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A Real-Time Noise Monitoring System Based on Internet of Things for Enhanced Acoustic Comfort and Occupational Health

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ABSTRACT Environmental noise directly affects well-being and productivity. On the one hand, high sound levels are related to a variety of health symptoms such as high blood pressure and stress. On the other hand, acoustic comfort increases concentration, facilitates communication and promotes productivity. The main objective of this research is to propose a modular and scalable solution for enhanced health and well-being using Internet of Things and mobile computing technologies and also, to present a real-time monitoring system for enhanced acoustic comfort with mobile computing compatibility for data visualization, analysis and notification. The results indicate the proposed system as an adequate sound supervision for enhanced acoustic comfort and well-being. The system was tested in a laboratory for two months using real-time continuous data collection. The average sound levels range from 47.35 to 52.99 dBA and from 46.22 to 51.84 dBA grouped by the day of the week and time of day, respectively. Continuous real-time monitoring is relevant for enhanced living environments since the analysis of the noise pollution levels of the ecosystem where the patients live may be related to their health symptoms. Moreover, the proposed method presents advances in installation and configuration due to the use of wireless communications technology.

INDEX TERMS Acoustic comfort, enhanced livings environments, environmental noise, indoor quality, Internet of Things.

I. INTRODUCTION

Acoustic comfort can be defined as the occupant's well-being and perception regarding environmental noise. 'Environmental noise' can be defined as an unwanted sound produced by human activities considered harmful or detrimental to health and quality of life, while 'noise' was identified as being a sound that is an 'out of place' sound or as a form of acoustic pollution [1].

Acoustic comfort can be defined as the well-being feeling of the home inhabitants concerning the acoustic environment and is closely related to the maintenance of low noise levels produced by several sources such as transport, home equipment, indoor activities and neighbourhood. Consequently, to provide acoustic comfort is necessary to minimize the environmental noise and support the satisfaction of the inhabitants [2]. The building manager should control environmental noise for enhanced living environments and occupational health. As people typically spend more than 90% of their time indoors, the building's attributes are closely related to the air-noise interaction as they affect noise more than air pollution. Buildings act as a shield for the dispersion of pollution, but the decreasing effect is much more significant for noise than for air pollution [3].

The individual sound level is influenced by various factors such as building infrastructure, the activity being performed, cultural habits and social activities [4]. Indoor acoustic comfort is determined by external noise pollution factors, such as traffic and neighbours, indoor activities such as conversations and music, impact noise such as footsteps, structural vibration sounds and equipment such as climatic systems and elevators [5], [6]. People typically adapt to noise levels in their home

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setting and begin to be unable to detect background noise pollution [7]. Occupants begin to adapt by becoming accustomed to high noise levels and are no longer aware of its harmful effects on their well-being.

In this case, real-time noise supervision is relevant to provide a correct acoustic comfort assessment. A building's acoustic comfort depends on the activities carried out indoors. Therefore, without applying real-time monitoring, it is difficult to identify and evaluate the existence and pattern of poor acoustic comfort conditions to plan interventions for improving the occupant's well-being [2], [8], [9].

An integrated supervision system for enhanced acoustic comfort includes ubiquitous access to real-time noise monitoring data using mobile computing technologies, which aggregate several types of data visualization and analysis methods for easier acoustic comfort management [10], [11].

Despite the rapid increase in infrastructure and industrial plants, environmental issues have influenced the need for real-time monitoring systems [12]. Among the panoply of applications enabled by the Internet of Things (IoT), smart and connected healthcare is a particularly important one [13]. With the proliferation of IoT devices and technologies, there is great potential to exploit their instant communication capabilities for environmental monitoring [14]. Currently, Smartphones can provide noise measurement data through mobile/cell phones in the form of 'citizen science' [15]. The Internet of Everything (IoE) concept aims to connect people, data, things and processes in a global network which, used intelligently, will provide significant enhancements on everyday life, particularly in the smart city context [16]. The concept of "smart city" has recently been introduced as a strategic device to encompass modern urban factors in a common framework and, in particular, to highlight the importance of Information and Communication Technologies (ICTs) in the last 20 years for enhancing the competitive profile of a city as proposed by [17]. Currently, cities face critical challenges in achieving socio-economic progress and people's quality of life goals [18]. The smart city is directly associated with an emerging approach to moderating the challenges generated by the urban population growth and rapid urbanization [19]. However, smart cities technologies have some limitations. The most critical issue in smart cities is the non-interoperability of different technologies [20]–[23]. The IoT can provide the interoperability to build a unified, urban-scale ICT platform for smart cities [24].

Ambient Assisted Living (AAL) is an emerging multi-disciplinary field aiming at providing an ecosystem of different types of sensors, computers, mobile devices, wireless networks and software applications for personal healthcare monitoring technologies [25], [26]. Simple interventions provided by homeowners, building operators or municipal authorities can produce significant positive impacts.

The main objective of this research is to propose a modular and scalable solution for enhanced health and well-being using Internet of Things and mobile computing technologies. Therefore, this paper presents a cost-effective and real-time acoustic comfort monitoring solution. The main contribution of the proposed solution is the support of multiple notification methods, easy configuration and installation, and mobile computing compatibility for data visualization, and analysis. A calibrated sound sensor was chosen to provide accurate data sensing. A hardware prototype composes the solution for ambient data collection named ***iSoundIoT***. Moreover, this system includes Web/mobile integration to provide data access. The ***iSoundIoT*** incorporates open-source technologies and is based on Wi-Fi communication. Furthermore, this solution also incorporates an ESP8266 microcontroller with built-in Wi-Fi technology as a communication and processing unit.

The main target of the proposed system is indoor environments ranging from workplaces to residencies. The proposed method can be easily installed and configured for occupational and personal use. On the one hand, the notification feature is relevant to alert the inhabitants when poor acoustic comfort scenarios are verified. On the other hand, continuous real-time data collection is essential for a comprehensive assessment of the indoor sound levels evolution during the day. Web and mobile software provide hourly, daily, weekly and monthly reports of sound level values and alerts. In addition, the proposed software also allows access to the real-time sound levels and the list of anomalies.

The paper is structured as follows: Section 2 focuses on the implications of acoustic comfort on health but also presents the related work; Section 3 is concerned on the methods and materials used in the implementation of the sensor system; Section 4 presents the experimental system results; Section 5 presents the discussion, and the conclusion is presented in Section 6.

II. ACOUSTIC COMFORT FOR ENHANCED LIVING ENVIRONMENTS

Scientific evidence reveals that enhanced acoustic comfort in companies or academics increases concentration and promotes better communication [27]–[30]. Not only does the acoustic comfort promote learning behaviours, but it also supports good teaching understanding [31]–[33]. In addition, providing acoustic comfort in hospitals reduces stress and sleeplessness created by high noise levels, decreases patient's recovery time and promotes staff productivity [34]–[36].

