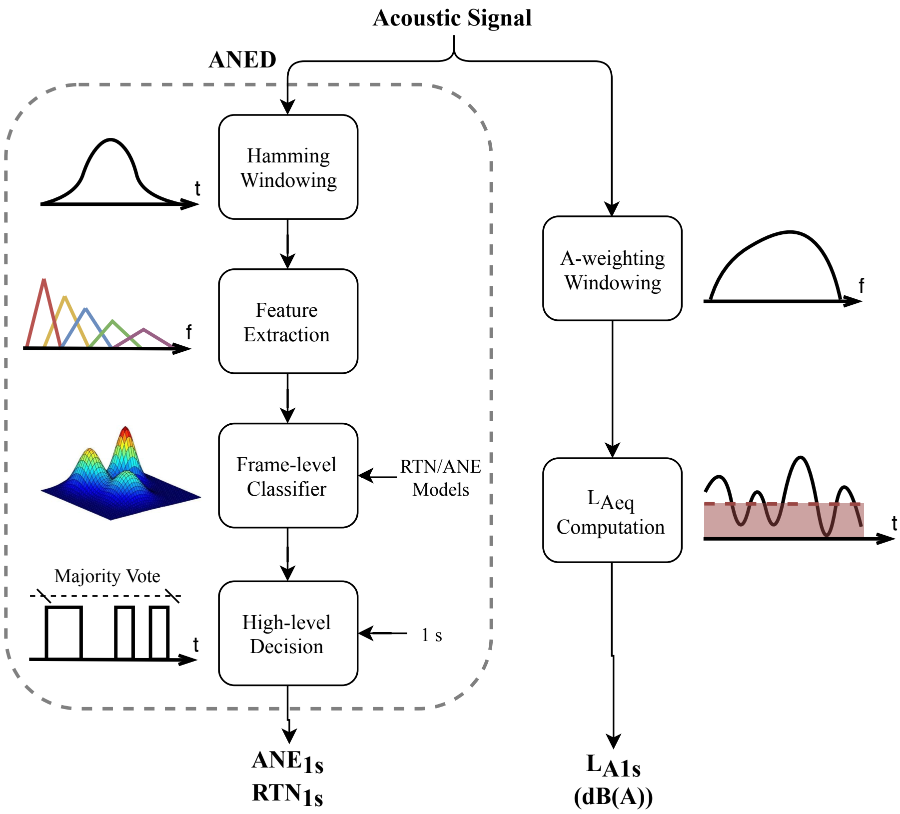

Figure 1: Block diagram of the DYNAMAP sensor deployed in the urban area of Milan.

Each node of the deployed WASN runs two parallel processes on the acoustic signal, as depicted in Figure 1. The first one is devoted to the application of the ANED, and the second one deals with the calculation of the A-weighted equivalent noise level at every second, i.e., L_{A1s} [15]. The ANED applies a Hamming windowing on frames of 30 ms length, with 50% of overlap to avoid losing samples [16]. After that, the audio frame is parameterized using 13 MFCCs. Next, a frame-level classification is conducted, using the GMM of both RTN and ANE. Finally, a majority vote technique is applied to determine the binary label of each 1-s period. Thus, the sensor outputs the A-weighted equivalent noise level and the binary classification of the ANED every second. Since the goal of the project is to tailor the road traffic noise map reliably, only the L_{A1s} for the periods labelled as RTN are subsequently taken into account for the update of the noise map noise level calculation, which takes place every 5 minutes.

Concerning the performance of the algorithm, previous studies were conducted using a preliminar audio database performed for ANED validation recorded in similar locations to those where the acoustic sensor were planned to be placed [13]. In these studies, an accuracy computed as macro-averaged F1 measure of 72.68% was achieved in a 4-fold scheme using a road traffic urban audio database, while the mean of this measure fell to 58.7% when a leave-one-out scheme was applied [11], e.g. testing the ANED with a continuous audio signal and training it with the rest of the audio signals. In this last case, the evaluation procedure is closer to the real operation within a sensor network, because the high-level decision of the ANED is assessed in a continuous audio signal every second, instead of the randomization of audio frames that is used in 4-fold cross-validation scheme.

