LIFE17 IE/IT/000562

ANCHOR Life
Advanced Noise Control strategies in HarbOuR

"Technical Report on the design of the Smart Port Noise Monitoring System (SPNMS) in Patras"

Deliverable number	*See 7.4 Quality Plan*
Dissemination level	*Internal*
Delivery date	*23/12/2019*
Status	Finalised
Author(s):	**Giorgio Baldinelli, Francesco Bianchi (CIRIAF),**
	Samuele Schiavoni (Monelletta impianti Industriali srl - CIRIAF)

LIFE Programme

This project is funded under the LIFE programme,
the EU's funding instrument for the environment and climate action.

Document Version Control

Version	Date	Change Made (and if appropriate reason for change)	Initials of Commentator(s) or Author(s)
00	16/12/2019	Initial Version of Deliverable	GB, FB, SS: Authors
01	23/12/2019	Final	GB, FB, SS: Authors

Document Review

Reviewer	Institution	Date and result of the review
Giuseppe Marsico	Partner	13/01/2020 – Fully accepted

Approved by (signature)	Date

Approved by at European Commission (signature)	Date

Index

Executive Summary

The ANCHOR LIFE deliverable "Technical Report on the design of the Smart Port Noise Monitoring System (SPNMS) in Patras" aims to design the system for the monitoring phase in the Patras Port (Action B.2). Starting from the "Guideline for the realization of noise monitoring system for urban ports" [1] where the specifications are listed, a comprehensive research has been conducted on the performance of the low-cost acoustic sensors (MEMS) and their application on several projects that developed a complete hardware and network system for large-scale noise monitoring. Finally, the SPNMS has been designed on the basis of the already developed system from other LIFE projects, DYNAMAP [2] and MONZA [3] that implemented monitoring systems with an objective similar to the ANCHOR LIFE one.

Introduction

The specifications of Smart Port Noise Monitoring System (SPNMS) has been declined in the deliverable B2 [1] of the ANCHOR LIFE project and in the project itself.

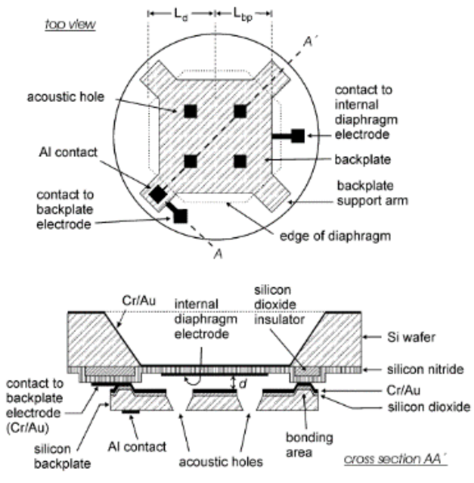
The specific objectives of a SPNMS are defined considering the different stakeholders involved in the port environment: the port authority, the local community and the companies operating in the harbour. For each stakeholderthe monitoring system should fulfil specific needs for the mitigation of the noise pollution in the Patras port and in the harbour environment. The port authority, with data collection and analysis from SPNMS, can adjust the port lay-out taking into account the highest noise emissions, the activities that are more disturbing and they can manage time schedule of port activities in order to avoid that noisiest activities are carried out contemporarily. In addition, the features of the monitoring system should create a connection between port authorities and the local community, allowing the port authorities to inform the citizens before the beginning of noisy activities; vice-versa the local community can report to port authorities in real time if disturbing events are taking place. The citizens will have the opportunity to check the monitored sound pressure level (SPL) on website where the data will be available. Finally, the companies that work in the port environment will be informed, thanks to the SPNMS, in real-time and with weekly or monthly reports about their noise emission with the aim to generate an awareness of their noise emission for immediate action, if they need, or future improvements.

In this report, firstly the performances of Micro Electro-Mechanical Systems (MEMS) microphone have been studied looking at several studies in literature in order to evaluate the use of this low-cost technology in the SPNMS. Then, several projects have been analysed to explore the best solution for the device and network aspects for the overall monitoring system. Finally, the specification of SPNMS have been declined to design it based on existing large-scale monitoring systems.

MEMS microphone studies

In the last decades, the use of microphones gained interest in consumer electronics and hearing aids [4]. Thinking just to the mass production of mobile phones, laptops, portable digital music players, etc. gives an idea of the possibility to have such devices at a (very) low price with a technology degree very similar to the high-quality measurement microphones. Several studies have underlined the good performance of the MEMS microphone considering their low cost.

A design of the diaphragm for a MEMS and a comparison with a traditional Brüel & Kjær 4939 1/4-inch microphone has been led by Scheeper et al. [5] in 2003. The 1/4 -inch microphone was developed, based on bulk micromachining technology with a special packaging of the silicon chip in a traditional metal microphone housing. The 2 microphones (MEMS and Brüel & Kjær 4939) have been compared according to the same standards and using the same procedures. Figure 1 shows schematics of the microphone chip (MEMS) studied in this work and the verified technical specification. The technical performance of MEMS showed already in 2003 the potentiality of this technology to perform high-quality noise measurements with low price.



Sensitivity	-33.0 ± 1.5 dB re. 1 V/Pa (22 ± 4 mV/Pa)
Noise level	24 dB(A) incl. 2670 preamplifier 23 dB(A) thermal noise
Temperature sensitivity	< ± 0.017 dB/°C
Sensitivity to static pressure variations	< 0.02 dB/kPa
Sensitivity to humidity	< 0.1 dB change in sensitivity in humid environment (40°C and 90% rel.hum.)
Frequency response	up to 20 kHz in free-field

Figure 1 - Top view of the microphone chip (top) and a cross-sectional view along the line AA' (bottom) and target specifications of the measurement microphone [5].

A further study with a comparison of several microphones with different range of prices has been led by Van Renterghem et al. [6] within the IDEA project [7]. The table retrieved from the paper is reported in Table 1 with the microphone details. The last microphones REF1 and REF2 are the top notch measurement microphones.

ID	Type	Membrane diameter	Microphone sensitivity[a] (dB re 1 V Pa^{-1})	Frequency range[a]	Power supply	Cost (including pre-amplification where needed)	Noise floor at 1 kHz (measured)
ELECTRET1	Electret	<1/8″	−45 dB	20 Hz to 20 kHz	Line powering	1 €	35 dB
ELECTRET2	Electret	<1/8″	−68 dB	20 Hz to 10 kHz	Line powering	3 €	41 dB
ELECTRET3	Electret	<1/8″	−40 dB	100 Hz to 10 kHz	Line powering	30 €	32 dB
ELECTRET4	Electret	<1/8″	−40 dB	40 Hz to 15 kHz	Line powering	50 €	36 dB
MEMS1	MEMS	<1/8″	−32 dB	100 Hz to 6 kHz	Line powering	30 €	23 dB
TYPEII	Electret	1/4″	−26 dB	20 Hz to 20 kHz	ICP preamplifier	300 €	15 dB
REF1	Electret	1/2″	−26 dB	3.5 Hz to 20 kHz	ICP preamplifier	2000 €	15 dB
REF2	Electret	1/2″	−26 dB	6.3 Hz to 20 kHz	ICP preamplifier	2000 €	13 dB

[a] Following product sheets.

Table 1 – Product details, prices and measured noise floors of the 8 selected microphones in the IDEA project [6].

A wide range of prices and technical specifications have been compared performing first some indoor measurements useful to determine the behaviour of the full measurement chain serving each microphone (pre-amplifiers where needed, Integrated Circuit Piezoelectric feeding, RC-circuit, the sound card of the Single Board Computers, weather protection, etc.). To retrieve these basic characteristics in a standardized way the microphones were tested in a full anechoic chamber. The main measured parameters were the noise floor (lowest sound pressure level that can be measured, which is limited by instrumentation noise in the circuit), saturation level (highest sound pressure level that can be measured, limited by the maximum movement of the membrane), and flatness of the frequency response and linearity (similarity of the sensitivity at different sound frequencies and sound pressure levels). In all cases, normal incident sound on the microphone membrane was considered. The reference microphones in this study, REF1 and REF2, with the Type II (it is not considered a low-cost microphone), show a noise floor measured value for 1kHz smaller than 15 dB. Comparing the low-cost microphones with the 15 dB noise floor value it is possible to state that the best performance for the “cheap” class (under 100 €) can be found for the MEMS microphone with a noise floor of only 23 dB. For the other electret microphones, noise floors are significantly higher. On the contrary, Figure 2 shows the frequency-dependent microphone sensitivity at 70 dBA. Pink noise was emitted by the loudspeaker over the full audible frequency range; REF1 and REF2 have an almost flat response up to 10 kHz. The MEMS microphone shows strong deviations from flatness over the sound frequency range considered.

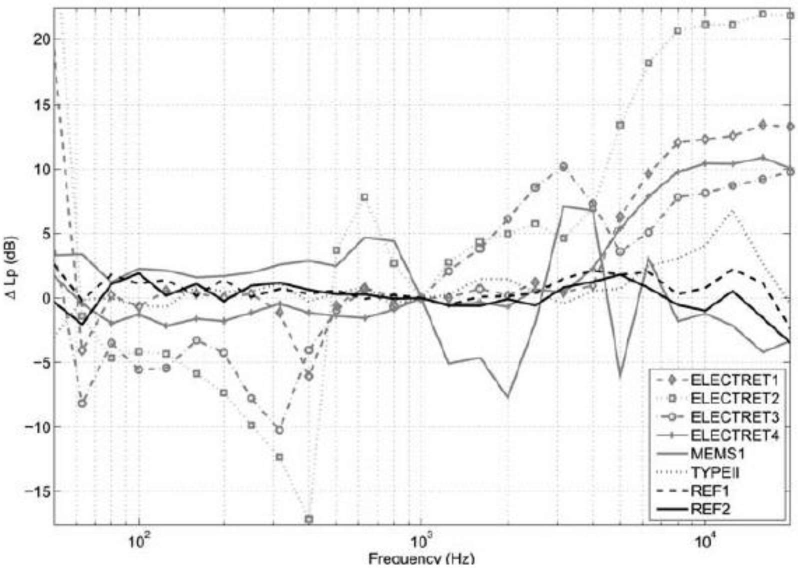


Figure 2 - Frequency response of the tested microphones as measured in an anechoic chamber for pink noise with a total sound pressure level of 70 dBA (measured at REF0), relative to REF0 [6].