Furthermore, acoustic comfort in residencies promotes a feeling of protection in occupants and increases the sense of security and privacy [37], [38]. Therefore, acoustic comfort promotes occupational health, productivity, happiness and increases well-being.

The effects of noise on health are not only related to annoyance, sleep and cognitive performance of adults and children but also with increased blood pressure [39]. Environmental noise pollution may be a novel risk factor for pregnancy-related hypertension, particularly more severe variants of preeclampsia [40]. Long-term exposure to railway and road noise, especially at night, may affect arterial stiffness, a major determinant of cardiovascular disease. Consequently, noise monitoring can be significant to the enhanced understanding of noise-related health symptoms and effects [41]. Poor sleep causes endocrine and metabolic disturbances, several cardio-metabolic and psychiatric problems and anti-social behaviour, both in children and adults. The duration and quality of sleep are risk factors significantly affected by the environment but amenable to modification through awareness, counselling and public health measures [42]. Pregnancy and child exposure to road traffic noise can be associated with a higher risk for childhood overweight as concluded by [43].

The World Health Organization (WHO) has recently acknowledged that contrary to the trend of other environmental stressors, noise exposure is increasing in Europe [44]. Therefore, most developed countries support laws to regulate noise for specific periods [24].

Epidemiological research associates the chance of heart attack to those who live near to very busy streets is about 20% higher than for occupants who live on quiet streets, and the risk of obesity increases in the vicinity of airports [45]. Another research by [46] observed a 66% decrease in the productivity for a 'memory for prose' task when participants were exposed to various types of background noise. Another research conducted in 2005 by [47] concludes that 99% of the individuals questioned stated that their concentration was reduced by office noise such as unanswered telephones and background conversation. Noise is negatively related to reading and writing; chronic exposure can influence children's cognitive development [48].

Furthermore, noise is an explicit distraction that interrupts office staff from working accurately and efficiently and increases stress levels [49]. In sum, environmental noise must be assessed as a severe public health issue worldwide. Overall, the evidence suggests that environmental noise should be placed at the forefront of national and international health policies to prevent unnecessary adverse health impacts on the general population [50].

Several public and private entities associate exposure to environmental pollution (noise and air) with health. There is good evidence from extensive population studies that environmental noise, regardless of its association with air pollution, has harmful health effects. Therefore, environmental planning and policy should take both exposures into account when assessing environmental impacts [51].

Noise levels variation in cities is determined by the cumulative effect of unfavourable or thoughtful elements of the city design at several scales of the general and neighbourhood layout of a city. The transportation system, the structures of the buildings, the population density, the street design and building facades, the amount of green space, and the quality of the housing concerning sound and vibration features determine the environmental noise impact inherent to each city [52].

In the same city, it is possible to identify high sound levels at some locations when compared with other quieter places of the same town. This phenomenon depends on the city's design, especially in cities created a long time ago, which do not take into consideration the current mobility needs of citizens [52].

Noise at hospitals is a critical source of stress for the patients. In 1977, noise levels in hospitals were already studied to encourage the establishment of a set of specifications which the vendors would agree to abide by when placing equipment in hospitals [53]. With the implementation of devices such as computers which produce environmental noise, it is almost easy to get used to this invasion of privacy [53]. A study carried at Zeynep Kamil Hospital is presented in [54]. In this case study, the highest average noise level measured is 81.25±3.21 dBA, and the lowest noise level is 52.51 ± 2.37 dBA, which is much higher than the internationally recommended noise levels. However, 80% of research respondents are unwilling to pay for noise reduction policies and for implementing noise-control interventions [55]. Therefore, cost-effective solutions should be developed to provide real-time noise monitoring.

In summary, based on the health damage caused by noise pollution, mechanisms for evaluation and control are needed [56]. However, to detect and avoid unhealthy acoustic conditions, the first step is to monitor the sound levels.

A. RELATED WORK

Currently, various healthcare projects for enhanced living environments and occupational health are reported in the literature. Several solutions are presented in this section, which incorporate open-source, low-cost, and mobility technologies selected according to the improvement and performance proposed by the authors. Numerous IoT applications for real-time environmental quality monitoring that include open-source technologies for collecting, processing and transmitting data from different places simultaneously and mobile computing technologies for data consulting are proposed by [57]–[61].

A new approach on the assessment of noise pollution involving the general public to turn GPS-equipped mobile phones into noise sensors that enable citizens to measure their exposure to noise in their everyday environment has been proposed by [62].

A method of compressing the noise events of an entire day (24 hours) into a one-minute summary that can be sent via SMS text messages and is simple enough to run on an inexpensive microprocessor was proposed by [63].

A mobile crowdsensing platform to gather noise measurements using mobile-embedded microphones that perform opportunistic/participatory measurements, includes a data warehouse system to manage data (storage, aggregation and filtering) and a Web application to provide city managers with multiple views of collected data was proposed by [64].

City Sensing is a new approach to monitoring the region and the environment using miniaturized cost-effective sensors to provide real-time monitoring along with interaction with citizens for enhanced smart cities [65].

A real-time IoT noise monitoring system can not only measure noise levels in different places and provide data to the municipal authorities to plan interventions to reduce environmental noise pollution but also offer a space-time map of noise pollution in the area and contribute to public security [66]. Therefore, it is necessary to ensure the monitoring of noise pollution and, thus, provide a safe and healthy environment through enhanced acoustic comfort.

Noise monitoring is an essential requirement for enhanced well-being and occupational health. Therefore, the development of cost-effective monitoring systems using open-source technologies for sound supervision is a trending topic.

The authors of [67] propose a low-cost prototype which was installed in public vehicles to monitor real-time traffic sound levels in a city. The system was developed using the FRDM-KL25Z microcontroller, a CMA-4544PF-W microphone and a MAX9814 amplifier. Moreover, the proposed architecture supports Wi-Fi and 3G communication technologies and incorporates GPS sensing data. Wi-Fi communication is managed using the ESP8266 module.

A wireless sensing network was designed for noise monitoring purposes by the authors of [68]. The sensor node was built using the Teensy 3.2 platform as a processing unit, a POW-1644P-B-R omnidirectional microphone which supports waterproof features and an Xbee module for data transmission using Zigbee protocol. The gateway was designed using the Raspberry Pi 3 and incorporates an XBee module for data communication. Four modules were used during two weeks of field trials to validate the proposed method with favourable results for real-time collection of noise level data.

An IoT approach for outdoor noise monitoring is proposed by [69]. The data acquisition system uses a Raspberry Pi, an audio codec, a power management board, and mobile connectivity for data communication. This system incorporates two microphones with different hearing ranges (14-119, and 20-140 dBA). Power is supplied by a battery and uses a solar panel to charge it. The system hardware cost is around 150 euros. Furthermore, the proposed method incorporates web compatibility for data access.

The development of an IoT acoustic sensor is presented in [70]. The authors propose a low-cost system using a Raspberry Pi 2 and a T-Bone GC 100 USB microphone. The hardware system is powered by ethernet, and the total cost of the system is 120 USD. The proposed method was validated and tested in La Viña, Lorca, Spain.