Nevertheless, the preliminary audio database didn't reflect the whole diversity and complexity of the acoustic environment of the WASN's operative sensors due to several facts: *i)* only two labour days but not any weekend day were included in this database, *ii)* only diurnal periods but not nights were reflected and *iii)* recordings were performed in the sidewalk of streets using tripods while final sensors locations are in buildings façades. The ANED performance, however, has not been still tested in the operative sensor network. An experiment was performed to study to what extent the preliminary ANED version obtained with the preliminary database was able to generalize to the new context across all the 24 sensors deployed in Milan [17]. It was concluded that the algorithm did not performed well, showing quite high false alarm rates especially at night periods, but also low reliability during the whole day.

Hence, a new labelled audio database obtained throughout the deployed sensor network was required to adapt the ANED to its final context of operation. In the next section, the new recording campaign as well a first study focused to evaluate how to perform this new ANED adaptation is explained.

3. ACOUSTIC CATEGORIZATION OF THE OPERATIVE URBAN WASN

In this section, we detail both the recording of a new acoustic database using the WASN deployed within the Milan's urban area, as well as the acoustic categorization of the sampled environments with the aim of performing an adaptation of the ANED to run in real-operation conditions. The analysis that explores differences and similarities among these acoustic environments is based on the computation of spectrum-time profiles (a general representation of the acoustic energetic distribution along one day in both time and frequency) for each sensor and day.

3.3.1. Recording campaign in real-operation conditions

Table 1 lists the sensor nodes of the WASN, indicating their identifiers, streets location and GPS coordinates within the district 9 of Milan where they have been installed. Several issues were taken into account; first, it is important to highlight that traffic noise profile changes between day and night. For that reason, the recordings considered the entire day period of each day. Moreover, two days were considered for the recordings to consider the RTN differences during weekend days and week days

To that effect, recordings were planed for the 24-node network during the first 20 minutes of each hour, 24 hour per day, and during the two selected days: weekday (Tuesday, 28 November 2017) and weekend day (Sunday, 3 December 2017). A total of 1116 recordings of 20 minutes each were finally gathered during this recording campaign, producing a audio database of 372 hours.

Sensor Id	Street	Geographic Coordinates
hb106	Via Litta Modignani	(45.5227587,9.1596847)
hb108	Via Piero e Alberto Pirelli	(45.5144707,9.2107111)
hb109	Viale Stelvio	(45.4929125,9.1919035)
hb114	Via Melchiorre Gioia	(45.4815058,9.1913241)
hb115	Via Fara	(45.4855843,9.1991161)
hb116	Via Moncalieri	(45.5098883,9.1968012)
hb117	Viale Fermi	(45.5089072,9.1802412)
hb120	Via Baldinucci	(45.5032677,9.1686595)
hb121	Via Piero e Alberto Pirelli	(45.5185641,9.2129266)
hb123	Via Galvani	(45.4857107,9.2005241)
hb124	Via Grivola	(45.5179185,9.1943259)
hb125	Via Abba	(45.5028072,9.179285)
hb127	Via Quadrio	(45.4839506,9.1845167)
hb129	Via Crespi	(45.4989476,9.1860456)
hb133	Via Maffucci	(45.4992223,9.1717236)
hb135	via Lambruschini	(45.5024486,9.1548883)
hb136	Via Comasina	(45.5247882,9.1655266)
hb137	via Maestri del Lavoro	(45.518893,9.1997167)
hb138	Via Novaro	(45.5187445,9.1678656)
hb139	Via Bruni	(45.5015796,9.1745067)
hb140	Viale Jenner	(45.4970863,9.1777414)
hb144	Via D'Intignano	(45.5082648,9.2027579)
hb145	Via Fratelli Grimm	(45.5184213,9.2062962)
hb151	Via Veglia	(45.4970074,9.1934109)

Table 1: List of the nodes of the WASN deployed in district 9 of Milan.

3.3.2. Spectrum-time profiles

The real-operation of the WASN becomes a challenge for the performance of the ANED algorithm, since every node of the WASN senses a different and specific acoustic environment. As a preliminary step to adapt the ANED to run properly on each and every sensor of the entire network, the first analysis focuses on an in-depth study of all the acoustic environments found in the network. We explore their similarities and differences based on their frequency-time energy distributions computed from the recorded raw audio signals.

