euronoise 2021
25th to 27th of October
Madeira, Portugal - online

A high density network of low cost acoustic sensors based on wired and airborne transmission of spectral data

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Abstract

The technological advent of low cost microphones and innovative airborne data transfer protocols allows the deployment of a new type of gathering of information from the acoustic urban environment. The CENSE network is a prototype network that is based on a hydrid data network with airborne transmission from autonomous sensor nodes to gateway nodes that are connected to the processing and storage servers using powerline network technology. This network, currently deployed in the downtown area of the city of Lorient, is designed to provide information about the acoustic environment at a high spatial and temporal resolution and a high level of privacy. In this paper, we propose to describe the whole infrastructure, the design of the sensors, the signal processing applied to the measurements, the data collection and some visualization tools. The feedback from this project allows us to consider the evolution of the network for operational use.

1 Introduction

The acoustic environment of urban areas has to be monitored in order to control the quality of life of urban citizens. While noise maps issued from modeling and questionnaires are reliable techniques for such a purpose they lack spatial and temporal resolution and are labor intensive. The technological advent of low cost microphones and innovative airborne data transfer protocols allows the deployment of a new type of gathering of information from the acoustic urban environment. The CENSE network is a prototype network that is designed to study the feasibility of numerous technical challenges that are to be addressed to reach the full potential of such approaches.

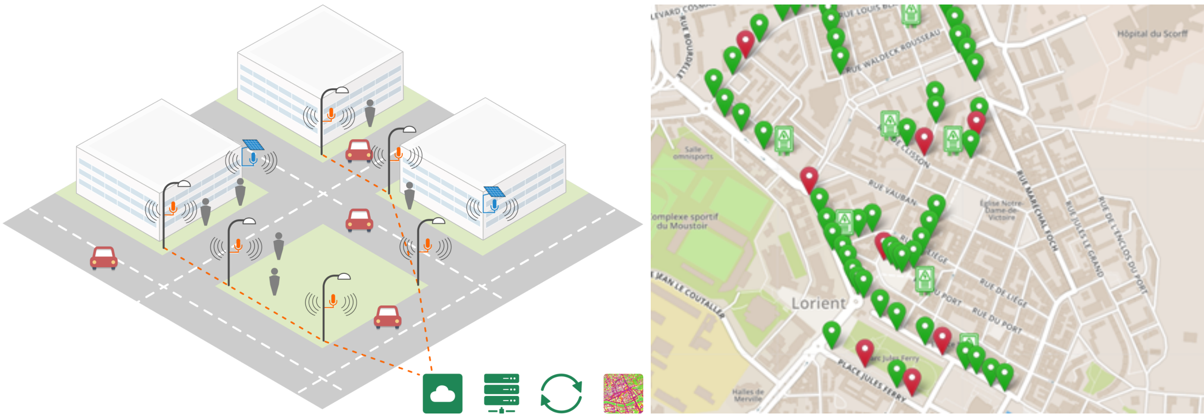

Fig. 1: Left, the CENSE network is composed of gateway nodes in red and autonomous leaf nodes in blue. The city lighting infrastructure is used to power the gateway nodes and to ensure an internet connection by using the Citybox technology. Right, display of the deployment in the City of Lorient, with the gateway nodes in green/red localization icon, depending if they are working/connecting or not. Each line of the lighting infrastructure is supervised by a controller (shown as a "power" icon).

Before presenting those challenges, we now list the benefits of such an approach. First, noise maps are produced using sound propagation models whose precision would be greatly enhanced by considering actual measurements. Second, assessing the quality of the acoustic environment requires the modeling of high level perceptual attributes for which the time of presence of sound sources such as traffic, voice and birds are of great importance. For all those matters, the availability of continuous monitoring through a high density network is a promising approach.

With this new kind of technology, some challenges have to be addressed. First, the hardware infrastructure needs to provide good quality acoustic measurements, with a sufficient quality of service and shall be easily maintained. Second, the data produced by the network needs to be translated into physical and perceptual measures that are mandatory to serve its purpose. Continuously monitoring the acoustic environment of an urban area thus requires a hardware infrastructure where each component is of critical importance. The CENSE project studies various aspects of the design of this infrastructure. In this paper, we present the typology of the CENSE network, the sensor design, and the network infrastructure in Section 2. Sensitivity and robustness of sensors are respectively discussed in Section 3 and 4. The data archival system and some visualization tools are then respectively presented in Section 5 and 6.