Finally, a total sound pressure levels ranging from 50 dBA up to 90 dBA were considered for assessing linearity in the frequency response. A linear response means that the deviations from a flat frequency response are independent of the total sound pressure level at the microphone. Highly linear behaviour was found for REF1, REF2, and TYPEII, over the full audible range, and for MEMS up to 10 kHz. Low performances have been retrieved for the other cheap microphones.

All the microphones were tested for their outdoor performance, that is the proper use for the monitoring purpose. Linear correlation analysis between the synchronized time series of two microphones is reported in the cumulative distribution curve of the coefficient of determination R^2 (figure 3). It is possible to notice how the MEMS microphone gives acceptable measurements with respect to the other low-cost microphone.

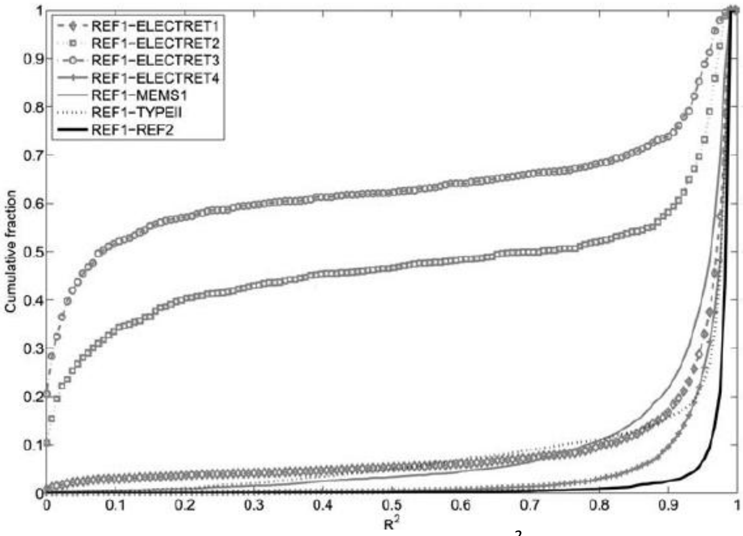


Figure 3 - Cumulative distribution curves of the correlation coefficients R^2 between each tested microphone and REF1 [6].

However, the MEMS microphone studied in this paper has shown some critical issue at low temperature and high humidity. Figure 4 shows scatter plots between the error relative to REF1 and the measured on-site air temperature and humidity.

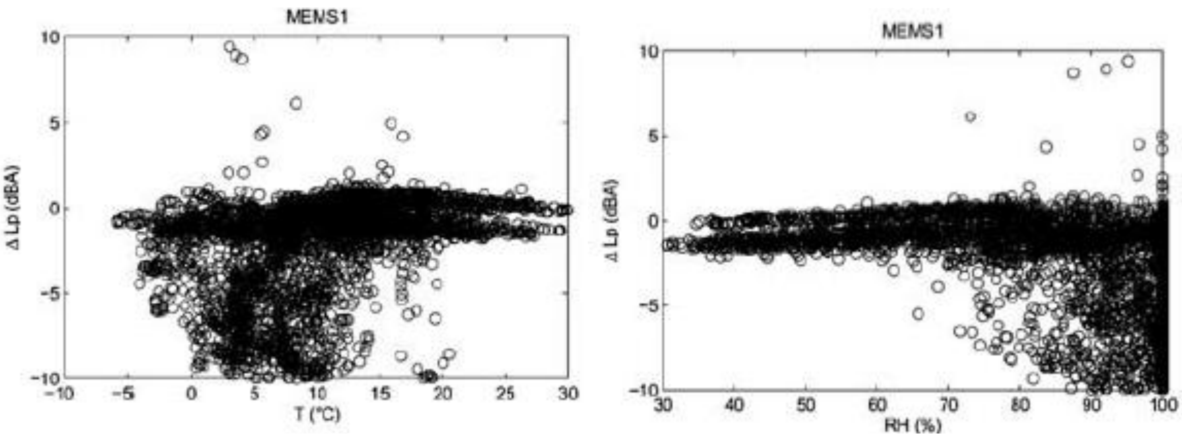


Figure 4 - Scatter plots between air temperature T (left), Relative Humidity (right) and the difference between the MEMS microphone and REF1 [6].

An advanced and accurate, low-cost sensor network has been developed by the Center for Urban Science and Progress (CUSP) of the New York University and presented in a paper [8] in 2016. A specific work about a comparison between custom MEMS device and other small size products from the same authors was done in 2014 [9]. The following plot (Figure 5) and Table 2 show the main results of the study in terms of frequency response and dynamic range measurements.

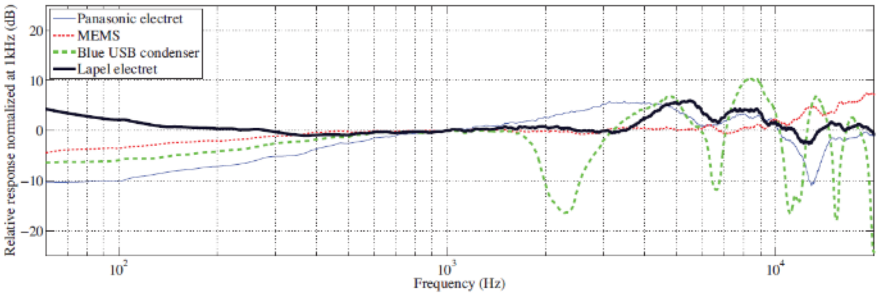


Figure 5 - Microphone frequency response comparisons [9].

Microphone	Noise floor	Dynamic range	Max SPL
Custom MEMS	44dB	62dB	106dB
Panasonic electret	42dB	60dB	102dB
Polson electret	52dB	54dB	107dB
Blue Snowflake condenser	56dB	49dB	106dB

Table 2 - Dynamic range and max SPL comparisons [9].

As shown in the frequency response plot, the custom MEMS operates closest to a flat frequency response showing a significant good behaviour respect to the other microphones.

Going into the details in [8], the aim of the monitoring device is to define a noise sensing network for the urban environment. The authors have performed several measurements according to the international standard IEC 61672 [10] in order to determine the deviceability to generate class II sound pressure level (SPL) data. The IEC 61672 [10] provides the criteria for determining a complete Sound Level Meter (SLM) ability to act as a class I or II device, including its directivity, which will be affected by the device and microphone housing. A comparison with a SLM type 1 outputs (Larson Davis 831 – calibrated at the beginning of each measurement stage using the type 1 Larson Davis CAL200) has been led as well (Figure 6).

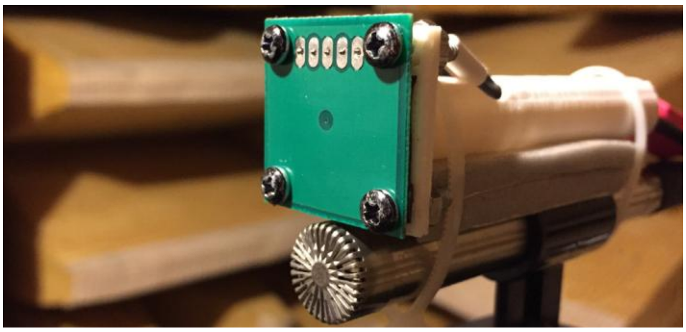


Figure 6 – MEMS microphone (top) and SLM type 1 (bottom) microphones mounted [8].

Measurements were conducted under low level (<20 dBA), fully anechoic conditions. The atmospheric conditions in the anechoic chamber were measured at the beginning and end of the measurement process (~2 h), and varied from 22 to 24°C in air temperature and 50–55 % in relative humidity. The main characteristics retrieved from the measurements are:

- self-generated noise;
- acoustical signal tests of a frequency weighting;
- long-term stability;
- level linearity;
- urban audio reproduction.

For the self-generated noise a measurement period of 60 s was conducted in the fully anechoic condition finding a SPL of 22.5 dBA for the reference SLM and 29.9 dBA for the MEMS microphone. The 29.9 dBA noise floor of the system could be partly attributed to the frequency response compensation filter. The filter gain at low frequencies brings up the noise floor of the system due to the low frequency roll-off of the analog MEMS microphone. The use of a MEMS microphone with a closer to flat response should serve to mitigate this problem as there will be less reliance on the need to compensate for reduced sensitivity at low frequencies.

The results from other measurements carried out to underline the good quality of MEMS microphone are represented in Table 3 where the deviceability to produce accurate SPL output for different frequencies was tested. The two microphones were subjected to a test signal made of 9 steady state 20 s sine waves, separated with 5 s of silence at octave frequencies from 31.5 Hz to 8 kHz. Table 3 shows the mean dBA response from the reference SLM, the MEMS and the difference between these two and the adjusted tolerance limits for type 2 devices.

Freq. (Hz)	DUT	Ref.	Δ
31.5	44.8	45.2	0.4[a]
63	63.6	63.7	0.1[a]
125	76.6	76.2	0.4[a]
250	85.3	84.9	0.4[a]
500	90.2	89.9	0.3[a]
1k	93.9	94.0	0.1[a]
2k	93.6	94.2	0.6[a]
4k	94.1	93.3	0.8[a]
8k	93.2	90.6	2.6[a]
Pink	79.9	80.0	0.1
White	87.5	88.0	0.5

[a] Indicates IEC61672-1 criteria met.