Specifically, each audio was parameterized using MFCC features every 30 ms, and the mean spectrum was computed per hour using the 48 energy subbands in which the spectrum is divided following the approach described in [18]. Then, the mean spectrum obtained for each hour of the day is used to define a spectrum-time profile per sensor and day. In Figure 2 an example of this spectrum-time profile is depicted for three network nodes during the weekday. During nights (between 22 and 04) lower subband energies can be observed, while during daily periods (between 04 and 22) higher energy levels can be observed. Furthermore, it can be appreciated that there are certain hours were some peak energy values appear, an aspect that variate depending on the sensor location. Finally, the general behavior along the frequency axis of the daily spectrum-time profile can be described as decreasing for higher frequencies, due to the low frequency nature of road traffic noise.

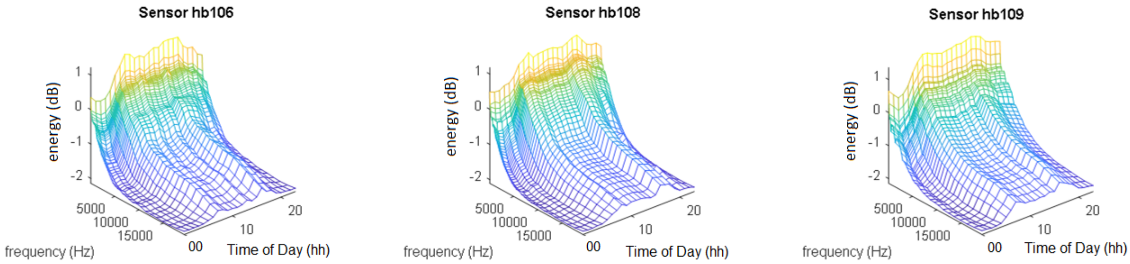

Figure 2: spectrum-time profiles of three network nodes at weekday.

3.3.3. Interpolation of missing data

The present work was performed during the test phase of the WASN, just before its real-operation phase, where some of the network nodes presented technical problems at some moment of the 24 hour of a day, which made unfeasible to obtain the complete spectrum-time profiles for all network nodes. Explicitly, during the conducted exhaustive recording campaign, 2 of the 24 sensors of the WASN were not fully operative due to different technical issues. Sensor hb114 only was available during 14 hours of the weekday, which made us discard its data for the subsequent acoustic analysis. Sensor hb138 was only offline during two hours, one for each of the two recording days: at 23 during the weekday and at 14 during the weekend.

For this reason, a simple yet effective two-dimensional interpolation technique was applied on sensor hb138 spectrum-time profiles in order to complete the data and enable its comparison to the rest of the sensors. A linear bidimensional interpolation was applied in both cases. For the weekday, the interpolation was performed assuming a certain regularity of the spectrum-time profiles, i.e., the first hour (00) was considered as a neighbor of the last sampling hour (23). The process was resolved by performing circular shifts of the spectrum-time profiles prior and after the two-dimensional interpolation.

In Figures 3 and 4 the original and interpolated data corresponding to sensor hb138 are respectively depicted. Notice that the original data in both figures (on the left-most part of each figure) contain zeroes at hours misrepresented during the recordings, which corresponds to a straight line across the frequency axis.