2 Network

Monitoring the urban acoustic environment requires hardware devices that are able to capture the acoustic pressure level. For that, the CENSE network considers a hybrid communication scheme where each node of the network is a sensor with acoustic monitoring capability. Those nodes can be leaf nodes. In this case the sensor is energetically autonomous and sends wirelessly the data to the other types of nodes, the gateway nodes. A gateway node is wired both in terms of power and network connectivity. All nodes have the same microphone that should be carefully chosen.

The degree of precision of the measure can vary greatly from device to device, from class A sonometers to low cost devices built on MEMS microphones. As discussed in [Picaut 2020], this degree of precision is balanced with the cost of the sensors. While high precision sonometers are of great interest for metrologic use, we believe that low cost sensors based on the MEMS technology has the potential of allowing the use of large scale and dense network of sensors at a reasonable price. The MEMS technology is known to be better than the electret one at the same price range.

Following the constraints of the project, the specifications of the microphone have been defined and more than 20 MEMS microphones have been considered [Ardouin 2018]. The Invensense ICS-43432 MEMS microphone is selected because of its good overall performance and the fact that it offers an I2S fully digital interface, thus reducing the risk of any electrical noise addition to the audio data.

Fig. 2: The leaf (left) and gateway (right) sensors.

The leaf nodes (Figure 2 left) harvest energy through a solar panel and draw energy from a battery when the solar panel is able to fulfill the needs. The processing hardware and software shall thus be carefully designed in order to reduce consumption. The STM32L4 is chosen for computing the data described in Section 4 and to format this data into a 6LoWPAN radio frame sent to the gateway node.

The gateway node (Figure 2 right) being wired, and having to perform various tasks compared to leaf nodes, it embeds a more powerful processing unit, the Raspberry PI 3. The gateway nodes receives data from up to 2 leaf nodes, performs the computation of the data from its own microphone and outputs all this data to the archiving servers, as described in Section 5.

Deployment

The installation of the sensors was planned in two phases on an experimental site in the heart of the city of Lorient in France. The first phase consisted of the installation of 78 gateway nodes, then in a second phase, the installation of 65 Nodes.

The deployment of gateway nodes is based on the installation of the sensors on the street lighting network; the sensor is then powered directly by the lighting mast, and an additional device on the mast (Citybox technology from Bouygues Energies & Services) allows the entire street lighting network to be transformed into a PLC-type system for transporting the data. In practice, each lamp post in the same lighting line must be equipped with a Citybox, even if there is no sensor on the mast concerned. An additional system (controller) allows controlling all the Citybox of the same lighting line. Finally, a 4G router is installed on each controller in order to transfer the sensor data to the CENSE servers. Once connected to the internet, several different supervision software can check the functioning of each equipment (routers, controllers, Cityboxes and sensors).

The installation of the gateway nodes was finalized in 2020. At this stage the network counted 73 sensors on 10 public lighting lines. Each gateway node was calibrated by a 94dB@1kHz acoustic calibrator before installation. The installation of the leaf sensor is still pending. The leaf nodes should be installed either on street lights (but without power and internet connection) or in front of buildings. These nodes will judiciously complete the acoustic measurements in areas where a power supply and an internet connection are not possible.

Maintenance

The maintenance of the network is a crucial element of the project. The entire network was developed specifically by the project partners, from scratch, be it for the design of the sensors, the installation of the network, and the implementation of an IT infrastructure for data management. One one hand, it allowed rapid intervention, one the other hand, numerous skills from very different technical areas were required to cope with unforeseen issues. Among the difficulties encountered were: the failure of some sensors after installation (a few units); the multiplicity of risks of measurement stoppage due to malfunctioning of either the sensors themselves, or the Cityboxes, or the controller, or the router; the maintenance of the servers; the maintenance of the technical equipment on site and the responsiveness of the interventions... In spite of these difficulties inherent to the initial choices for the development of the network, the whole network was successfully implemented during the first months of the study, allowing the acquisition of a large amount of data and the experimentation of different sound analysis.