A wireless acoustic sensor network is presented in [71]. Data collection is done using an IoT system developed by the authors. The developed prototype uses a Raspberry Pi model B as a microcontroller unit, a Logilink UA0053 USB sound card and a CMA-4544PF-W microphone. The main objective of the study was to evaluate the functional architecture of the IoT prototype to produce noise maps of the city, combining geostatistical data in the Valencian Community in Spain.

The authors of [72] present an AAL platform based on WSN for acoustic events identification and remote real-time patient monitoring. This study proposed the use of the Jetson TK1 board, which incorporates the NVIDIA Graphical Processing Unit and a CMA-4544PF-W microphone. The proposed method presents an accuracy of 82%, considering a set of 14 indoor environment scenarios.

III. MATERIALS AND METHODS

The ***iSoundIoT*** is proposed as an essential tool to assure acoustic comfort for enhanced living environments and occupational health. This system is a wireless solution based on the ESP8266 module which supports the IEEE 802.11 b/g/n networking protocol. This module is used both as a processing and communication unit. The collected data is stored in a SQL Server database using Web Services. For data access, a Web portal named ***iSoundWeb*** and a mobile application named ***iSoundMobile*** was created by the authors using ASP.NET C# and Swift, respectively. The ***iSoundMobile*** and the .NET Web Services are hosted at the same Windows Server instance. The .NET Web Services are used to share the data collected by ***iSoundIoT*** prototype and to support the network requests from the ***iSoundMobile***. The ***iSoundMobile*** is directly connected to the SQL Server database using SQL Server authentication. Figure 1 shows the system architecture and the software connection diagram.

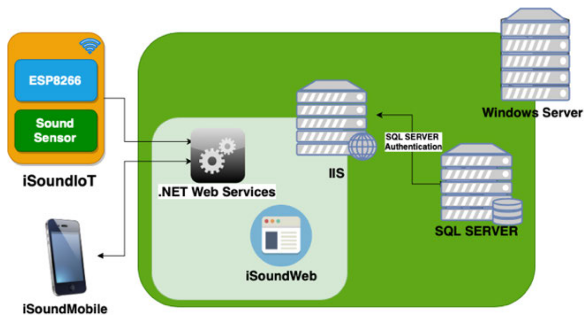


FIGURE 1. System architecture.

The authors' goal is to develop a cost-effective and accurate system that not only can be easily configured and installed by the average user but also provide real-time notifications to alert the building manager when the acoustic levels exceed parameterized values. Therefore, the authors selected a cost-effective but very reliable sound sensor and a microcontroller with native Wi-Fi support. The proposed system consists of two major components, a FireBeetle ESP8266 microcontroller developed by DFRobot and an analogue sound level meter developed by Gravity (Fig. 2). The system incorporates two LED units for visual alerting of the occupants and a buzzer for hearing alerting.

A brief introduction of each component used is shown below. The DFRobot FireBeetle ESP8266 is a Wi-Fi chip with integrated antenna switches, RF balun, power amplifier, low noise amplifier receiver, filters and power management modules. It supports 802.11 b/g/n protocols, Wi-Fi 2.4 GHz, WPA/WPA2, has a standby power consumption of <1.0mW (DTIM3) and can operate in the temperature range of −40 °C∼125 °C. This microcontroller is one of the most used ESP8266 development boards that support 4MB of flash

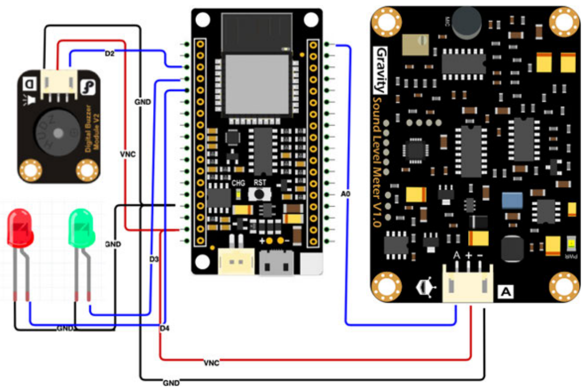


FIGURE 2. iSound prototype hardware.

memory, 11 GPIO pins, and one analogue-to-digital converter (ADC) pin with 10-bit resolution. It also has a built-in voltage regulator and a USB for power.

The DFRobot Gravity Analog Sound level meter is a calibrated noise sensor that can accurately measure the sound level of the surrounding environment. This sensor incorporates an instrument circuit and a low noise microphone. It supports 3.3∼5.0V input voltage and provides a 0.6∼2.6V output voltage. The dBA value is linear with the output voltage. The voltage output of the sensor is converted to a calibrated sound level, as described in equation 1.

$$dBA = Output\ Voltage \times 50 \tag{1}$$

The sensor has a measurement range of 30dBA ∼ 130dBA with a measurement error of ±1.5dB. The input current is 22 mA at 3.3V and 14mA at 5.0V. This microphone uses a frequency weighting A and is according to IEC 61672 standards [73]. The frequency response is 31.5Hz ∼ 8.5KHz, and the time characteristic is 125ms. The current consumption is 22mA at 3.3V or 14mA at 5.0V. The sensor size is 60mm * 43mm.

The DFRobot Digital Buzzer module is a buzzer module that supports an input voltage of 3.3–5.0 V.

Moreover, the proposed system uses two 3V LEDs. The green LED is used to notify the end-user of healthy acoustic comfort conditions, and the red LED is used to inform the end-user of poor acoustic comfort conditions.

Regarding the decision making on the components to be considered in the proposal system to replicate the experiments presented in this paper, it is relevant to consider several features. The microcontroller must support Wi-Fi communication features, particularly the 802.11 b/g/n protocols. The sound sensor must provide a measurement range of 30 to 130 dBA and an error inferior to ±2dBA. Furthermore, the proposed system must incorporate light and audio hardware components to provide warnings and system status information *in situ*.

The range of human hearing is usually recognized between 20 Hz and 20 kHz. However, based on the guidelines proposed by the WHO, noise-induced hearing impacts occur predominantly in the higher frequency range of 3 000–6 000 Hz, with the most significant effect at 4 000 Hz [74]–[78]. Therefore, the frequency response of the selected sound sensor can address the frequency range, which predominantly affects humans.

The dBA sound levels are continually collected and stored in the database every 15 seconds. This update timer has been set to have a detailed evolution of the dBA levels because in particular scenarios, human activities can significantly affect the sound levels for a short time. Nevertheless, the update timer can be updated by the end-user according to the environment and application specifications. On startup, the system hardware performs network management. If wireless networks are not available for Internet access, the system will create a hotspot. This hotspot will enable the user to connect by inserting the credentials for Internet access.