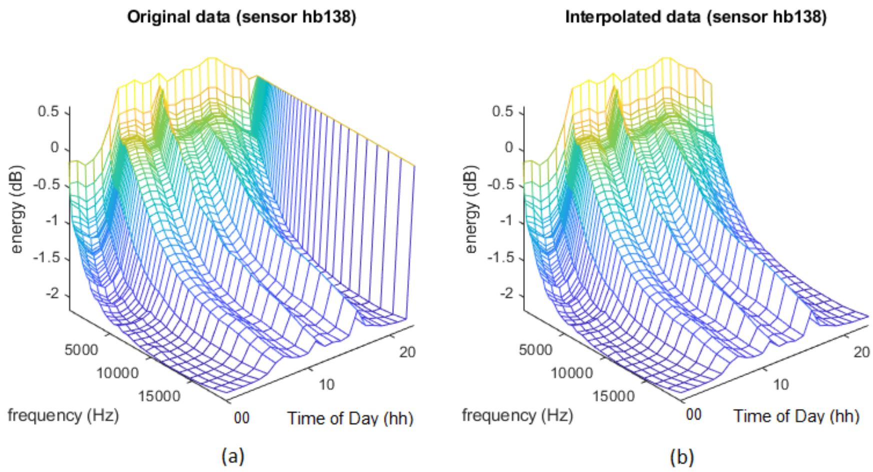

Figure 3: Original data (a) and interpolated data (b) of the sensor hb138 on 2017-11-28.

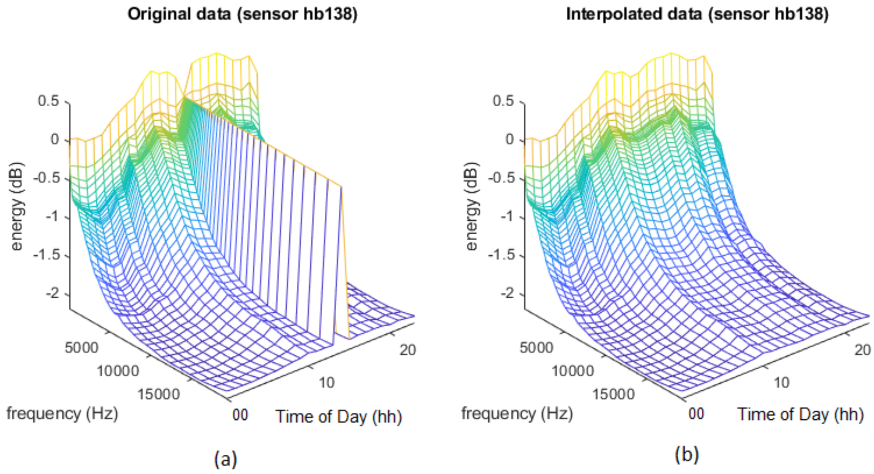

Figure 4: Original data (a) and interpolated data (b) of the sensor hb138 on 2017-12-03.

3.3.4. Similarity analysis of spectrum-time profiles

A similarity analysis was conducted among the available spectrum-time profiles of each recorded day in order to determine to what extent the spectral distribution of the signal varies from one location to another, or from one day to another.

In Figure 5, the spectrum-time profiles of the 23 available sensors during weekday are depicted, which have been clustered into two groups of sensors (cluster 1 and cluster 2) according to their similarities after a detailed visual inspection. In Figure 6 an example of comparison between dissimilar spectrum-time profiles for the week day, each one from a different cluster, are depicted. The same comparison is also shown in Figure 7 for the weekend day, where it can be observed that the differences are reduced but they are still evident. It is to note that these two clusters of sensors according to their spectrum-time profiles have been found to be coherent (i.e., they are composed of the same list of sensors for each defined group) along the two included days of the analysis (a weekday and a weekend day).

In what concerns to variations of spectrum-time profiles for a given sensor along the two analyzed days, significant differences can be appreciated. Weekday contains higher acoustic energies during day than in the same periods of weekend day, as previously observed in the Rome suburban environment [19]. In Figure 8, two examples of this kind of comparisons are depicted for sensors hb106 and hb121, respectively. Lower energy values are obtained during the time period from 06 to 20 in the labour day compared to the same period of the weekend day. Beyond these examples, this behavior is quite regular for the rest of sensors, which reinforces the idea of lower traffic activity in the sensed urban district of Milan during weekends, compared with working week.

4. CONCLUSIONS

In this paper, the acoustic analysis of the WASN of the LIFE DYNAMAP project operating in the Milan's pilot urban area has been described. The different acoustic environments of the deployed WASN have been studied in order to adapt the ANED algorithm to run in real-operation conditions properly. To that end, an in-depth analysis of the acoustic database of 372 hours obtained after an exhaustive recording campaign using the deployed sensor network has been performed.

