






Edge and Fog Computing for IoT: A Case Study for Citizen Well-Being

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Abstract. Citizen well-being during indoor and outdoor activities is a prerogative in the paradigm of smart city. Air quality, together with thermo-hygrometric, light and noise comfort are some of the most relevant parameters that affect the perception of the state of well-being. An internet of things (IoT) network based on LoRaWAN end-nodes has been set up with the aim to provide an approach to improve the well-being of citizens living in an urban district in Savona (Liguria region, Italy) under the umbrella of the PickUP project. The main focus of the project was the design of innovative methods and tools for energy and environmental management and the reduction of consumption in heterogeneous districts. The proposed IoT architecture comprises a Fog node constituted of a Raspberry Pi 4 to analyze in near-real-time the heterogeneous data and to provide feedback to the proper actuators in case of need of changes in the ventilation and heating of the occupied room. Moreover, the infrastructure provides insights about the air quality in outdoor areas to local authorities, in order to implement mitigation action or strategies. Results demonstrate the usefulness of the proposed architecture with a precise focus on social impact, but also reveal economic implications linked to an intelligent use of energy resources and to the development of energy efficiency strategies.

Keywords: Edge and fog node · LoRaWAN · Citizen well-being · Energy efficiency · Air quality

1 Introduction

The quality of both indoor and outdoor environments is fundamental to guarantee and evaluate citizen well-being because it is nowadays assessed that quality of indoor environment affects human health [1] as well as exposure to pollutant air, posing severe risk for morbidity and mortality [2].

In working places, physical environmental conditions contribute to guarantee a comfortable and productive space [3, 4]. At home, where people usually spend more than 60% of their life, the overall quality of life and health strongly depends on indoor environmental quality (IEQ) parameters, such as indoor air quality (IAQ) (e.g., airborne contaminants), aesthetics, potable water surveillance, ergonomics, acoustics, lighting and electromagnetic frequency levels [5]. The same features are considered for assessing the value of a property [6].

All the aforementioned issues trigger a growing and permanent interest towards safety, health, well-being, and sustainability in working, public and private indoor environments, contributing to define the Quality of Life of an area.

Some IEQ parameters are related to the energy efficiency and management of indoor environments [5, 7], which need to be monitored in order to assess the level of comfort. In most cases, structural and functional changes for improving life inside the buildings are devoted to optimize the management of energy production and demand [8]. However, retrofitting existing structures must consider the benefits both on IEQ and energy saving [9]. Furthermore, indoor sensors in public buildings must comply with local regulations, be compact, positioned in safe positions, not accessible to unauthorized people, autonomous and capable of guaranteeing continuous and long-term monitoring [10, 11].

In working spaces, the goal of reducing energy consumption is usually achieved by limiting air circulation or by using regulated forced ventilation, creating an airtight space, unsafe for people's health. A typical example of this condition is the increase in carbon dioxide (CO₂) levels due to human respiration, which causes fatigue and reduced productivity [12]. Volatile organic compounds (VOCs) that arise from a wide spectrum of sources, such as building materials, furniture, detergents and even human activities (such as sweat), could be responsible for the so-called Sick Building Syndrome [13–16].

Within the urban districts, a significant share of consumption is due to buildings. Statistics estimate that buildings in Europe are responsible for the majority (40%) of final energy consumption, with 14% of the overall share being ascribable to non-residential buildings. For example, the reduction in energy consumption and in the consequent emission of greenhouse gases have a valuable economic and environmental impact [17]. Analogous considerations are especially valid for ancient buildings, neglecting modern concepts of energy efficiency.

Outdoor air quality is often controlled by local stakeholders interested in development or application of mitigation strategies to improve citizen's well-being. Monitoring is often performed through networks of sensors installed, in most cases, in the busiest streets of downtown.

To evaluate the conditions of well-being in relation to buildings and urban districts, it is essential to implement autonomous and smart sensor networks capable of continuously monitoring the most important IEQ parameters, to balance the minimization of energy consumption and the improvement of air quality (indoor and outdoor).

This was the main driver for the realization of the PickUP project (www.pickup-energy.it), whose general objective was to develop a tool to evaluate (i) the energy exploitation and environmental quality of heterogeneous urban districts, in order to reduce consumption and its impact on the environment, and (ii) the comfort of internal public spaces. The demonstration phase took place in the urban area of the city of

Savona (Liguria, Italy) and the test bench was represented by two sites: the headquarters of the Municipal Police “Clelia Corradini” and a large U-shaped building that houses the “Colombo-Pertini” primary and intermediate schools.

The developed IoT network was established to assess the internal energy efficiency of the Municipal Police station and the well-being of its workers, and to monitor the outdoor air quality in the vicinity of the primary and intermediate school.