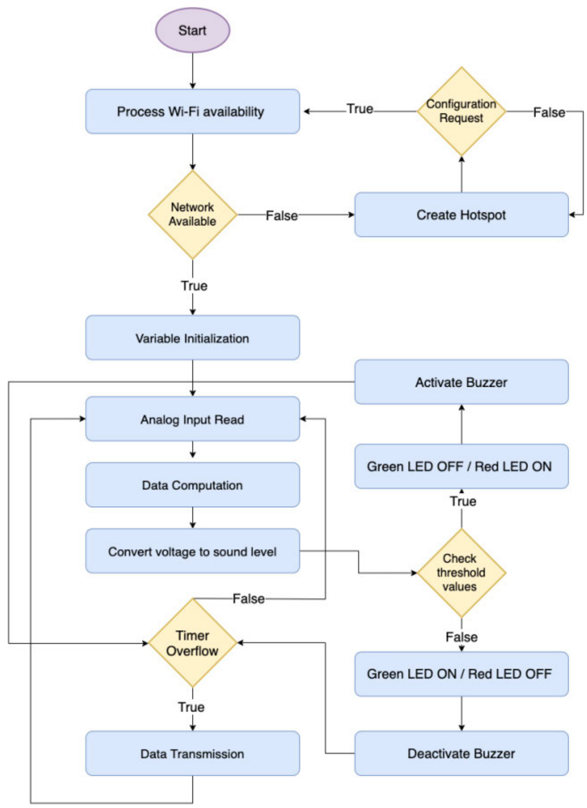


FIGURE 3. Flowchart of the proposed hardware system.

Moreover, if the user does not enter the credentials, the system will continue to work offline using the last configured threshold values using the visual (LEDs) and audio (buzzer) alert methods. The system performs variable initialization and continuous data collecting using the sound sensor. The voltage sensor output is converted to a calibrated sound level, and the average value is calculated. Every 15 seconds, the data is sent to the remote database for enhanced acoustic quality assessment. The flowchart of the proposed system is represented in Figure 3.

TABLE 1. Summary of similar research on noise pollution monitoring (MCU – microcontroller unit).

Authors	MCU	Sensor	Architecture	Connectivity	Low-Cost	Open-Source	Alerts	Data Access	Easy Installation
Alsina-Pagès, R. et al. [67]	FRDM-KL25Z	4544PF-W	IoT	Wi-Fi /3G	YES	YES	NO	NO	NO
Peckens C. et al. [69]	Teensy 3.2 (node) Raspberry PI 3 (gateway)	POW-1644P-B-R Microphone	WSN	ZigBee	YES	YES	NO	NO	NO
Maijala P et al. [69]	Raspberry PI 3	two microphones	IoT	3G/4G	YES	YES	NO	Web	NO
Noriega-Linares, J and Ruiz, J.[70]	Raspberry Pi 2	T-Bone GC 100 USB	IoT	Ethernet	YES	YES	NO	NO	NO
Garcia J. et al. [71]	Raspberry Pi 1	Logilink UA0053 USB	IoT	Ethernet	YES	YES	NO	Web	NO
Alsina-Pagès et al. [72].	Jetson TK1	4544PF-W	WSN	Ethernet	YES	YES	NO	NO	NO
Proposed	ESP8266	DF Robot Sound Meter	IoT	Wi-Fi	YES	YES	YES	Web and Mobile	YES

TABLE 2. Proposed system cost.

Component	Cost	Source
DFRobot FireBeetle ESP8266	11.90 USD	DFRobot
DFRobot Gravity Sound level meter	39.50 USD	DFRobot
DFRobot Buzzer	1.90 USD	DFRobot
3V Green LED	1.19 USD	Digi-Key Electronics
3V Red LED	1.17 USD	Digi-Key Electronics
Cables and Box	10.00 USD	Digi-Key Electronics
Total	65.66 USD	-

The ***iSoundIoT*** hardware has an estimated cost of 65.66 USD considering 10 USD for cables and boxing parts (Table 2).

The proposed method combines several low-cost components to provide multiple types of warnings using visual and hearing physical interfaces. On the one hand, physical alerts can be seen and heard by people inside the same space where the system is installed. On the other hand, software alert methods can notify people in real-time, anytime and anywhere. Physical alerts are performed using a buzzer and LEDs that allow the system to alert people locally if no wireless networks are available. This system's advantage plays a significant role in ensuring acoustic comfort, as people in the physical space can be alerted, and this functionality does not depend on the system's internet connection.

TABLE 3. Noise monitoring equipment available on the market.

Equipment	Range dB	Cost
Castle Sonus GA216B	55-120	507.38 USD
Castle Sonus GA216I	75-140	685.15 USD
Castle Sonus GA116I	75-140	1106.11 USD
SONIK-SE 01GA142SE	40-143	1519.67 USD

Table 3 presents a summary of the solutions available on the market. The prices were obtained from Castle Group Ltd, excluding taxes (accessed on 07/04/2020).

Currently, most indoor sound level monitoring solutions available in the market are more expensive and are based on random sampling. Nevertheless, these techniques are restrictive because they provide only information related to a specific sampling and are devoid of spatiotemporal data. Some of these solutions are compact, portable, and support data logging, but do not allow real-time data to be available for building managers, enabling rapid and efficient intervention to improve indoor quality. These solutions do not support mobile compatibility for data consulting and notifications.

On the one hand, in most available monitoring solutions, the collected data is stored in the device's memory and requires specific procedures for data downloading and manipulation with dedicated software. On the other hand, these solutions are extremely accurate and designed for specific industrial activities.

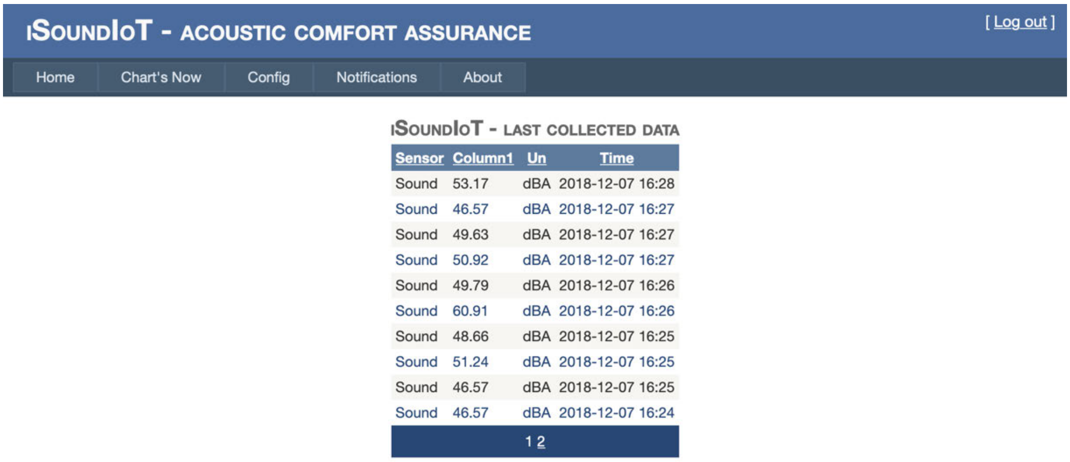


FIGURE 4. iSoundWeb last collected data.