Table 3 - Acoustical signal tests in mean dBA, varying frequency (column DUT is the MEMS microphone and the column ref. is the SLM type 1) [8].

The low-cost device met all of the adjusted type 2 criteria for dBA frequency weightings when compared to the type 1 SLM. In addition, the response of the MEMS and SLM were compared for a 20 s, continuous level pink and white noise signal, showing a maximum difference in response of 0.5 dBA. In order to test the long term stability, the device was subjected to a 30 min 1 kHz sine wave at 94 dBA observing a difference of 0.07 dBA between the dBA reading at the beginning and at the end of this period (type 2 tolerance of ±0.2 dBA).

The device was also subjected to sine waves, linearly increasing up to 94 dBA in level, to test the linear response varying SPL at different frequencies (31.5 Hz to 8 kHz in octave increments) in order to evaluate the level linearity. Figure 7 shows, for a 1 kHz sinusoidal signal, the point where the device under test meet the adjusted type 2 tolerance (±0.6 dB). The MEMS device can effectively operate within type 2 level linearity tolerances above 40 dBA on average for frequencies ranging from 31.5 Hz to 8 kHz. This lower limit can be reduced using a lower noise microphone and pre-amplifier combination; however, for the context of the urban sound environment, going towards the lower limit is not useful.

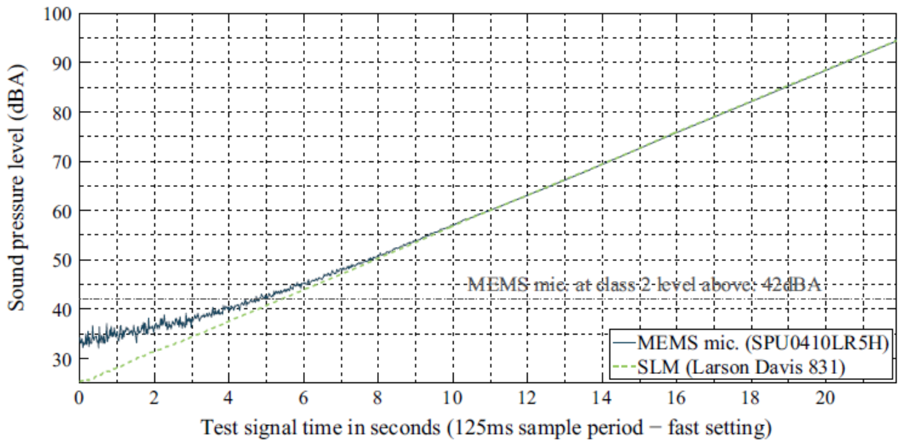


Figure 7 - Linear level response of DUT vs. SLM to 1 kHz sine wave up to 94 dBA showing adjusted type 2 tolerance point [8].

Finally, the device has been studied for the ability to capture meaningful SPL data: a 15 min urban audio recording was replayed a total of 4 times under anechoic conditions with the reference SLM and MEMS microphone mounted directly adjacent to each other on-axis to the speaker. As can be seen in Figure 8, the low-cost device closely follows the measurements made by the type 1 SLM. It seems that the MEMS microphone system slightly overestimates the dBA values on the rise portion of transient sound events and slightly underestimates on the falling edge. A correlation analysis was carried out on the resultant averaged SPL time histories from the two microphone measurements. The correlation coefficient (R^2) was calculated between the entire dBA (fast time weighting) time history for each device. The total R^2 value for this 15 min urban signal was 0.9723. The mean difference between the SLM and MEMS device time history values was 0.4 dB, with a standard deviation of 0.1 dBA, minimum values of 0.1 dBA and maximum values of 1.8 dBA.

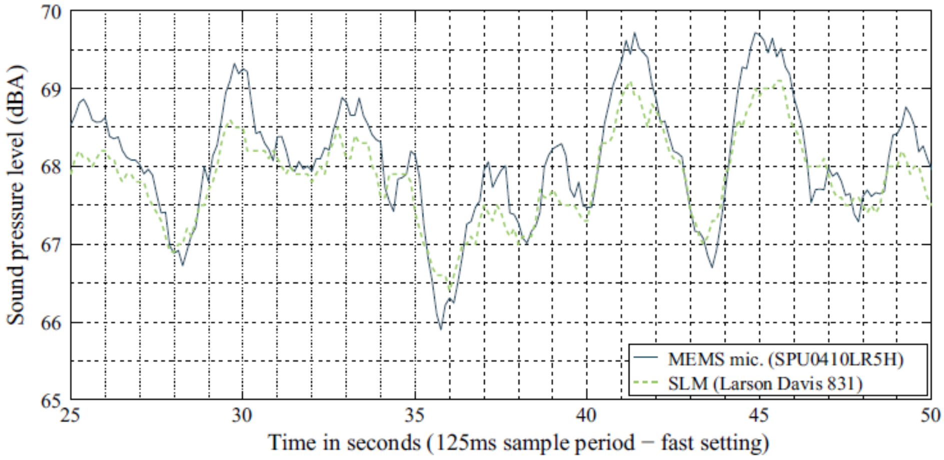


Figure 8 - Sample of MEMS vs. SLM time history SPL values of urban audio recording reproduced under anechoic conditions [8].

Thus, the MEMS microphone device studied in this work can produce accurate SPL data of high quality. The main limiting factor of its noise floor means it cannot effectively operate in ambient conditions levels < 30 dBA, or at type 2 accuracies at levels < 40 dBA. Anyway, for specific applications, the capabilities of this solution allow to generate real-time acoustic data at or above the type 2 level.

Devices and network developed in other projects

In the previous paragraph the good value for money of the MEMS microphone was underlined. However, in the ANCHOR project, the MEMS will be embedded in a more complex monitoring device with a high level network to fulfil several objectives. The design of SPNMS (Smart Port Noise Monitoring System) starts with an overall view of adopted solutions in other existing projects.

Life+ DYNAMAP [2]

DYNAMAP (2014-2019) is a LIFE+ project aimed at developing a dynamic noise mapping system able to detect and represent in real time the acoustic impact of road infrastructures [11]. In particular, an automatic monitoring system, based on customised low-cost sensors and a software tool implemented on a general purpose GIS platform, has been developed and applied to two pilot cases: Milan and Rome [12].

The Life+ DYNAMAP Project developed a device that embeds a pc monitoring system. A low cost small computer equipped with high quality sound board is the main component of the device (Figure 9) [13]. Some analyses can be performed directly by the device, which later send processed data to the central server.. Moreover, the device can be remotely fully updated and reprogrammed. It can be coded with specific algorithms executing particular complex tasks as noise recognition, source position tracking etc. Anyway, those systems show high power consumption, that is actually at least 2–3W, so they need direct power supply or big solar panels limiting the number of the sensor points.

Figure 9 – DYNAMAP device [13].

As said before, the device can pre-process data directly on board by implementing the ANED algorithm developed in the project for the recognition of the anomalous noise event detection [14]. The pre-processing allows to send low data stream to the central unit because they are already filtered in the device. Some basic specifications for this monitoring station are listed below [15]:

- 40–100 dB(A) broadband linearity range;
- 35-115 dB working range whit acceptable THD (Total Harmonic Distortion) and narrowband floor noise level;
- 1 second time base Leq(A) level;
- possibility of audio recording;
- internal circular backup data storage of calculated data;
- VPN connection;
- GPRS/3G/WiFi connection.

A sketch that represents the project from the monitoring phase to the sound mapping is represented in Figure 10.

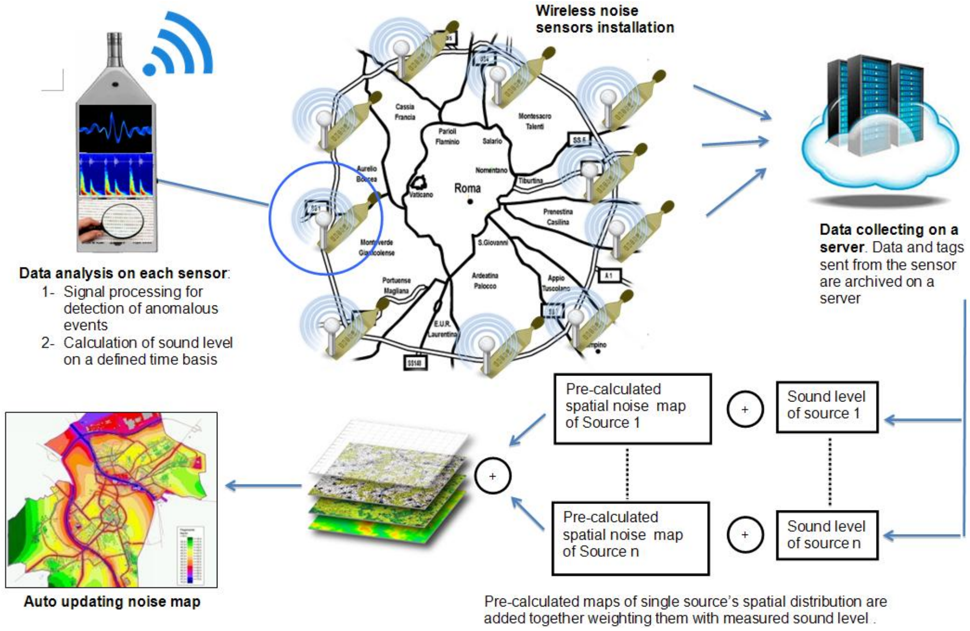


Figure 10 – DYNAMAP working principle [15].

The experience of DYNAMAP on the low-cost monitoring device was inherited from a local project performed in Pisa called *SENSEable* [16].