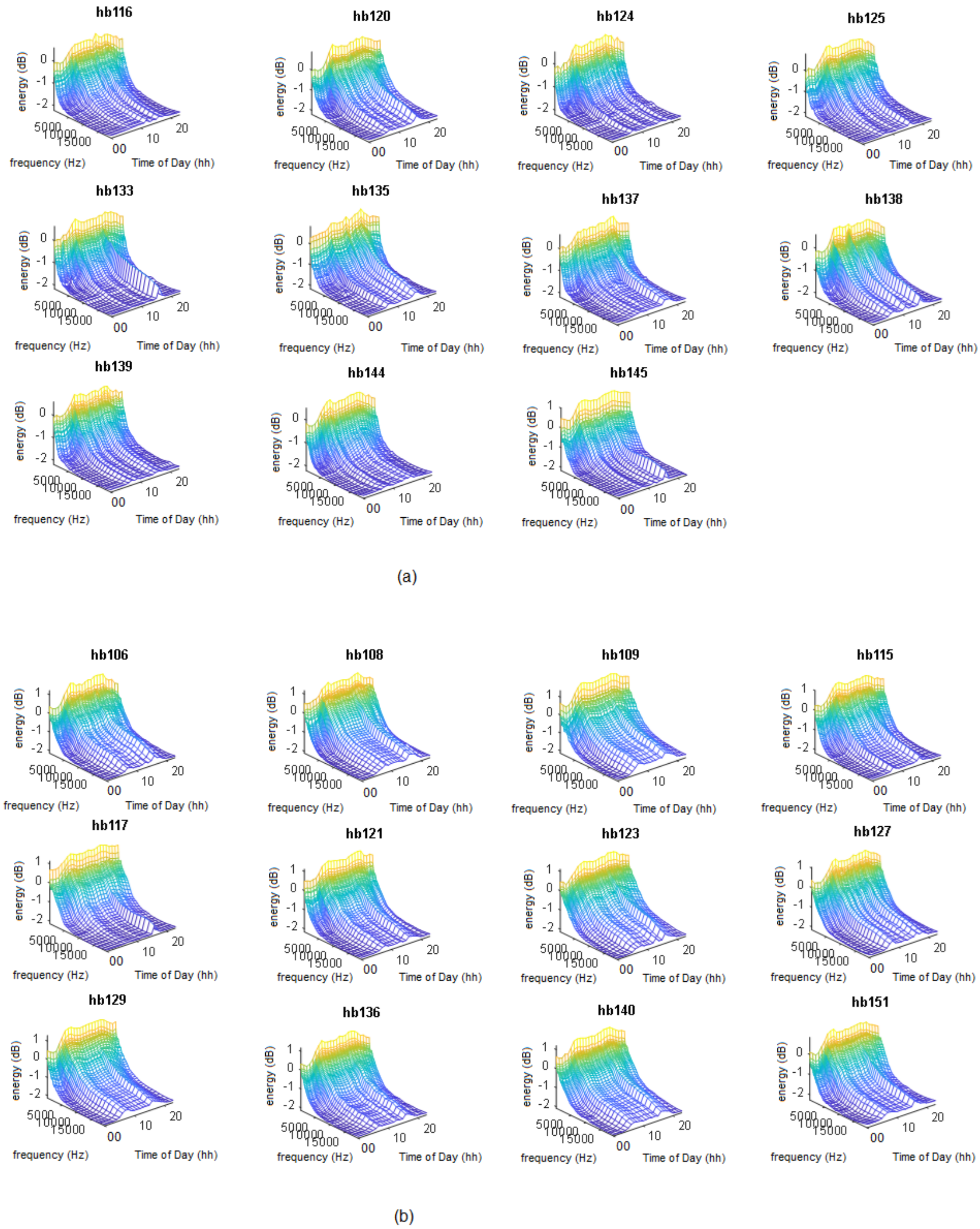

Figure 5: Spectrum-time profiles of the 23 operative sensors during the 28 December 2017: cluster 1 (a) and cluster 2 (b).