3 Acoustic sensitivity analysis

In order to study the acoustic behavior of the developed sensors, several tests are performed to evaluate the linearity, directivity, sensitivity and background noise characteristics. Those tests are done in an acoustic test room, see Figure 3. As the metrological characteristics are relatively similar between the gateway node and the leaf nodes, the tests are performed only on the gateway node. Those tests are based on the comparison of acoustic data measured by the gateway node with a reference microphone, using controlled reference signals. Since the CENSE sensor is configured to produce sound spectra, the tests are limited to values measured in one-third octave bands over a frequency range from 20 Hz to 12500 Hz.

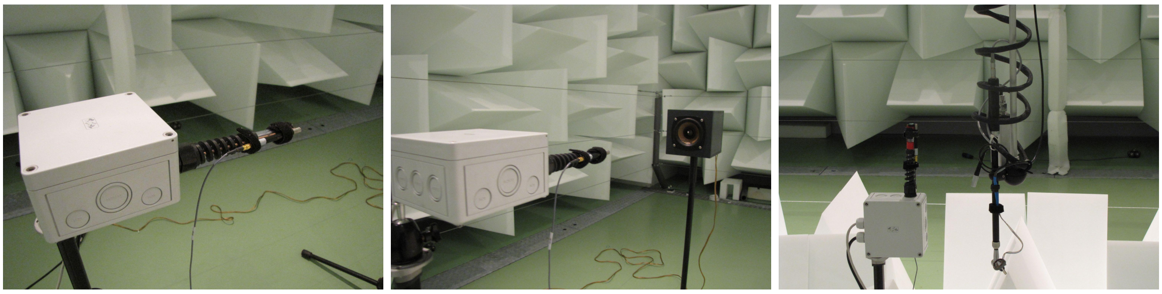

Fig. 3: Acoustics testing for the CENSE sensor. Illustration for the evaluation of the background noise (left), the linearity in amplitude (center) and the directivity (right)

Concerning the background noise of the sensor, a series of 8 measurements of 10 seconds duration are averaged to produce an average noise level of the background noise per third octave band between 20 Hz and 12 500 Hz. The results obtained show very clearly that the CENSE sensor has a threshold of about 22 dB, over all the frequency bands concerned, compared with 7-8 dB for the reference microphone. Compared to the sound level measured by the reference microphone, the difference is between 10 and 21 dB, which is relatively important. In the 20 Hz and 12.5 kHz range, the sensor gives on average a background noise level of 35.5 dBA against 22.1 dBA for the reference microphone. This result is expected since it is difficult to foresee an equivalent level of performance between these two sensors whose metrological classes are very different. Nevertheless, the noise level measured from 50 Hz onwards (33.9 dB, 33.1 dBA) remains overall below the noise level that can be expected in an outdoor environment.

The frequency sensitivity analysis is now performed using a multi-frequency calibrator, producing calibrated signals of 94-104-114 dB for the octave bands from 31.5 Hz to 16 kHz. In parallel, the same measurements are made using the reference microphone. Both transducers are first calibrated at the 1000 Hz frequency, and the sound levels are then measured for the other frequency bands, in order to evaluate the deviation from the expected sound level. The overall performance is very good for the octave bands from 250 Hz to 4000 Hz, with a difference of less than 0.5 dB. For the 125 Hz, 8k Hz and 12.5k Hz octave bands, the differences are a little larger, from 1 to 2 dB. For the 2 lowest octave bands (31.5 Hz and 63 Hz), the differences are much more important (from 4 to 10 dB approximately). The observed differences are most probably due to the frequency response of the MEMS sensor, whose frequency response curves show very clearly a strong attenuation below 100 Hz and a progressive increase in response from about 6 kHz. It should be noted that the differences observed for each frequency band do not seem to depend on the sound level, which gives information on the linearity of the sensor for high levels. In addition, the analysis of the linearity in level is carried out by using a pink noise, transmitted by a loudspeaker placed at 50 cm from the sensor and the reference microphone, and whose amplitude is modulated. A linear interpolation is then used to evaluate the linearity slope. From 125 Hz to 12.5 kHz, the slope measured for the sensor is very close to unity, which is the expected theoretical behavior. Below 80 Hz, for the lowest levels, the measurements made are of the order of magnitude of the background noise level, so it is difficult to evaluate the linearity.