The aim of this project was the development of tools and practices useful for analysing and studying the urban landscape. The final objective of this project wants to create a wide series of acquired data that represent the “urban sensing” collecting and relating several measurements to describe different aspect of people's social behaviour of Pisa city. A prototype network for measuring sound levels with sensors connected and located in several points of the city has been developed. The individual measuring devices consist of a small microcontroller equipped with a low-cost acoustic sensor and a ZigBee interface, powered by a solar panel. The devices are positioned at the windowsills or terraces of homes with internet connection, thanks to the collaboration of citizens (crowdsourcing) who voluntarily participate to the project. The sensors are able to detect a range of SPL that varies from 35 dB (A) to 100 dB (A), with a constant frequency response within 0.5 dB from 30 Hz to 16 kHz. From some tests performed on periods of ten minutes, it was found that the values measured by the system differ on average by 0.2 dB (A) compared to those measured simultaneously at the same point with class I SLMs. The data acquired and elaborated were made available in a public web page.

RUMEUR [17]

The project RUMEUR (2008) developed a noise sensors network in the Paris region. Three goals want to be achieved within the project: understanding phenomena, assessing actions against noise and communicating the information in all transparency on the sound environment in Ile-de-France. The systems are composed by permanent stations to monitor on the long-term road, rail and air noise, and short-term campaigns are carried out to assess the impact of major events or to characterise specific environments. The data collection is made with different devices that allow to perform long, medium and short-term acquisition depending on the site and analyses performed in the Paris region [18]. For long-term measurements fixed devices have been used to give an indication of how noise changes over time. For medium term measurements the purpose of the acquisition and consequently the device structure are designed for assessing the acoustic impact of structural modifications such as urban projects, modifications of flight paths and flight procedures for aircraft. Lastly, the short-term measurements are performed with semi-mobile equipment and laboratory vehicles for assessing the noise from specific temporary events or some critical points.

The RUMEUR project presents a widespread network and for this reason the use of mobile phones networks for the data transmission has been chosen. It provides a wide coverage at ever-increasing transmission speeds and at steadily declining prices. The strength of the project is the website platform that is publicly accessible [17]. The sites available to date within the RUMEUR platform in Île-de-France correspond to measurement stations deployed and operated by Bruitparif. In the map(Figure 11) presenting the measurement sites, the green dots show the active measurements and the orange dots show measurements completed. The blue dots correspond to measurement sheets that have been published as part of ad hoc measurements lasting from a few hours to a few days.

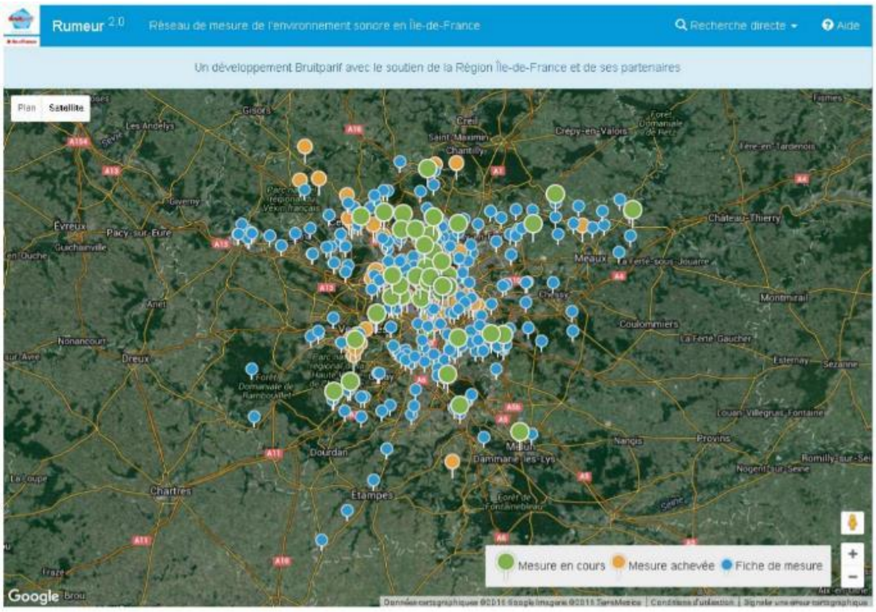


Figure 11 – RUMEUR web platform with the overview of the measurement points [17].

For each measurement point, the raw and elaborated data can be chosen and represented with annual, month, week and day profile (Figure 12). The treatment and analysis of data collected allow the project manager to create reports for the authorities and the stakeholders. This large network of the Ile-de-France gives important information about the noise exposure of the population, becoming a true decision-making tool to support the implementation of noise policies by the authorities.

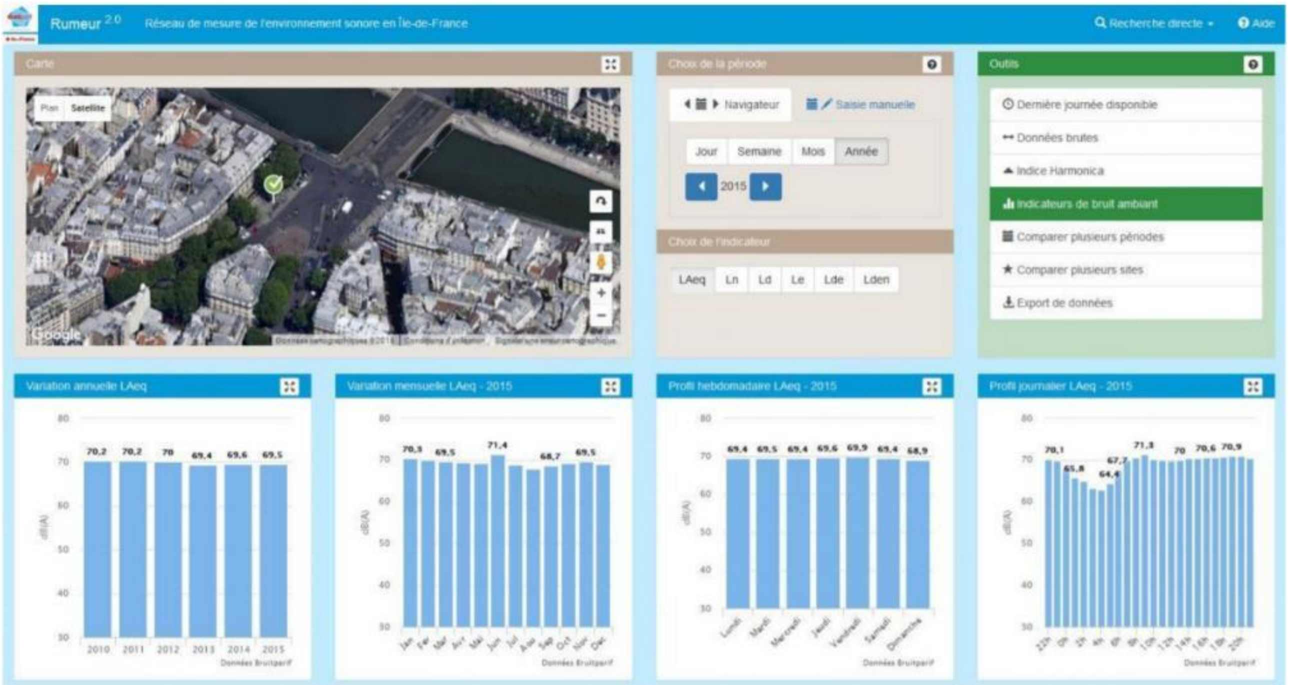


Figure 12 – RUMEUR public web site with the data elaboration for a specific measurement point [17].

DREAMsys [19]

A consortium composed in 2009 by NPL, Castle Group, QinetiQ and Hoare Lea Acoustics, developed a Distributed Remote Environmental Array Monitoring System – DREAMSys. The consortium aimed to develop a novel, low-cost, distributed wireless noise monitoring system, known as DREAMSys, to enable measured noise data to be used to enhance strategic noise maps. DREAMSys consists of a large number of individual measurement devices. The specific MEMS microphones and device have been developed within this project by the consortium.

The following key features were specified for the new MEMS measurement microphones [20].

- Acoustic dynamic range greater than 75 dB(A) (self-generated noise <25 dB(A) and limit of distortion >100 dB(A));
- Acoustic frequency range from 20 Hz to 20 kHz;
- Membrane resonant frequency greater than 30 kHz;
- On-chip temperature measurement accuracy of better than 1°C;
- Operating voltage from 3.3 V to 5 V with <0.1 dB change in microphone sensitivity for 1% change in voltage;

- Operating current lower than 5 mA;
- Analog output voltage range of 1V full scale;
- Prototype microphones have already been tested, but development of the final version of the microphone is still underway.

The technical parameter for the rest of the hardware are following reported [20].

- On-board power supply capable of continuous operation for at least 15 days;
- Weather proofing to IP66;
- Data storage capacity for at least 15 days of measurements;
- Wireless data transmission for remote data collection (using GSM);
- A wireless link fail or not be available;
- Dynamic Range greater than 70 dB (30 dB(A) to 100 dB(A));
- Frequency weighting A- & C- and time weighting F according to IEC 61672-1, class 2;
- Calculation of L_{Aeq}, L_{Ceq} L_{max} plus 3 user-defined L_N levels in contiguous programmable time periods (10 minutes typically);
- Overload and under range indicators;
- Data automatically corrected for microphone specific temperature effects;
- Time stamped data and synchronous timing between all the devices;
- Device and location identifications;
- Indication of operational and battery status;
- Calibration mode for periodic alternative direct digital link to allow data collection/ interrogation.

Efficient use of power was a key consideration in designing the electronics. For this reason, a processor was avoided, and all calculations are performed with a floating-point-gate-array implementing the simple arithmetic to calculate the L_{eq} values. The GSM network has been used to provide the wireless functionality. Each unit is fitted with a data SIM card and is capable of transmitting its stored data via SMS.

Some first measurements performed in UK (Wraysbury Reservoir, Staines, UK) are shown in the Figure 13 [21].