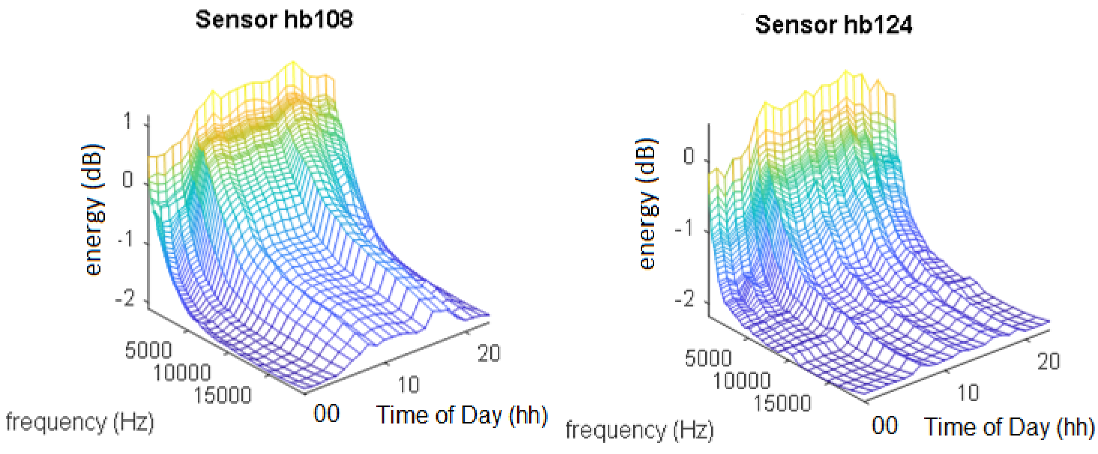

Figure 6: Example of sensors with dissimilar spectrum-time profiles at week day.

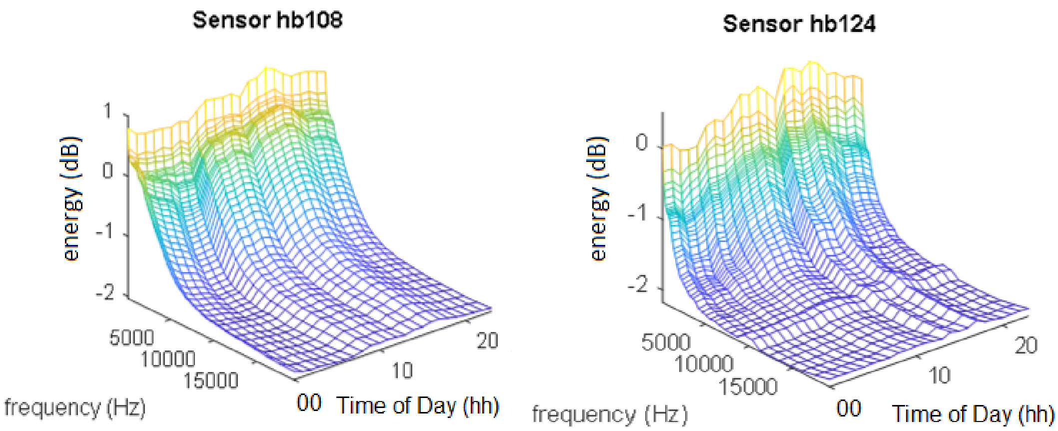

Figure 7: Example of sensors with dissimilar spectrum-time profiles at weekend day.

The methodological approach to perform an acoustic categorization of each node of the network has been addressed with the evaluation of spectrum-time profiles to analyze the similarities and differences between nodes in the WASN, taking into account the full band of audio spectrum and the entire time along one day.

The results show that there are some reasonable similarities and differences that could drive the next step towards the ANED adaptation in the urban environment. Specifically, significant differences have been found between labour and weekend days for a given sensors' data, which confirms the need of including both days' data for the algorithm ultimately adaptation. Regarding the comparison among sensors, two clusters of sensors have been defined after the preliminary visual inspection of their spectrum-time profiles. These two clusters are coherent with previous analyses in which sensors' streets were categorized according to a non-acoustic parameter related to traffic flow conditions.