The evaluation of the directivity of the transducer is performed by a series of 1501 acoustic measurements, each measurement being associated with a source position around the sensor. The results obtained, compared to the reference microphone, show that the CENSE sensor is indeed omnidirectional over all frequency bands above 400 Hz (limit of use of the sound source). The body of the CENSE sensor does not appear to have a negative effect. If the sound sources are located behind the microphone supporting device (a configuration not evaluated by the directivity measurement system used), a masking effect remains possible. However, in most real measurement setups, the probability that a sound source is located exactly behind the sensor body is low.

In order to evaluate the overall acoustics performance of the CENSE sensor, we have considered the following criteria: the background noise level is lower than 30 dB; the sensitivity is less than 2 dB; the linearity slope is less than 1 dB and the offset is less than 2 dB and the standard deviation of the directivity is less than 2dB. With these criteria, the sensor results appear to be acceptable for the frequency bands between 400 Hz and 5000 Hz. It is probably possible to extrapolate the directivity results below 400 Hz, so that a frequency range including the 1/3 octave bands from 125 Hz to 5000 Hz, which includes road noise and the speech spectrum, can be considered according to the same criteria. At low frequencies (below 100 Hz), the problems of background noise and sensitivity (frequency response of the MEMS) do not allow the results to be used under good conditions. The spectral range at high frequencies is limited primarily by the differences observed in terms of sound level, once again due to the frequency response of the MEMS. To overcome these sensitivity problems, a correction of the response curve of the MEMS microphone could be considered by applying an audio-digital filtering within the sensor.

4 Robustness analysis

The reliability, accuracy and robustness of the developed acoustic sensors are controlled and analysed based on an experiment that consisted in i) placing an acoustic sensor inside the climate chamber (Heraeus HC 2020), ii) instrumenting the sensor with a sound calibrator (Brüel & Kjaer type 4231) at the PEX tube end, iii) calibrating the sensor (94dB@1kHz) and iv) measuring the $L_{Aeq,1s}$ indicator continuously during 6 cycles of temperature and humidity programmed in the climate chamber, as illustrated on Figure 5. The source calibrator is used as a sound source throughout the meteorological cycles that consisted in one-hour duration stages with stabilised temperature and humidity. The test has a total duration of about two days.

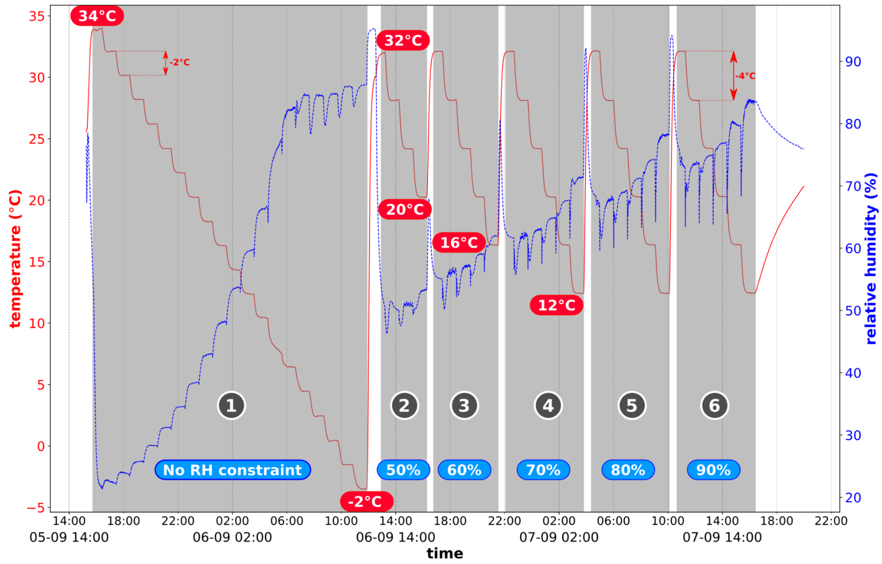

Fig. 5: Climate cycles: (red continuous line) temperature and (blue dotted line) relative humidity.