Figure 13 – DREAMsys measurements in Wraysbury Reservoir, Staines, UK [21].

IDEA project [7]

A main goal of the IDEA (Intelligent, Distributed, Environmental Assessment – 2008/2012) project is the development of an extensive noise and air pollution measurement network. For such a network to be applicable, low-cost sensors were needed. Therefore, an important focus in IDEA is getting experience with the use of cheaper and thus less accurate sensors [22]. Some studies already previously discussed in this report are referred to IDEA-project about the MEMS microphones analyses [6].

An important task of the IDEA-project was an early and automatic identification of malfunctioning sensors. This task was not trivial, since very high or low sensor readings could either indicate periods with strong or no pollution, but also bad sensor behaviour. For this purpose, in the IDEA-project a low-cost noise sensor has been developed, actively checking that actively checks its condition and indirectly the integrity of the data it produces. The main design concept is to embed a 13 mm speaker in the noise sensor casing and, by regularly scheduling the emission of a frequency sweep, estimate the evolution of the microphone frequency response over time [23].

To develop such a low-cost sensor in the IDEA-project the sensor must be capable of actively testing its condition periodically or on demand with a hardware and algorithm that imply [23]:

- adding an active component to the sensor - for example a speaker - to generate a test signal;
- triggering the stimulus on demand or on schedule and sample the sensor response to the stimulus;
- comparing the sensor response to the stimulus with a reference response and quantifying this comparison with a value ranging from 0 (no similarity) to 1 (exact match);

- finding a threshold in the quantification value to classify the sensor signal response into pass or fail;
- reporting the result of the test via the sensor network and triggering an alert if necessary;
- designing a casing for the sensor components that facilitates environmental monitoring while providing basic protection from the environment.

Thus, the proposed noise sensor consists of a microphone and a speaker facing each other inside a protective casing (Figure 14). The noise sensor then connects to a network node equipped with a sound card with enough computing resources to process audio and relay data over a network connection.

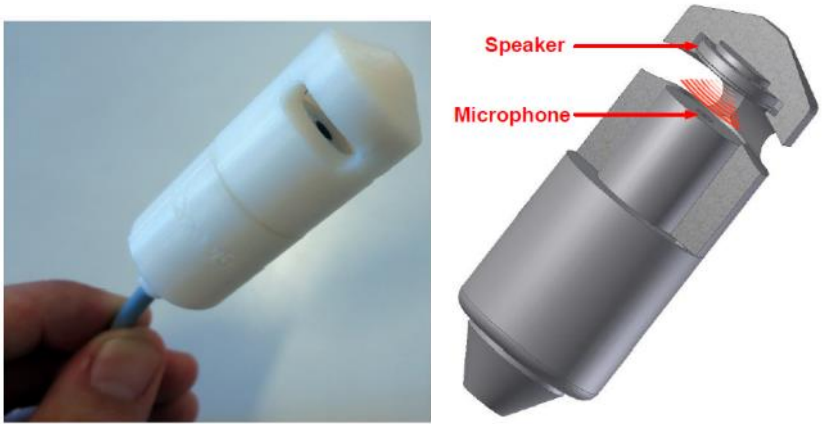


Figure 14 - The self-testing noise measurement sensor developed in IDEA [23].

In the IDEA-project, a flexible network architecture was designed [24]. Distributed computing (load balancing) is an important aspect, since computational power is needed at various locations within the network. CPUs are used to control a number of sensors and perform more demanding computational tasks, for instance, detecting bad sensors. For even more advanced analyses like source recognition, access to computer grids will be facilitated by the network. The cheap single board computers (SBCs) basic functionality is to forward measurements received from the sensors to the storage servers, as illustrated in Figure 15. These are small CPUs with minimal computing power, though equipped with a network card and a sound card. The most demanding task at such SBCs are the noise measurements and the processing to 1/3 octave band levels. They are still limited in terms of storage and networking capabilities. Therefore, several measures were taken to minimize data loss and make efficient use of the available network bandwidth.

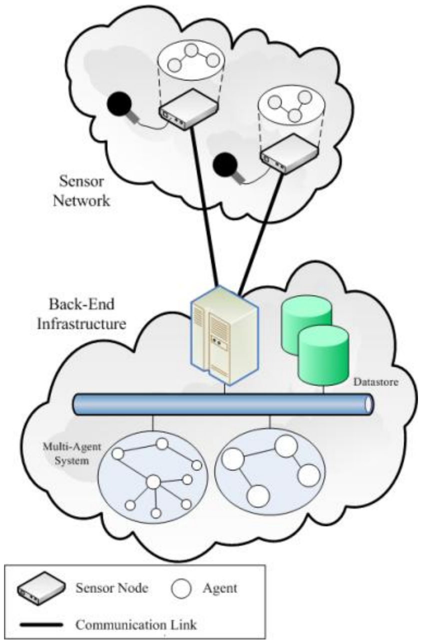


Figure 15 - Overview of the network infrastructure for intelligent sound monitoring (IDEA) [24].

An important aspect analysed the data buffering. All data coming from the attached sensors is directly stored on the onboard compact flash (CF) memory card. As a consequence, no data is lost, in case of a power outage. The SBC also stores repeated 1 second wav files recordings during several seconds. This allows the server to request an up-load of sound recordings up to several seconds after the occurrence of the sound. This latency is used by an algorithm to decide whether a sound is a typical sample that should be stored.

SENTILO Barcelona [25]

Barcelona city developed a sensor platform (2012) to improve the environmental sustainability. SENTILO, the name of the platform, is designed to be an instrument that links the sensors and actuators and all the applications that manage the urban services. A noise monitoring network has been developed with the objective of smartly managing the noise in Barcelona [26]. The core of the network is composed by class I sound level meters and a complementary network equipped with low cost sensor. The two systems have different final uses sketched in the Figure 16.

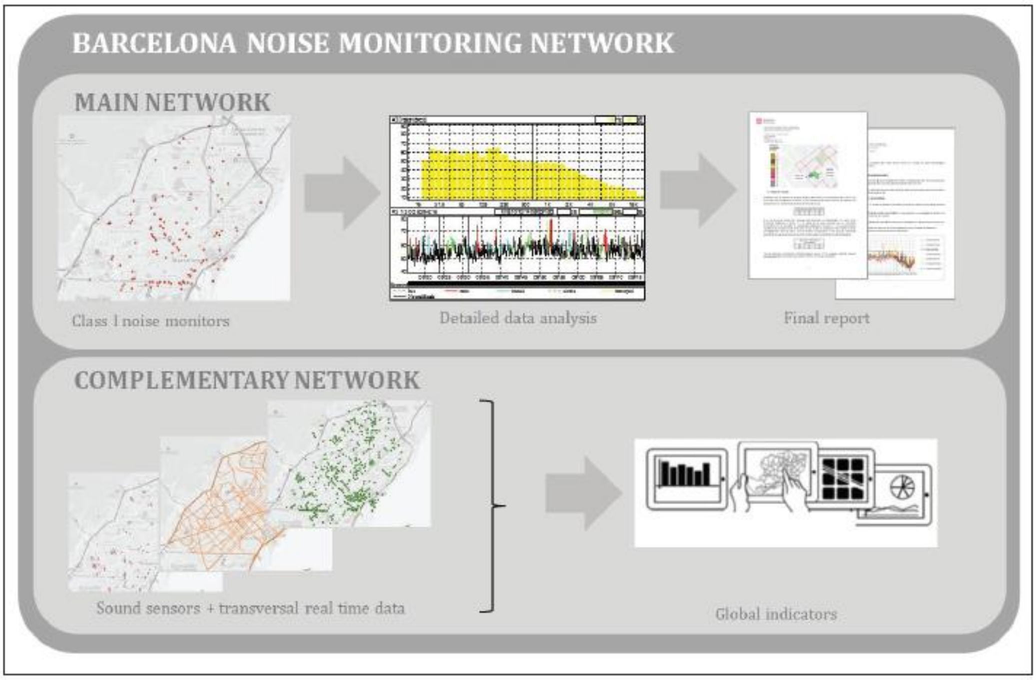


Figure 16 – Noise monitoring network basic (Sentilo) [26].

The main network with 25 noise points (Class I noise monitors) is devoted to evaluate sound levels in challenging areas, to quantify the noise reduction due to the implementation of action plans, to update the noise map, to identify noise sources and evaluate them in complex scenarios. The complementary network is composed by several measurements points with low-cost sensors to increase the real-time noise indicator able to detect the change of the noise-level trends. The technical characteristics of these sensors are listed in Table 4.

Type approval	-
Integration time	1 – 15 minutes
Acoustic indicators	LAeq
Tolerance	LAeq± 2 dB(A)
Measure range	40-100dB(A)
Calibration and verification	Verification of the calibration of the sensor must be able to be undertaken in situ using an acoustic calibrator which fulfils the requisites established under IEC 60942.
Others	Weatherproof LAN / 3G connectivity

Table 4 – Low-cost sensors technical specification (Sentilo) [26].

The complementary network uses the SENTILO platform to serve as a link between sensors and actuators and the application that manage the urban services. The architecture of platform SENTILO is shown in Figure 17, where the intermediary role of the platform between the acquisition process and the urban service (applications) is clear. Barcelona city adopted this platform not only for the noise pollution (although it is the main objective) but for a wide type of sensors (CO_2 monitoring is an example).