Future work will be focused on the application of automatic clustering techniques to know to what extent the preliminary findings in this work can be confirmed or refuted. After that, the ANED algorithm will be adapted to run in the WASN deployed in the urban environment, according to the conclusions derived from the automatic clustering. Finally, the performance of the algorithm will be validated using acoustic data in real-operation

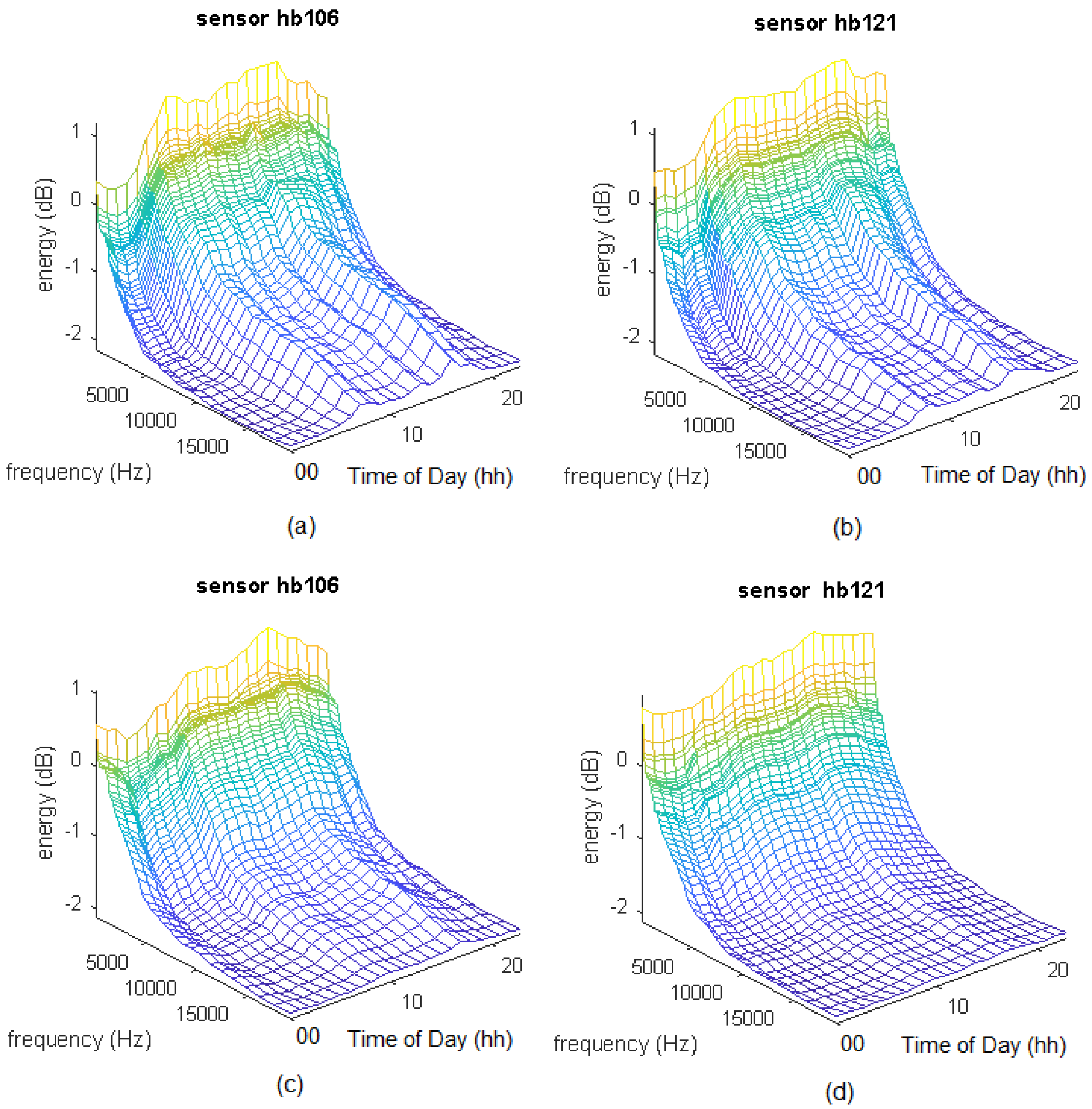

Figure 8: Comparison of spectrum-time profiles between the two analyzed days for sensors hb106 (a: weekday and c: weekend) and hb121 (b: weekday and d: weekend).

conditions.

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