The temperature range of each cycle is adapted for each climate cycle according to the operating range of the climate chamber. Four gateway sensors are tested. The temperature and relative humidity inside the climate chamber are recorded during each test by a HOBO U12 temperature and relative humidity (T/RH) data logger connected to an external computer and managed by the dedicated software HOBOware 3 that records time stamped one-minute average values of both temperature and relative humidity. An identical experiment is carried out with a 01dB FUSION Class 1 sonometer. The series of measurements are organized in three phases by alternately placing the different acoustic sensors in the climatic chamber. A first series is performed with the sonometer only, a second series with the low-cost sensors #1 and #2, and a last series with the sensors #3 and #4. Clocks of the acoustic sensors (i.e. the low-cost sensors and the sonometer) and of the computer that manages the HOBO sensor are synchronised prior to each series of measurements.

The data set (i.e. the temperature, relative humidity and $L_{Aeq,1s}$ indicator data) issued from all sensors (i.e. the low-cost acoustic sensors, sonometer and T/HR data logger) are first concatenated to build a single experimental database. One-minute averaged values of temperature T_{sensor}, relative humidity RH_{sensor} and acoustic indicator $L_{Aeq,1s}$ are computed over the same time periods as reference meteorological data T_{ref} and RH_{ref} issued from the reference T/RH sensor. The database is then cleaned up by removing data for which the temperature in the climate chamber is not stabilised, that is when the temperature gradient between two successive records is higher than 0.01°C.

A statistical study is then carried out based on the previous clean data set in order to study the behavior of the sensors according to the climate conditions. Table 1 presents the general results for all meteorological conditions concerning the mean, median and standard deviation of the recorded $L_{Aeq,1s}$ indicator values. It shows that the measurements performed by the low-cost sensors are very close to the expected value of 94 dB(A) with a very weak standard deviation of the same order of magnitude as that of the sonometer, apart for the sensor #3 for which the standard deviation is slightly greater than for the three other sensors which may be due to a tightness defect between the PEX tube and the sound calibrator. A pairwise comparison is then carried out for each acoustic sensor between the $L_{Aeq,1s}$ indicator and the ambient temperature or relative humidity. This analysis showed that the sound levels recorded by the low-cost sensors tend to linearly increase as temperature increases or as humidity decreases, which is consistent with the expected behavior of MEMS microphones. The standard deviation additionally remains constant and low whatever the temperature. The behavior of the sonometer according to temperature is opposite to the one of low-cost sensors, which is typical of the integrated electret-type microphone. An opposite trend is observed according to the humidity for the low-cost sensors and the sonometer with a slightly greater dispersion than with respect to the ambient temperature.

Table 1: Mean, standard deviation and median values of the $L_{Aeq,1s}$ indicator for all climate conditions.

sensor	**mean (dB(A))**	**std (dB(A))**	**median (dB(A))**
sonometer	93.83	0.13	93.79
sensor #1	93.73	0.11	93.75
sensor #2	93.37	0.15	93.41
sensor #3	93.91	0.34	93.79
sensor #4	93.67	0.10	93.65

The distributions of $L_{Aeq,1s}$ indicator values are then analysed within categories of temperature and relative humidity value defined over ranges of 5°C and 10% respectively. Results shown on Figure 6 show that both the ambient temperature and humidity have a weak effect on the acoustic measurements. The standard deviation of $L_{Aeq,1s}$ remains of the same order of magnitude for the low-cost sensors as for the sonometer regardless of the ambient temperature or humidity.