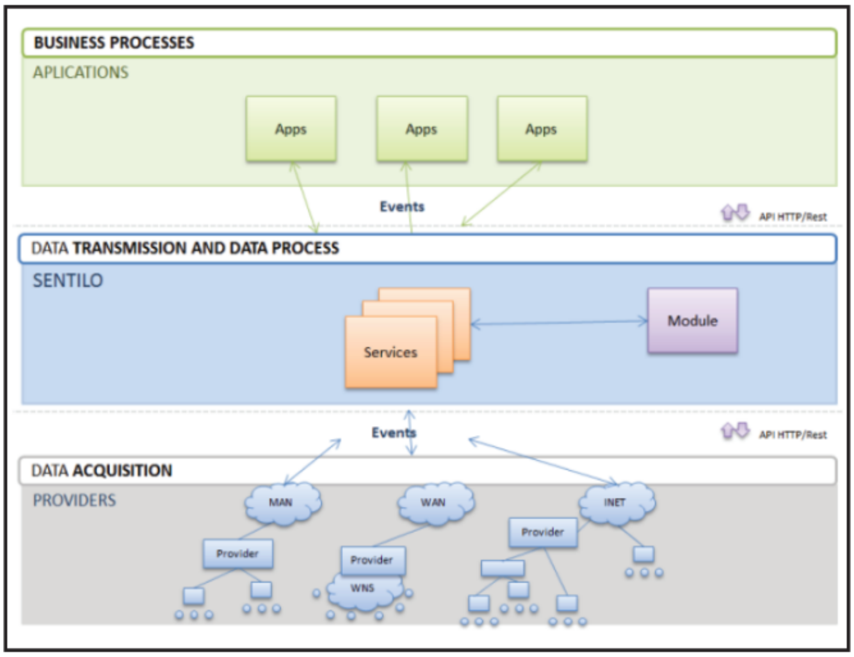


Figure 17 – SENTILO structure [25].

SONYC [27]

In the SONYC project (Sounds Of New York City, 2014), a network of over 55 low-cost acoustic sensor nodes across the city has been deployed to facilitate the continuous, real-time, accurate and source-specific monitoring of urban noise [28]. This large-scale analysis of urban noise activity includes predictive noise impact models and interactive 3D visualizations to reveal noise patterns across space and time. A number of sensor nodes have been operational since May of 2016, resulting in the collection of vast amount of calibrated sound pressure level (SPL) data and its associated metrics.

The projects sensor network is based on a consumer computing platform where low cost and high power are of paramount concern. The design philosophy is based on the creation of a network that provides dense spatial coverage over a large area, through the deployment of inexpensive and physically resilient sensors [29].

The acoustic sensor nodes consist of the popular Raspberry Pi 2B single-board-computer (SBC) sits at the core of the node running the Linux Debian based Raspbian operating system, providing all main data processing, collection and transmission functionality. The majority of nodes make use of a 2.4/5 GHz 802.11 b/g/n USBWi-Fi adapter for internet connectivity; however, a number of nodes also employ a low-cost power-over-ethernet (POE) module which provides internet connectivity and power over a single ethernet cable. Initially, only 2.4 GHz Wi-Fi modules were used, but in some locations with high levels of ambient 2.4 GHz traffic, such as those close to high-rise residential buildings, connectivity was intermittent. The main components of the node are showed in Figure 18.

Figure 18 - Main part list for complete node at relative scale (SONYC) [28].

The sensing module has been already described in the first part of the report [8],[9].

The data collection infrastructure consists of a number of physical and virtual servers handling: data ingestion, persistent data storage, secure data access, sensor control, data decryption, and sensor team/stakeholder data visualization via various dashboards (Figure 19).

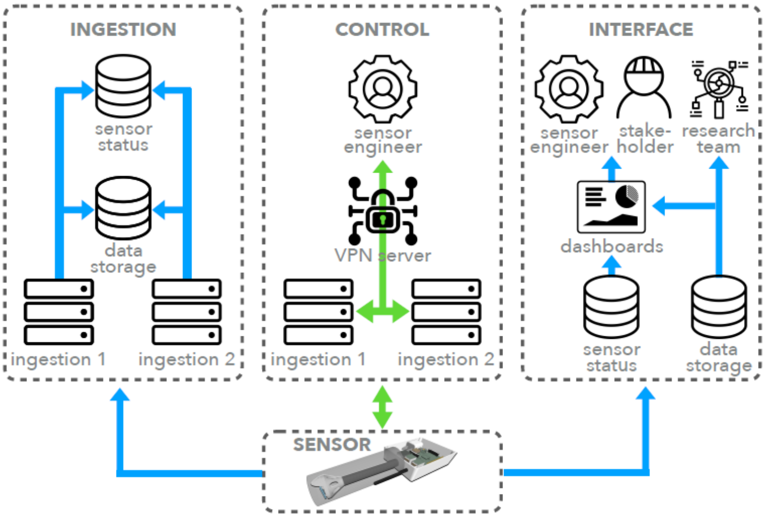


Figure 19 - Infrastructure overview showing core system operations with data flow in blue and control flow in green [28].

It is interesting to analyse the “Data ingestion” that consists of two high power physical servers that act as the representational state transfer (REST) interfaces for all sensor data upload. Sensors are assigned to one of these independent servers to send data to when they establish a connection for load balancing, scalability, and high availability. Once data is uploaded to the ingestion server, it is cached to a local solid state drive (SSD), before it is securely transferred to the persistent network data storage drive. When a daydata folder is untouched for 24 h, it is compressed into a single compressed archive for faster future access.

Without entering in the control aspects, the SONYC sensor network currently has three main groups who require access to its varying data types. For sake of brevity and for the scope of this report just the stakeholders interface visualisation is reported.

Figure 20 shows the dashboard, which has been developed with the DEP (U.S. Department of Environmental Protection) to refine the data displayed and how it is aggregated and abstracted to provide useful and actionable information about urban noise. The map view allows the user to select a sensor of interest whose map icon colours reflects the percentage of the last hour that the SPL exceeded 10 dB above ambient level. This percentage value and its associated sensor is shown in the upper right corner with an ordered list of locations of possible concern, suggesting that excessive noise events are occurring in these locations. The plot below shows SPL data for the past 24 h and a corresponding heatmap below, coloured on a scale representing the previously mentioned percentage of the hour in an excessively noisy state. This dashboard is being used alongside a DEP built alerting system that informs inspectors when a localized cluster of noise complaints occur. Nearby sensor data are used to prioritize enforcement visits to those areas where excessive noise levels are detected for an extended period of time. Through collaborative iterations of this dashboard and alerting system, SONYC is integrating with the DEP operational procedures for data-driven noise enforcement.

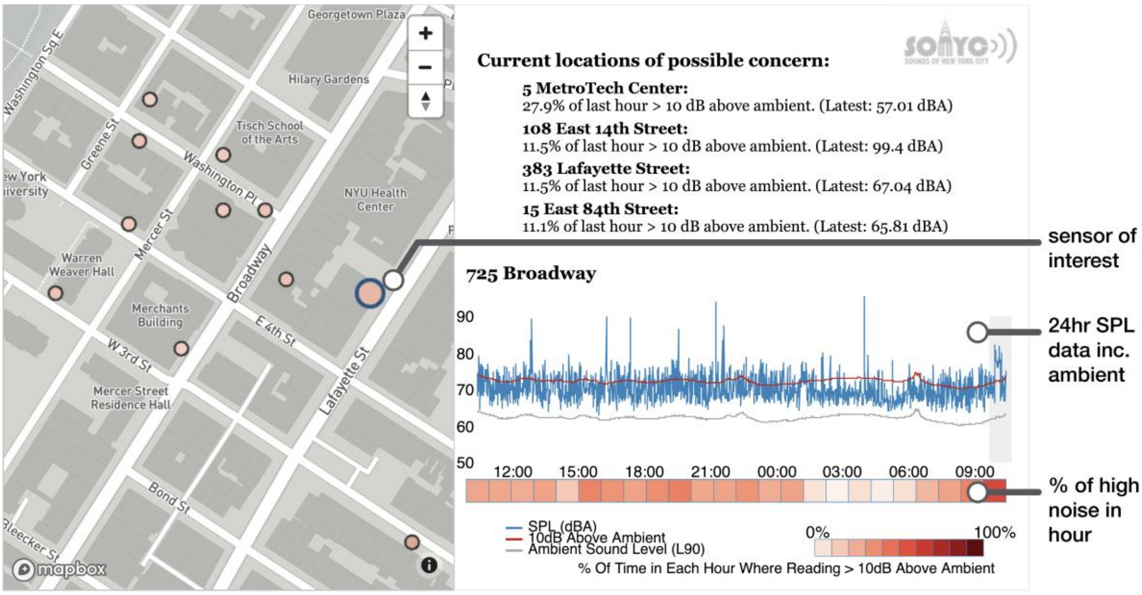


Figure 20 - Dashboard showing real-time sensor data across a heavily deployed area of NYC [28].

Life+ MONZA Project [3]

LIFE MONZA (2016-2020) project foresees to carry out some noise monitoring activities planned in a pilot area, referring to standard methods, using sound level meters of class I precision, and also by developing and using a smart low-cost monitoring system [30]. The pilot area monitored, consists of a district of the city of Monza as shown in Figure 21.

Figure 21 – Pilot area boundaries (left) and selected noise monitoring positions (right) [30].

The Smart Noise Monitoring System (SNMS) network was developed to adequately cover the pilot area and the different types of roads. The smart monitoring system consists in 10 low cost noise monitoring units installed in strategic position in the Libertà district, acquiring the noise time history, every second, of the sound pressure in terms of broadband and 1/3 octave band levels. The transmission system on board of each control unit is designed to guarantee a minimum transmission time per hour to a central server unit from which data can be visualized in almost real time, elaborated and downloaded.

The 10 control units were installed on the façade of public buildings such as schools and the civic centre or on light poles (Figure 22).

Figure 22 – The installation of the system in the public building façade (left) and light pole (right) [31].