However, in living environments, the accuracy of 4 dBA is adequate to promote occupational health and well-being [79]. In particular, the commercialized system available at [80] presents an economical price (164.19 USD) and also supports calibration features with IEC 61672 standards [73]. This system supports a measurement range of 30-130 dBA, with an accuracy of ±1.4 dB, Microsoft Excel compatibility, and provides proprietary software for sound data analysis. However, in a similarity to all the systems presented in Table 3, the sound data is stored in the device's memory with a limitation of 32,700 records. Moreover, for data consulting purposes, this system must be connected to a PC using USB port for detailed analysis using Microsoft Excel or the included downloadable proprietary software and does not provide real-time data access anytime and anywhere through mobile devices or web applications. Therefore, the development of novel acoustic comfort monitoring systems based on state-of-the-art technologies that offer real-time data access, visualization and analysis is critical for enhanced acoustic comfort.

The ***iSoundIoT*** incorporates open source technology, combining sensitivity, flexibility and accuracy of measurement in real-time for effective acoustic comfort promotion. This solution provides a definitive software solution for a practical, intuitive, fast access analysis of the building noise pollution as well as alerts in case of poor acoustic comfort to plan interventions for enhanced living environments and occupational health.

The Web portal was developed with ASP.NET C#. This Web software aims to be an integrated acoustic management system (IAMS) for enhanced living environments (Figure 4).

This IAMS provides analysis and visualization of the integrated acoustic comfort and incorporates hourly, daily, weekly and monthly reports of the alerts as well as the average values of the collected sound levels. This Web application allows access to the real-time sound levels and the list of anomalies.

The ***iSoundWeb*** was developed to be used by the building manager for enhanced data analysis of the sound levels. The IAMS can be used as a decision-making tool that facilitates the identification patterns of poor acoustic comfort conditions according to the WHO guidelines [75], to plan interventions or improve insulation in indoor living environments. Furthermore, this web application incorporates specific user profiles to access dashboards and chart views to facilitate the identification of unhealthy scenarios designed for city authorities and building managers.

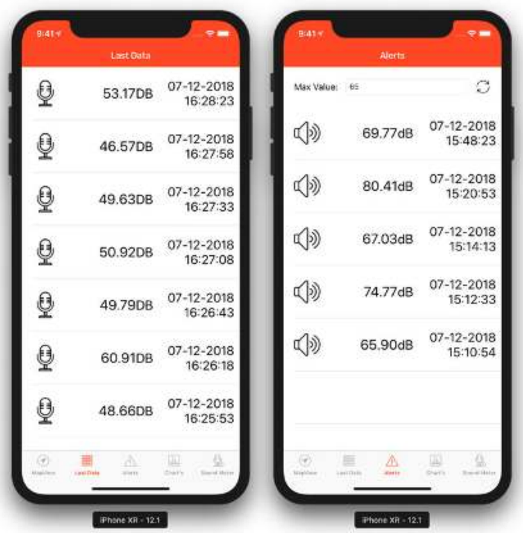


FIGURE 5. iSoundMobile last collected data and alerts history and configuration.

To provide easy and quick data consulting a native mobile application was developed by the authors (Figure 5). The ***iSoundMobile*** was developed for iOS 10 and the following versions using Swift programming language and the Xcode IDE. The end-user can carry all their acoustic data in their pocket to check the sound levels anytime and anywhere using the mobile app. Moreover, this mobile application supports several features such as access to real-time data alerts history, map view to handle various ***iSoundIoT*** systems considering their location, graphical data and a sound analysis feature using the Smartphone's microphone.

The mobile application alerts feature was developed with push notifications using the Apple Push Notification Service (APNS). The APNS is a notification service designed by Apple which supports push notification features in the mobile applications installed on Apple devices. The user can check the location of the ***iSoundIoT*** modules using a map view to provide geographic information of the spaces monitored. Furthermore, the ***iSoundMobile*** allows the user to check the last collected data values and the history of the alerts triggered by the solution to notify the building manager using a table view mode.

The system is preconfigured using well-studied values as setpoints for the alerts. The 75dBA level (LAMax) is used for configuration based on the guidelines provided by the WHO [75]. Users can parameterize a specific dBA value as a threshold to trigger the notifications according to the requirements of the installation. A maximum of one notification can be triggered every 15 minutes. Moreover, the warnings are automatically disabled if they are triggered continuously in 45 minutes. Therefore, the user can receive a maximum of 3 notifications in continuous mode to avoid spam.

Mobile notifications provide timely and relevant data when the sound levels exceed the parameterized values, whether if the mobile phone is locked or in use. Notifications can be viewed in the lock screen or at the top of the screen when the device is in use and has a specific alert sound to be easily identified by the user. A mobile notification is composed by the application name, the application icon and a relevant message. The proposed solution incorporates several types of alerts to notify the building manager when unhealthy acoustic comfort situations are verified. Alerts can be sent using mobile applications via push notifications, e-mail and SMS (Figure 6).

SMS notification is managed through Twilio, a cloud communication platform. Push notifications are performed using the Firebase Cloud Messaging, which is a cross-platform solution for messages and notifications. According to scientific evidence, the SMS alerts were planned to address the elderly who are more familiarized with this communication service [81].

On the one hand, these notifications can be used by the building manager to detect unhealthy situations in real-time and adopt behavioural changes to promote acoustic comfort for enhanced productive and healthy environments. On the other hand, with this real-time feature, the building manager can comprehend when the repeated harmful situations are noticed and plan new changes to avoid them. The ***iSoundIoT*** notification architecture is proposed in Figure 7.

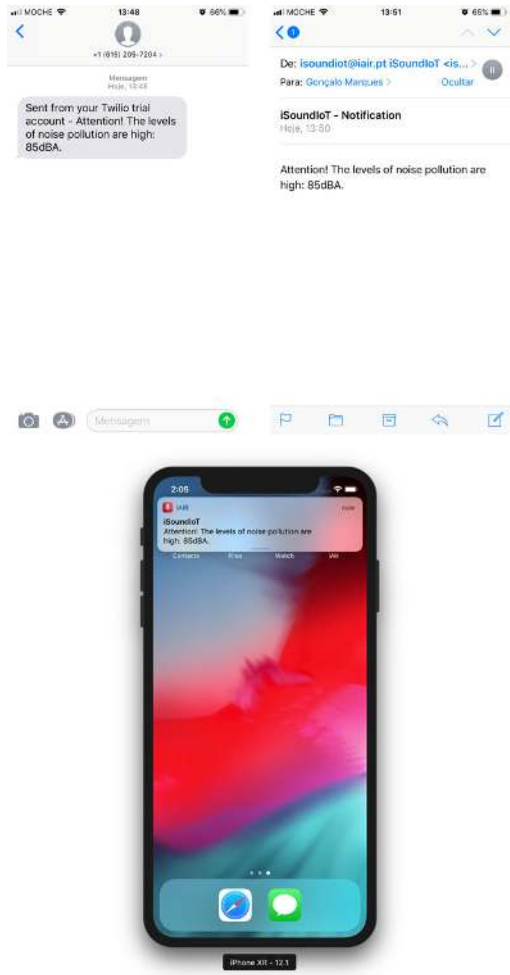


FIGURE 6. Push notification, SMS and e-mail alerts.