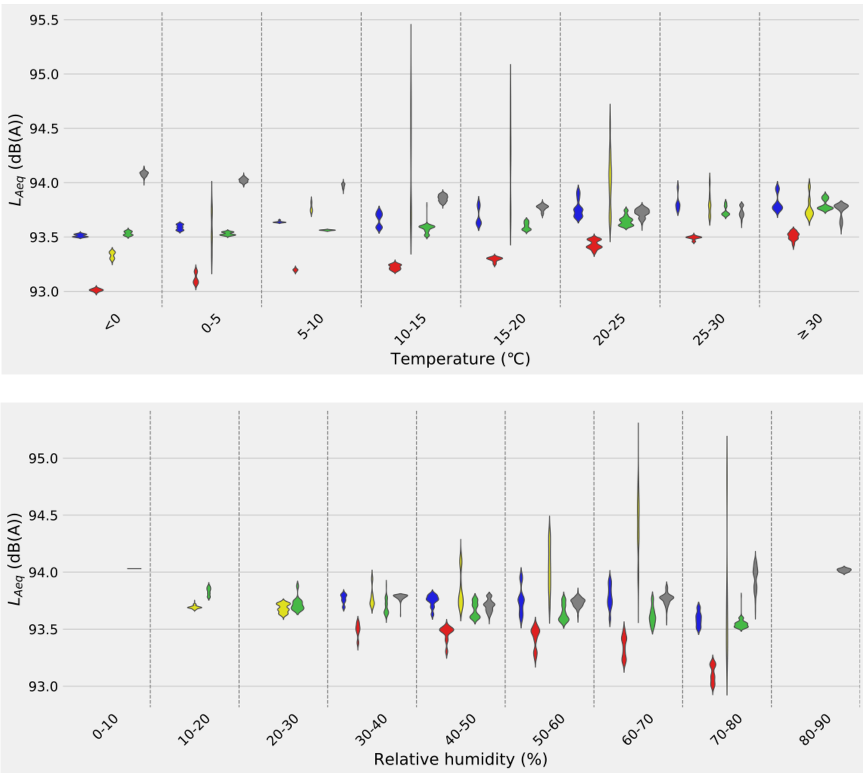

Fig. 6: Categorical plots of the $L_{Aeq,1s}$ values according respectively to the temperature (top) and relative humidity (bottom) for the sonometer (grey) and low-cost sensors (colors).

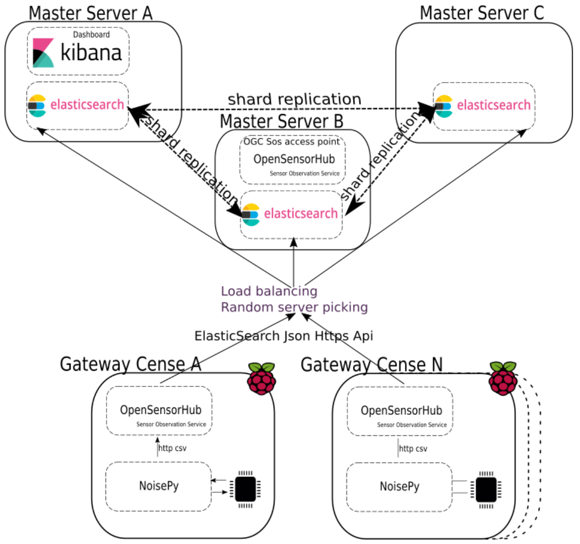

Fig. 7: The archiving architecture. Each gateway node sends data to a randomly chosen server that next ensures duplication.

5 Data Archiving

Each node produces acoustic data, pressure level statistics, and third octave spectral data, that are sent every 10 seconds. Control information, such as temperature and humidity inside the sensor are sent every 60 seconds. If the sensor is a leaf node, information about battery voltage and connectivity are also sent every 5 minutes.

Acoustic pressure statistics are the Laeq and Leq computed every second (520 bytes). Third octave spectra with frequency range 20Hz-12500Hz are computed every 125 ms using a rectangular window Fast Fourier Transform (15 kbytes). Bandwidth testing showed a bandwidth consumption of 1769 bytes per second. Each gateway node is responsible for sending its data through the internet to an archiving architecture using the opensensorhub protocol, see Figure 7. OpenSensorHub (OSH) software allows one to easily build interoperable and evolutive sensor networks with advanced processing capabilities and based on open-standards for all data exchanges.

The storage architecture of the CENSE project is designed to maintain high availability. To this end, the data are distributed on 3 distinct sites, as shown on Figure 7. The archiving system should therefore be operational even if one site is no longer reachable. Each data is duplicated at least on two sites, so no data loss can occur.