The following main specifications of monitoring units have been defined:

- acoustic parameters: overall A-weighted continuous equivalent sound pressure level, “L_{Aeq}” and continuous equivalent sound pressure level, “L_{eq}”, as 1/3 octave band spectrum data;
- timing for data recording: data are acquired with a time basis of 1 second in order to permit the recognition of unusual events in the eventual analysis phase;
- timing for data transmission: data will be sent to the remote server every hour;
- data transmission network: the data will be transmitted through the 3G cellular telephonic network;
- power supply: small solar panel (30 cm x 20 cm) and battery for energy storage or direct connection to electricity network;
- sensors location: on streetlight or on façade, height 4 m above the ground level;
- sensor type: ¼ or ½ inch low-cost microphone with removable rain protection;
- floor noise < 35 dB(A);
- frequency response at nominal frequencies of 1/3 octave from 31.5 Hz to 8 kHz within the class I specs ± 1dB.

Two types of microphones have been used:

- for sensors placed on poles that use solar panel energy: in order to obtain high energy efficiency, digital MEMS microphones that do not require the use of an external ADC were used. The MEMS microphones have been adapted onto a ½ inch cylindrical plastic support to allow the insertion of a standard acoustic calibrator.
- For sensors placed on façades that use power supply connection, electret microphones have been used. For reasons related to shielding for electromagnetic compatibility they have been adapted onto a ¼ inch cylindrical plastic support to allow the insertion of a standard acoustic calibrator.

The system has been mainly based on monitoring units designed in the Life+ DYNAMAP project, tailoring the data transmission, storage and post-analysis to the needs of the LIFE+ MONZA project.

Figure 23 shows the web interface developed in the project for the downloading and visualization of the data.

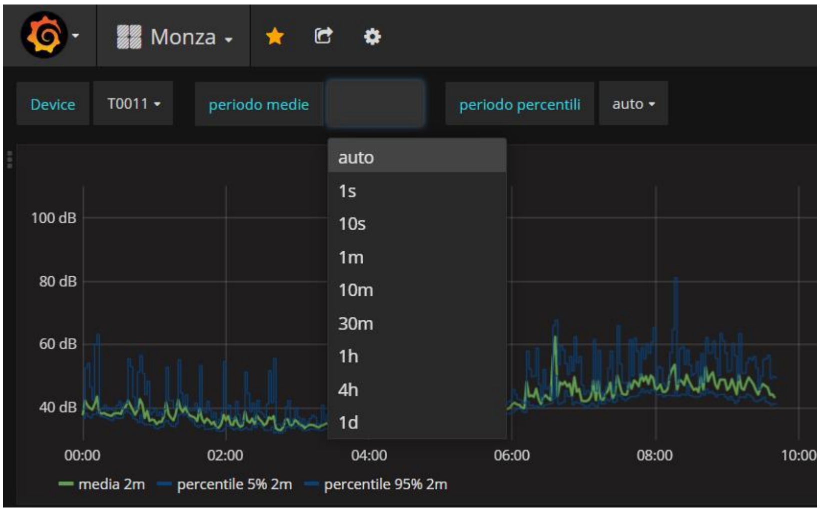


Figure 23 - Web interface with possibility of selecting the time period to view and/or download [31].

SPNMS design

The SPNMS design takes into account three aspects: Hardware and measurement quantities, network architecture and nodes location.

Hardware and measurement quantities

The MEMS performances analysis underlines the possibility to use this low-cost sensor for general measurements in the field. In addition, from their use in several project, where large-scale networks are involved, they are indicated as those that can allow the realization of a widespread and continuous acoustic monitoring. The adoption of these sensors must pay attention to the maintenance aspect, to ensure that the level of certified sensors is maintained over the time.

Thus, for the sensing device the ¼ MEMS microphone with a temperature and frequencies response in the Class I specification (according to IEC 61672 []) will be installed in the node device. To avoid power network unavailability, a solar panel will be embedded in the box case of the device with a direct link to an internal battery to ensure 24h continuous acquisition. The device will be provided with sensing component protection against the weather conditions (rain and wind shield) and bird, keeping in the safe conditions the rest of the hardware assuring the protection IP67 for the entire box case. It will be necessary to have the possibility to install the device in the light poles and in the wall façades (in height) to have different solutions for the mounting phase in the port of Patras.

The device will acquire the A weighted continuous sound pressure level L_{Aeq} (measurement range equal to 35-120 dBA) in 1/3 octave band spectrum data with time acquisition rate of 1 second. This data can be collected from the central server unit where it will be possible to elaborate the raw data to obtain several quantities for statistical analysis:

- instantaneous A, C and unweighted Sound Pressure Level with Fast time weighting (L_{AF}, L_{CF}, L_{ZF});
- 1 hour equivalent A, C and unweighted equivalent Sound Pressure Level ($L_{Aeq,1h}$, $L_{Ceq,1h}$, $L_{Zeq,1h}$);
- Day, evening and night A-weighted Sound Pressure levels (L_{day}, $L_{evening}$, L_{night}) and L_{den}, as defined by 2002/49/EC.

Network Architecture

Figure 24 shows the network architecture . Each node will be equipped with a SIM card for the GPRS, 4G/5G network connection for sending the data to a Noise Monitoring Server through the internet connection. The possibility to send data with Wireless network technology (Wi-fi) will be explored if in the site where the monitoring system will installed this technology is already working and widespread in the site. The data transmission rate can be programmed to manage the needs of acquisition and the needs of energy power. The Noise Monitoring Server will have the aim to collect, storage the data in a database and elaborate them to define the measurement quantities described above.

The elaboration of the acquired data will be shown in a front-end uploaded in the web page of the ANCHOR Project with an easy readability for expert stakeholders or citizens. The real-time acquisition of the nodes will be showed in a specific section of the ANCHOR website to check the noise pollution in the harbour instantaneously. The front-end will give the possibility to retrieve the measurements in the archive and to analyse the statistical quantities based on different timing.

Another section of the website will give the possibility to the citizens to submit their reports for alerting the port authorities of the noise pollution. On the contrary, the port authorities will inform the citizens by SMS or mail (after a subscription handle in the website) in case of anomalous work in the port that can create unexpected noise event.

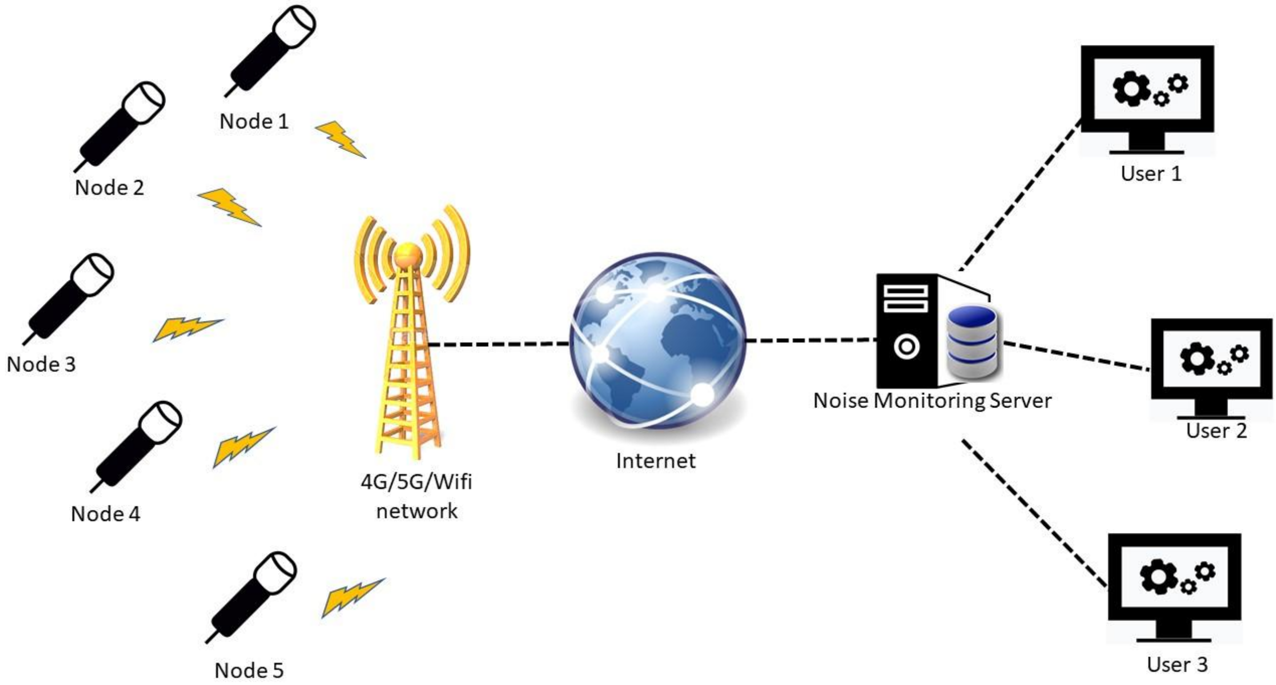


Figure 24 – ANCHOR network architecture.

Nodes location

Generally, speaking about the harbour environment, the nodes of the SPNMS will be defined according to noisy events presence and occurrence, the area morphological characteristics, the presence of screens or barriers and the location of receivers, particularly sensitive ones, such as schools and hospitals.

Regarding the measurements point in the Patras harbour, a total of 10 monitoring stations will be installed, 1 for noise emission assessment (Emitter Stations ES) and 1 at the most exposed receiver (Receiver stations RS) of each of 5 areas identified at the Port of Patras (Figure 25).

Figure 25 – Port of Patras splitted in five monitoring zones.

Based on the wanted SPNMS characteristics, the system developed in DYNAMAP life project seems suitable. In particular, the versatility of DYNAMAP system has been already helpful in the MONZA project and it can allow to fulfil the needs of the SPNMS feature. Actually, the monitoring system in the DYNAMAP life project , as well as in MONZA life project, has been developed in a commercial station by BLUEWAVE srl [32] with the product NOISEMOTE. The main specifications are reported in the Table 5 with a picture of the system (Figure 26).