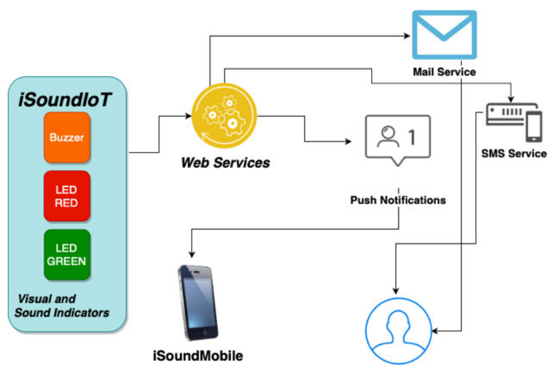
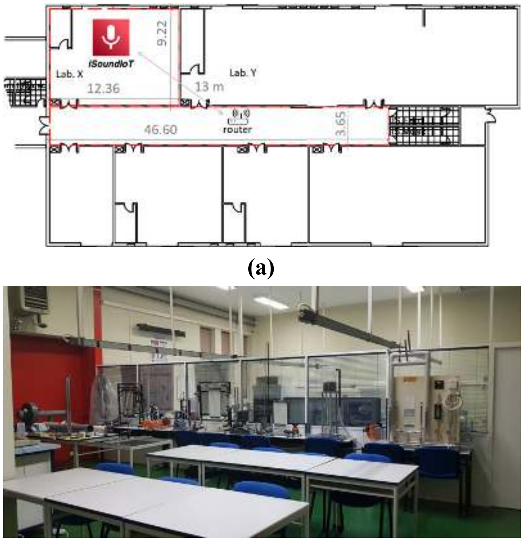


FIGURE 7. iSound alerts configuration setting.

IV. RESULTS

For testing purposes, an environmental laboratory was monitored. The environment represented in Figure 8 (a) was used for sound level monitoring tests/experiments using real-time sound levels of supervision for two months. The sound data was continually collected from April to June 2019, for 61 days. As most Portuguese universities' laboratories, the space is used for both laboratory experiments and



(a)

(b)

FIGURE 8. **Installation schema of the tests conducted (a), laboratory monitored space (b).**

teaching activities. The room, built in the early 2000s for environmental science research, is occupied almost 8 hours a day for teaching activities with around 15 students and is enclosed by walls, one opening window and continuous suspended tiled ceiling. The room is approximately 20 square meters, with a floor-to-ceiling height of 3 meters. The laboratory uses natural ventilation and does not have noise isolation treatment. The laboratory is used for environmental science classes and experiments. It incorporates the use of industrial machines for air conditioning experiments, which include several components such as electric motors and ventilation systems. These systems are used during teaching activities for experimental purposes and produce high noise levels. Since the main objective is to test the functional architecture inside buildings, an ***iSoundIoT*** module was installed (Figure 8).

Moreover, one sensor module is enough to test the local and remote notification features as well as to make a complete evaluation of the environment sound levels. Considering the IoT approach, all the modules are handled by the backend application using a unique identifier. Therefore, it was not necessary to test the system using a high number of modules since the functional architecture does not depend on that, which leads to a significant advantage related to the modularity of the system.

The module is powered using a 230V-5V AC-DC 2A power supply. The threshold value used for the notifications features was configured to 75dBA based on the guidelines provided by the WHO [75] (LAMax).

Average sound levels grouped by the day of the week are presented in Figure 9. The values range from 47.35 to 52.99 dBA. The lowest average values are collected during the weekend, as the building is typically unoccupied in these days. During the working days, the laboratory values range from 50.15 to 52.99 dBA on Monday and Friday, respectively. Wednesdays and Fridays have high average

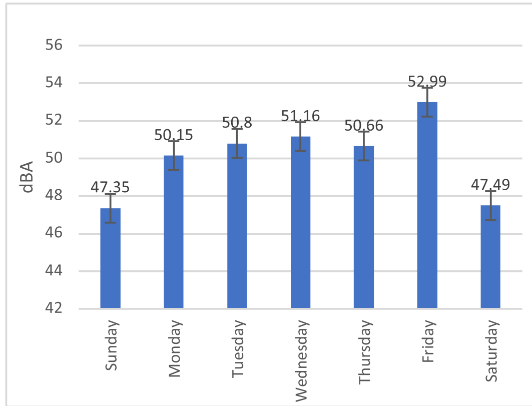


FIGURE 9. **Average sound levels grouped by the day of the week.**

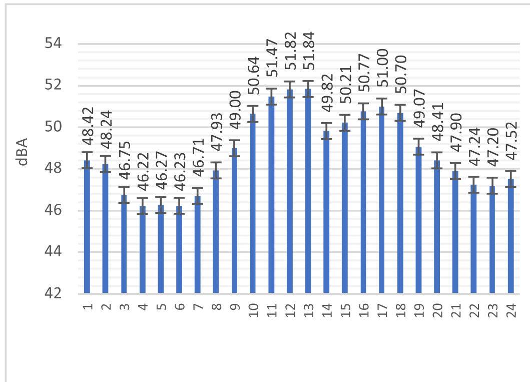


FIGURE 10. **Average sound levels grouped by hour.**

values at 51.16 and 52.99 dBA, this is related to the realization of air conditioning experiments.

Figure 10 shows the average dBA sound levels grouped by hour. The analysis shows that the lowest average sound value is recorded at 4 A.M (46.22 dBA), and the highest value is registered at 1 P.M (51.84 dBA). The room is used for teaching activities from 9 A.M. to 2 P.M. and from 3 P.M. to 6 P.M. with an hour pause for lunchtime from 2 P.M. to 3 P.M.. Therefore, the sound levels start to increase at 9 A.M., due to the start of lectures and decreases at 7 P.M. when the last class finishes. Moreover, the lectures which have more student attendance rate are typically between 10 A.M and 1 P.M., where the higher dBA sound levels are recorded.

The distribution of the number of notifications according to the day of the week is shown in Figure 11. During the weekend, as the laboratory is typically not used, there is no registration of any notification. The average number of notifications per day ranges from 9 to 18 on Monday and Thursday, respectively. The two most significant days are Thursdays and Fridays, which is relevant as it leads the authors to conclude that the use of air conditioning testing machines has a high impact on acoustic comfort.