Each gateway node collects data through its sensors (the one physically embedded in the gateway node and the ones of the two leaf nodes that are wirelessly connected) then aggregates into an embedded OpenSensorHub instance. This aggregated data is transferred to a random server through a secured http request using the open source elastic search interface. The receiving server then duplicates the data to another elasticsearch server for data safety. Elasticsearch (https://github.com/elastic/elasticsearch) is a search engine based on the Lucene library. It provides a distributed, multitenant-capable full-text search engine with a web interface and schema-free JSON documents.

One should be aware that, even if the data is duplicated, it is possible to delete the data in the database. An incremental backup is thus performed in order to prevent any non reversible modification of the database due to mis manipulations or intrusions.

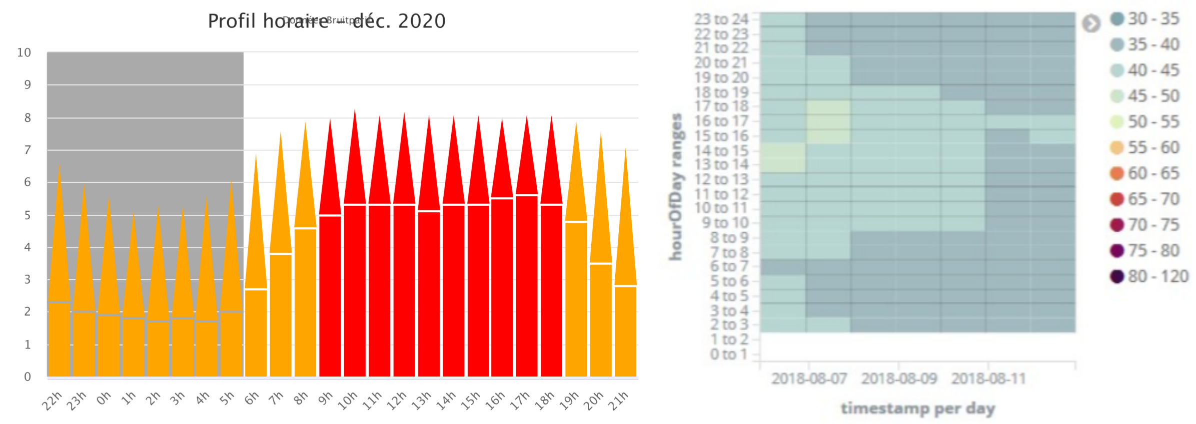

Fig. 8: Left, evolution of the laeq over a week for a given sensor using the kibana dashboard. Right, the Harmonica profile for a given sensor of the CENSE network for the month of December 2020

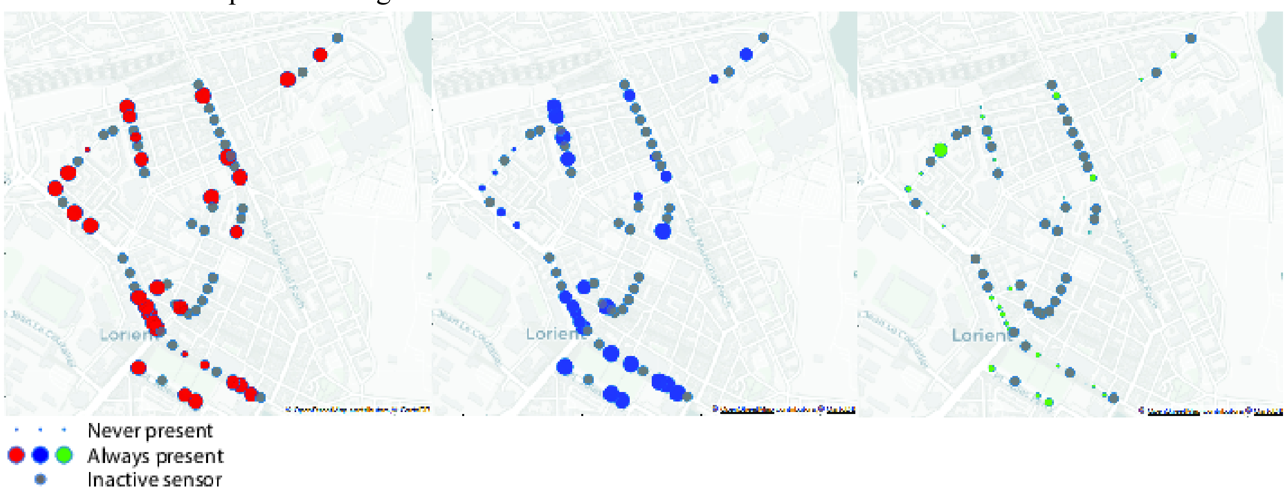

Fig. 9: Estimation of the time of presence of traffic (red), voice (blue), and birds (green) from spectral data using deep learning techniques