Measured quantity:	Leq A fast, 1/3 octave spectrum
Trigger audio recording:	yes
Acquisition time base:	1 second
Measurement range:	35 – 120 dB(A)
Data transmission:	GPRS, 3G
Powering:	solar panel
Operation:	continuous h24
Internal battery:	yes
Rain shield and windshield:	yes
Mounting:	lamp post, wall

Data transmission frequency:	programmable
Box dimension:	20 x 12 x 9 cm
Solar panel dimensions:	33 x 30 cm
Protection:	IP67
Weight:	2 Kg
Microphone:	½ inch mems system
Long term drift:	less than 0.2 dB/year
Temperature and frequency response:	IEC 61672 Class I specifications

Table 5 – NOISEMOTE specifications.

Figure 26 – NOISEMOTE device.

The long term drift and the Class I specification according to IEC 61672 are the main feature that allow to contain the measurement uncertainty in the 1 dB(A).

The system is provided with a software that allows to check the measurements in real-time and to show the data archive with the statistical elaboration. Some screenshots of the software utilised in the DYNAMAP project are following reported. Figure 27 shows the main page of the front-end with the sensor map and their location. In the DYNAMAP project the city of Rome was one of the pilot cases.

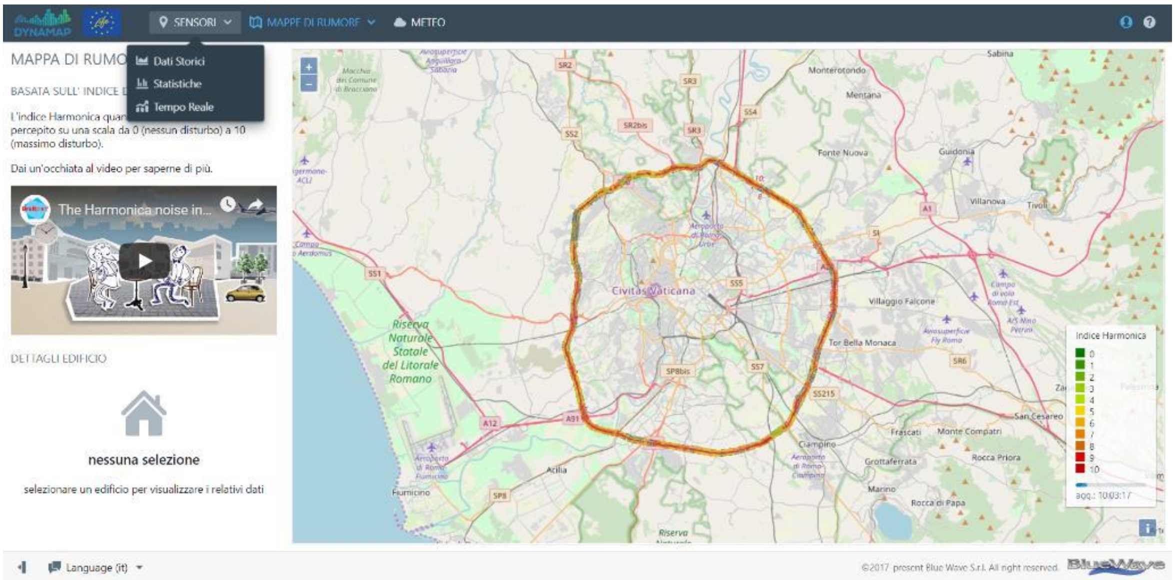


Figure 27 – DYNAMAP software Homepage.

Figure 28 shows the statistical elaboration from the data acquired. In the left-bottom part of the figure the specific node parameters under study are reported and the measurement quantities can be plotted with different statistical timing daily, weekly, monthly and annual.

Figure 28 – Statistical data visualization (DYNAMAP website).

The last plot (Figure 29) is the real-time plot that can be choose for a specific node.

Figure 29 – Real-time data visualization (DYNAMAP website).

Bibliography

[1] ANCHOR Life+ Project – Deliverable B2 – “Guideline for the realization of noise monitoring system for urban ports”.

[2] Web site - http://www.life-dynamap.eu/

[3] Web site - http://www.lifemonza.eu/

[4] Elko, G.W. & Harney, K.P. 2009, “A history of consumer microphones: the electret condenser microphone meets micro-electro-mechanical-systems”, Acoustic Today, Vol. 5, no. 9, pp. 4-13.

[5] Scheeper, P.R., Nordstrand, B., Gulløv, J.O., Liu, B., Clausen, T., Midjord, L. & Storgaard-Larsen, T. 2003, "A new measurement microphone based on MEMS technology", Journal of Microelectromechanical Systems, vol. 12, no. 6, pp. 880-891.

[6] Van Renterghem, T., Thomas, P., Dominguez, F., Dauwe, S., Touhafi, A., Dhoedt, B. & Botteldooren, D. 2011, "On the ability of consumer electronics microphones for environmental noise monitoring", Journal of Environmental Monitoring, vol. 13, no. 3, pp. 544-552.

[7] Web site - http://www.idea-project.be/en/

[8] Mydlarz, C., Salamon, J. & Bello, J.P. 2017, "The implementation of low-cost urban acoustic monitoring devices", *Applied Acoustics,* vol. 117, pp. 207-218.

[9] Mydlarz, C., Nacach, S., Roginska, A., Park, T.H., Rosenthal, E. & Temple, M. 2014, "The implementation of MEMS microphones for urban sound sensing", 137th Audio Engineering Society Convention 2014, pp. 740.

[10] International Standard – IEC 61672 – Electroacoustics - Sound Level Meters – Part 1, 2, 3 – 2013.

[11] Bellucci, P., Peruzzi, L. & Zambon, G. 2016, "LIFE DYNAMAP: An overview of the project after two years working", Proceedings of the INTER-NOISE 2016 - 45th International Congress and Exposition on Noise Control Engineering: Towards a Quieter Future, pp. 6338.

[12] Benocci, R., Bellucci, P., Peruzzi, L., Bisceglie, A., Angelini, F., Confalonieri, C. & Zambon, G. 2019, "Dynamic noise mapping in the suburban area of Rome (Italy)", Environments - MDPI, vol. 6, no. 7.

[13] 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. 2016, "DYNAMAP - Development of low cost sensors networks for real time noise mapping", Noise Mapping, vol. 3, no. 1, pp. 172-189.

[14] Alías, F., Alsina-Pagès, R.M., Orga, F. & Socoró, J.C. 2018, "Detection of anomalous noise events for real-time road-traflc noise mapping: The DYNAMAP's project case study", *Noise Mapping,* vol. 5, no. 1, pp. 71-85.

[15] Nencini L., Socoró J.C. 2015 “Dynamap project: hardware specifications update” TecniAcustica, Valencia 21-23 October.

[16] Web site - https://senseable.it/

[17] Web site - https://rumeur.bruitparif.fr/

[18] Mietlicki, F., Mietlicki, C. & Sineau, M. 2020, "An innovative approach for long-term environmental noise measurement: RUMEUR network in the Paris region", Euronoise 2015, pp. 2309.

[19] Web site - http://projects.npl.co.uk/dreamsys/

[20] Barham, R., Goldsmith, M., Chan, M., Simmons, D., Trowsdale, L., Bull, S. & Tyler, R. 2009, "Development and performance of a multi-point distributed environmental noise measurement system using MEMS microphones", 8th European Conference on Noise Control 2009, EURONOISE 2009 - Proceedings of the Institute of Acoustics.

[21] Barham, R., Chan, M. & Cand, M. 2010, "Practical experience in noise mapping with a MEMS microphone based distributed noise measurement system", 39th International Congress on Noise Control Engineering 2010, INTER-NOISE 2010, pp. 1702.

[22] Van Renterghem, T., Botteldooren, D., Thomas, P., Can, A., Dauwe, S., Dhoedt, B., Rademaker, M., De Baets, B., Touhafi, A., Dominguez, F., Theunis, J. & O'Donoghue, R. 2010, "Towards an extensive noise and air quality measurement network", 39th International Congress on Noise Control Engineering 2010, INTER-NOISE 2010, pp. 1606.

[23] Domínguez, F., The Cuong, N., Reinoso, F., Touhafi, A. & Steenhaut, K. 2013, "Active self-testing noise measurement sensors for large-scale environmental sensor networks", Sensors (Switzerland), vol. 13, no. 12, pp. 17241-17264.

[24] Botteldooren, D., De Coensel, B., Oldoni, D., Van Renterghem, T. & Dauwe, S. 2011, "Sound monitoring networks new style", Australian Acoustical SocietyConference 2011, Acoustics 2011: Breaking New Ground, pp. 626.

[25] Web site - https://www.sentilo.io/

[26] Farrés, J.C. 2020, "Barcelona noise monitoring network", Euronoise 2015, pp. 2315.

[27] Web site - https://wp.nyu.edu/sonyc/

[28] Mydlarz, C., Sharma, M., Lockerman, Y., Steers, B., Silva, C. & Bello, J.P. 2019, "The life of a new york city noise sensor network", Sensors (Switzerland), vol. 19, no. 6.

[29] Mydlarz, C., Nacach, S., Park, T.H. & Roginska, A. 2014, "The design of urban sound monitoring devices", 137th Audio Engineering Society Convention 2014, pp. 793.

[30] Bartalucci, C., Borchi, F., Carfagni, M., Furferi, R., Governi, L., Lapini, A., Volpe, Y., Curcuruto, S., Mazzocchi, E., Marsico, G., Luzzi, S., Bellomini, R., Nizzola, C.M., Maggi, M. & Fasanella, A. 2018, "LIFE MONZA: Project description and actions’ updating", Noise Mapping, vol. 5, no. 1, pp. 60-70.

[31] MONZA Life+ Project – Deliverable B3 – “Prototype realization and installation”.

[32] Web site - https://www.blue-wave.com/