Figure 12 shows the distribution of the average triggered number of notifications grouped by hour. The alerts are triggered from 10 A.M. to 9 P.M. The period that shows

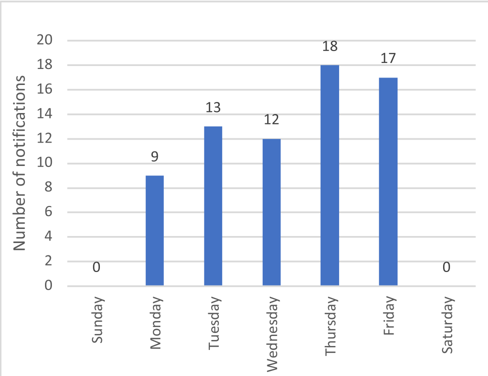


FIGURE 11. Average number of notifications grouped by the day of the week.

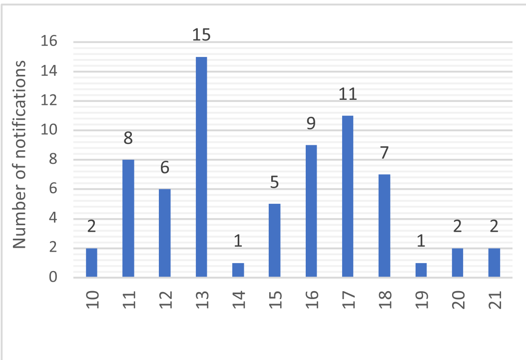


FIGURE 12. Average number of notifications grouped by hour.

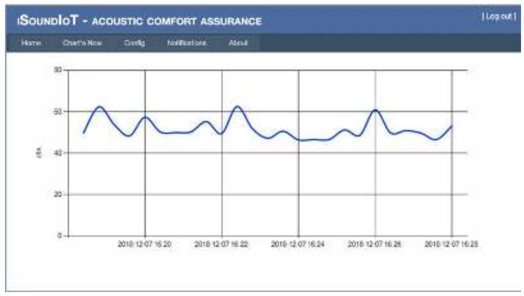


FIGURE 13. Noise monitoring data (dBA).

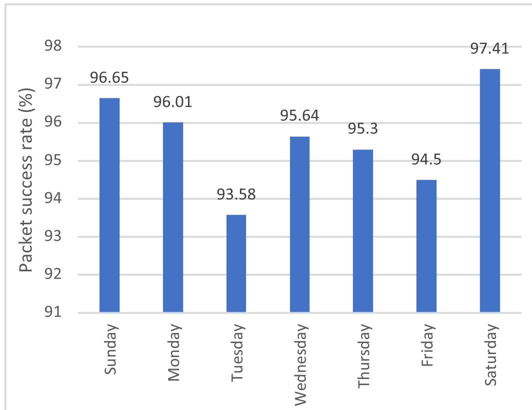


FIGURE 14. Average packet success rate grouped by the day of the week.

more notifications is at 1 P.M. with 15 notifications triggered. Moreover, the periods from 11 A.M. to 1 P.M. and 3 P.M. to 6 P.M. show the most critical times to be analyzed and studied for enhanced acoustic comfort.

In total, 545 alerts were triggered during the two months of continuous monitoring. The notification feature presents an efficient and effective method to act in real-time and promote acoustic quality. The number of alerts triggered has shown that under certain conditions, dBA sound levels are significantly higher than those considered for healthy standards [75]. However, the average noise levels meet the requirements of the standard value of 75 dBA proposed by the WHO and are in accordance with several studies [82]–[87].

The ***iSoundIoT*** provides data consulting in graphical and numerical form using both mobile and Web applications. A sample of the data collected by ***iSoundIoT*** is shown in Figure 13 that represents the sound level data measured in dBA.

The average packet success rate, according to the day of the week, is shown in Figure 14. The authors have counted the number of collected samples grouped by day of the week. The packet success rate ranges from 93.58% (Sunday) to 97.41% (Saturday). The ideal number of packets successfully stored by day is 5760, considering 15 seconds update time. The best results are verified during the weekend since during these days there is no activity in the environment. Therefore, the system is less subject to interference from other industrial equipment.

The authors can correlate the average packet success rate with the activities that are conducted in the environment during the working days. The use of industrial machines for air conditioning experiments, which include several components such as electric motors and ventilation systems during the working days lead to high sound levels but also to electromagnetic interferences in the environment that can affect the system functionality. Consequently, the success packet rate is higher when the sound levels are lower.

V. DISCUSSION

One the one hand, the graphic display is easier to interpret than a numerical format. The visual information available in Figures 15 and 16 provides an agile and effective method to analyze the collected data when compared to a numeric table where the user needs to apply filters to extract knowledge [88]–[91]. The graphics provided by the proposed solution aim to deliver a temporal evolution of the collected data in conjunction with mobile and web applications. On the other hand, the web portal also allows the user to access the data quickly to provide a more precise analysis of the detailed temporal evolution. Thus, the system is a powerful tool for noise analysis.

An integrated management system increases efficiency, leading to reduced costs, providing a centralized method

FIGURE 15. iSoundMobile map view and chart view.

FIGURE 16. iSoundMobile crowdsourcing feature.

for viewing and analyzing data [91], [92]. The ***iSoundWeb*** supports the commitment to increase the acoustic comfort to improve the occupants' well-being. The Web portal incorporates hourly, daily, and monthly reports, which easier inform the building manager regarding the acoustic behaviour. The reported features provide a clear, uniform image of the noise pollution to associate the problems with hours of the day to create patterns. Therefore, is assumed that the proposed system offers an integrated approach for enhanced acoustic comfort which provides real-time noise monitoring and can be used as an essential tool for the building manager to achieve the acoustic objectives and avoid unhealthy acoustic conditions. Using the ***iSoundWeb***, the building manager can also export all acoustic data history in an Excel file for further analysis using third-party software. It is imperative to control noise pollution effectively, and the authors believe that the first step is to provide real-time monitoring to perceive its variation in real-time and detect unhealthy situations for enhanced living environments.

Figure 15 shows the map view and chart view mode features of ***iSoundMobile***. Using the map view, the building manager can access the last recorded sound value for each ***iSoundIoT*** module used. Firstly, this can be a significant feature when the user has several modules in different locations. Thus, it is a quick and effective method to analyze the acoustic comfort of several areas simultaneously. Secondly, this is a practical approach to select the ***iSoundIoT*** module to use the rest of the application's features. Moreover, the chart view feature, shown in Figure 15, provides an efficient visual of the noise values evolution to identify unhealthy noise values variation throughout the day.

Crowdsourcing is a concept where the information is collected by a large group of people who submit their data via the Internet, social media and mobile applications. These people can be paid or volunteer. Crowdsourcing allows not only avoiding costs but also speeding and providing the ability to work with people with different skills. On the one hand, this methodology enables building a database of data where people can add new information that, otherwise, would be impossible. On the other hand, using mobile applications to provide quick and flexible data collection through crowdsourcing allowed everyone with a Smartphone app to contribute. Due to the well-studied health effects of environmental noise and combining the resources present in a Smartphone with participatory sensing, a crowdsourcing feature was developed in the ***iSoundMobile*** application for noise monitoring without using the ***iSoundIoT*** hardware.