6 Visualization

Archived data can be accessed using low level request protocol using the elastic search engine as it allows database replication for further data processing purposes by serving json files. For example, the acoustic data is pushed to the servers of bruitparif (https://www.bruitparif.fr) that services a range of display tools available at the following url: https://rumeur-lorient.bruitparif.fr. Among those tools, the harmonica [Mietlicki 2014] profile is available, see Figure 8 (left).

Higher level data visualization and monitoring can also be performed using a Kibana interface, a proprietary data visualization dashboard software for elasticsearch (https://www.elastic.co/kibana). Figure 8 (right) shows an item of a kibana dashboard plotting the evolution of the LAeq over a week for a given sensor.

Perceptual attributes describing the acoustic environment such as pleasantness can be inferred from energy level indicators and time of presence of specific sources. By recording spectral data, the CENSE project aims at allowing the automatic estimate of those quantities using deep learning techniques [Gontier 2019, Gontier 2020]. Figure 9 shows the presence of three sources of interest: traffic, voice and birds.

Conclusion

This paper presented the CENSE network, a prototype network that is based on a hydrid data network with airborne transmission from autonomous sensor nodes to gateway nodes that are connected to the processing and storage servers using powerline network technology. In order to provide meaningful information from those sensors while retaining a high level of privacy and a low data rate, the audio data is transferred using a compressed spectral data format. This network, deployed in the downtown area of the city of Lorient, is designed to provide information about the acoustic environment at a high spatial and temporal resolution. Indeed, it provides an unprecedented spatial density of 32 sensors per square kilometers, and each sensor provides information at a 1 Hz rate.

By providing a monitoring capability of an unprecedented spatial and temporal resolution, this network will allow researchers to answer many scientific and technological questions regarding the characterization of the acoustic urban environment. One important question is how such a tool can complement noise maps and questionnaires to better model and describe the acoustic urban environment.

Acknowledgements

The authors want to thank the city of Lorient and in particular J.C. Baron and P. Crépeaux from the “Pôle cadre de vie et development durable” (Life and sustainable development center). This work was funded under the ANR project CENSE No. ANR-16-CE22-0012.

References

[Ardouin 2018] Ardouin, J., Charpentier, L., Lagrange, M., Gontier, F., Fortin, N., Ecotière, D., ... & Mietlicky, C. (2018, December). An innovative low cost sensor for urban sound monitoring. In *INTER-noise and noise-con congress and conference proceedings* (Vol. 258, No. 5, pp. 2226-2237). Institute of Noise Control Engineering.

[Gontier 2019] Gontier, F., Lavandier, C., Aumond, P., Lagrange, M., & Petiot, J. F. (2019). Estimation of the perceived time of presence of sources in urban acoustic environments using deep learning techniques. *Acta Acustica united with Acustica*, *105*(6), 1053-1066.

[Gontier 2020] Gontier, F., Lostanlen, V., Lagrange, M., Fortin, N., Lavandier, C., & Petiot, J. F. (2021). Polyphonic training set synthesis improves self-supervised urban sound classification. The Journal of the Acoustical Society of America, 149(6), 4309-4326.

[Picaut 2020] Picaut, J., Can, A., Fortin, N., Ardouin, J., & Lagrange, M. (2020). Low-Cost Sensors for Urban Noise Monitoring Networks—A Literature Review. *Sensors*, *20*(8), 2256.

[Mietlicki 2014] Mietlicki, C., Mietlicki, F., Ribeiro, C., Gaudibert, P., & Vincent, B. (2014, September). The HARMONICA project, new tools to assess environmental noise and better inform the public. In Proceedings of the Forum Acusticum Conference, Krakow, Poland (pp. 7-12).