The ***iSoundMobile*** allows collecting environmental sound data in real-time using the Smartphone microphone (Figure 16). Firstly, this mobile crowdsourcing approach can provide spatiotemporal sound data which is particularly relevant for comparing noise values in the user location without the ***iSoundIoT*** hardware. Secondly, the mobile app offers the possibility to study the necessity of real-time noise supervision in their living environments. This way, the user can evaluate his living environment sound levels using his Smartphone. If necessary, the user can acquire the ***iSoundIoT*** hardware to provide continuous real-time monitoring for planning interventions for enhanced indoor quality.

Due to the quality and relevant contribution of several existing solutions [67]–[72], a summarized comparison review is shown in Table 1.

The ***iSoundIoT*** is more cost-effective when compared with the proposed solution presented by the authors of [67], which uses an FRDM-KL25Z as processing unit plus an ESP8266 as a communication unit. Furthermore, the ESP8266 has 160 MHz CPU, and 16MB flash memory and the FRDM-KL25Z has a 48MHz CPU and a 128KB flash memory. Compared to the wireless sensor networks (WSN) architectures, proposed by the authors of [68], the IoT approach of the ***iSoundIoT*** provides a significant advantage regarding the scalability and installation as it is only required to configure the Wi-Fi internet connection and it is not necessary to configure the sensor nodes and coordinators. The solutions presented in [69]–[71] use the Raspberry Pi as the processing unit. The Raspberry Pi has superior performance in comparison with ESP8266 in terms of its storage and clock speed. However, the Raspberry Pi is more expensive and needs higher energy consumption. Neither one of the solutions shown in Table 1 provides alerts, easy installation and mobile application for data consulting.

Furthermore, when compared to low-cost open-source initiatives available in [93], [94], the proposed system provides physical hearing alerts, a web application for improved analysis of the variation in acoustic comfort quality in real-time, a remote notification using the mobile application and incorporates easy installation and configuration methods. Only the methods proposed by [69] and [71] support remote real-time data access.

Moreover, these solutions are not compatible with mobile devices. The incorporation of the ESP8266 module leads to several benefits. On the one hand, the ESP8266 is a cost-effective microcontroller which can be used for processing and communication. On the other hand, the ESP8266 provides easy Wi-Fi network configuration.

The ***iSoundIoT*** provides Wi-Fi network discovery process at startup. First, the system tries to connect to a Wi-Fi network which is previously saved. When the system cannot find a previously saved Wi-Fi network, it turns to a hotspot. At this moment, the user can connect to the hotspot and configure the SSID (service set identifier) and password for the network, which will be used by the ***iSoundIoT***. Therefore, the ***iSoundIoT*** prevents installation costs, which for the majority of similar applications, must be done by qualified people. In addition, the system also prevents the ''invasion'' of privacy related to the entry of unknown people into the home of the end-user.

Another essential advantage of the proposed system is the scalability associated with the modularity of the system. The building can be monitored by using only one ***iSoundIoT*** module, but other additional units can be added. The sound sensor was selected considering the cost but also the calibrated output and accuracy as the principal aim is to test the functional architecture of the proposed system. As the system is intended to be used indoors where electricity is accessible, energy efficiency was not a significant concern in the proposed solution. Furthermore, the research was focused on the real-time data collection and alert features.

Noise monitoring is relevant not only to support planned interventions for enhanced acoustic conditions but also to support medical diagnostics. Due to the well-studied impacts of environmental noise on human health, the system can provide a viable monitoring solution which offers historical data on the acoustic comfort allowing the medical team to correlate patients' symptoms with their living environment.

Indoor living environments will progress to follow the evolution of the external environment and its inhabitants. The smart home concept incorporates the most efficient technologies to achieve significant features to provide productivity and well-being for enhanced occupational health. The smart home should promote acoustic comfort and good state of mind by controlling noise to avoid, among other diseases, depressive states. The interconnection between the civil engineering, computer science and health sectors has yet to be explored both at the national level and in the European Community.

The results show and confirm the ability of the proposed system as an essential tool in the detection of unhealthy behaviours. The proposed notification methods allow the building manager to promote real-time interventions for the maintenance of health conditions. The Web application, in turn, allows a correct analysis of acoustic comfort to identify patterns of occurrence of unhealthy situations.

There are multiple devices in the market that incorporate sound monitoring features. Currently, smartphones and smartwatches can monitor dBA sound levels. However, these systems do not incorporate easy to install methods for noise supervision that work continuality in a pervasive manner without the intervention of the user and can be accessed in real-time anywhere and anytime. Furthermore, these methods do not have continuous notification features when abnormal situations happen and also do not incorporate enhanced methods for noise monitoring and assessment in a specific environment. Therefore, the innovative and intellectual contribution of the proposed method is to present a solution that incorporates notifications, easy-installation, remote data access to the monitored data in real-time and an enhanced web portal for noise monitoring and assessment. The iSound solution can be divided into three main components, such as the hardware for data collection, the web portal and the mobile application for data consulting. In summary, the main contribution of the proposed method is not achieved by the separated functionalities of the different components but in the combination of all its parts and features.

VI. CONCLUSION

This paper presents an IoT architecture for real-time monitoring of noise pollution composed of a hardware prototype for ambient data collection and mobile computing technologies for data consulting. The results obtained are promising, representing a significant contribution to noise monitoring systems based on IoT. On the one hand, the monitored data inside buildings can be particularly valuable to offer support to a medical diagnosis by clinical professionals as the medical team can analyze the history of noise pollution parameters of the ecosystem wherever the patient lives and relate these records with his health complications. On the other hand, it is possible to supervise noise pollution in real-time, to plan interventions and to control the sound level for enhanced smart cities.

The system has advantages both in installation and configuration, due to the use of wireless technology for communications, but also because it was developed to be compatible with all domestic house devices and not only for smart or high-tech houses. The existing commercial solutions are costly and do not provide advanced forms of data analysis and visualization. The proposed solution is cost-effective, which allows a correct evaluation of the acoustic comfort. Through real-time monitoring of acoustic comfort, it is possible to identify non-healthy behaviours and to plan ways to avoid them. However, the presented system has specific limitations as it needs additional experimental validation, particularly in outdoor environments.

Several improvements to the system's hardware and software are planned to make it much more appropriate for specific purposes, such as schoolrooms, seniors' homes and hospitals, as future work. Moreover, the implementation of enhanced methods of noise data mining using artificial intelligence and machine learning approach is planned for poor acoustic comfort prediction.

IoT systems are expected to not only contribute to enhanced living environments but are also an integral part of the daily routine [95]. Methods such as the proposed by the authors should be regulated and required at least in the public buildings to promote productivity and occupational health.

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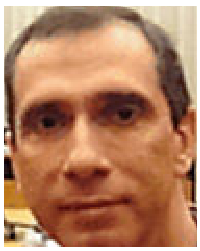

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