Specifically, indoor well-being monitoring was performed through a network of smart sensors, able to acquire air temperature, humidity, concentration of CO₂ and VOC, light and noise levels. This choice was based on the fact that although the most relevant parameters are those related to the volatile chemical compounds in the air, other factors can also affect the comfort and health, including temperature, humidity, light and noise levels, particles, pollen or mold spores. Temperature and CO₂ are also fundamental from energetic point of view, since the most impacting equipment is related to air conditioning and ventilation, whose proper functioning is strictly related to temperature and CO₂.

Outdoor well-being was evaluated in the open spaces of the school and in the nearby streets, monitoring air particle matter and pollution (e.g., PM1, PM2.5, PM10) other than environmental ancillary parameter such as air temperature, humidity and atmospheric pressure.

2 Low Power Wide Area Networks

IoT enabled technologies allow the creation and adaptation of “smart buildings”, conceived as sensor networks distributed in several areas throughout the whole building, in a relatively affordable way. Wireless sensors are particularly suitable to this aim, since they avoid heavy infrastructural operations [18, 19].

Low Power Wide Area Networks (LPWAN) identify a class of low-power-consumption wireless technologies designed for use in Wide Area Networks (WAN), presenting different technical characteristics (concerning communication frequencies and standards of adopted protocol) and licensing models. This class of networks, explicitly created to implement machine-to-machine (M2M) communication, allows obtaining greater efficiency compared to common mobile networks. It also provides a significantly reduced cost (in energetic and economic terms), and the ability to natively allow a higher number of nodes connected to the infrastructure. Depending on the specific technology used, LPWAN can support data packages up to some kilobytes long, with a transfer rate of a few hundreds of Kbps, guaranteeing a range of action of several kilometers. In LPWAN, the sensors represent nodes, which are usually compact, autonomous in data acquisition, powered for years through small batteries, and easy to configure and operate. Such nodes are generally versatile and do not require infrastructural interventions for their installations, also in ancient or not-cabled buildings. The use of autonomous nodes allows extending the monitoring network outdoors, integrating them into mobile platforms.

Among the others LPWAN, Long Range Wide-Area Network (LoRaWAN), which relies on Long Range (LoRa) radio modulation scheme, allows the creation of private networks. LoRa is a proprietary spread spectrum modulation derived by Chirp Spread Spectrum (CSS) technique with integrated Forward Error Correction (FEC) developed

by Semtech. This technology enables long-range data transmission and operates in the unlicensed Industrial, Scientific and Medical (ISM) frequency bands (868 MHz and 433 MHz in Europe, 915 MHz and 433 MHz in USA). Using 125 kHz, 250 kHz and 500 kHz of bandwidth, smaller payloads of a maximum of 250 bytes can be transmitted over a distance of tens of kilometers also in urban environments. Battery-powered devices equipped with LoRa radio transceivers usually have several years of lifetime. LoRaWAN networks are assembled in a star-of-stars network topology, where several end-nodes are linked to one or more gateways which route the packets through a back-end communication channel, such as Ethernet [20, 21].

All aforementioned features make LoRa technology an optimal solution for the implementation of energy and comfort monitoring systems of buildings or for acquisition of environmental parameters.

3 Architectural Design and Implementation of the Communication Infrastructure

A monitoring infrastructure based on LPWAN technologies has been designed, implemented and installed on the test sites selected within the project PickUP. Such infrastructure aimed at fulfilling two complementary objectives. Firstly, to integrate the elements producing/collecting the data (i.e., sensors) and, secondly, to create the telecommunications backbone of data between the sensors and the remote nodes (i.e., cloud servers), delivering the information elaboration logics and hosting the PickUP platform. This infrastructure has been designed considering the need for allowing the remote control and monitoring of the state of individual installed units. This functionality resulted to be specifically useful in the context of the current SARS-COVID-19 pandemic. Most of the PickUP experimental activities were performed during 2020 restrictions and emergency status.

Following the architectural models proposed by the Open Fog Consortium in 2017 [22], the developed architecture consists in a communication and integration layer structured on three levels, characterized by different devices and protocols according to their role within this infrastructure. The three levels are labelled as: “Edge”, “Fog” and “Cloud” (Fig. 1).

The main goal of this communication and integration architecture is to enable the efficient data collection from sensors, and their secure transfer to the remote elaboration components. This architecture also implements bidirectional communications Cloud-Edge to enable simple actuation functionalities.

Specifically, the Edge level is composed of sensors monitoring environmental parameters (e.g. temperature, humidity, CO₂, VOC, PM concentration, noise, lighting) suitable for both the indoor and outdoor scenarios. All installed sensors are based on LoRa technology for implementing the physical layer, and LoRaWAN protocol for the communication layer.

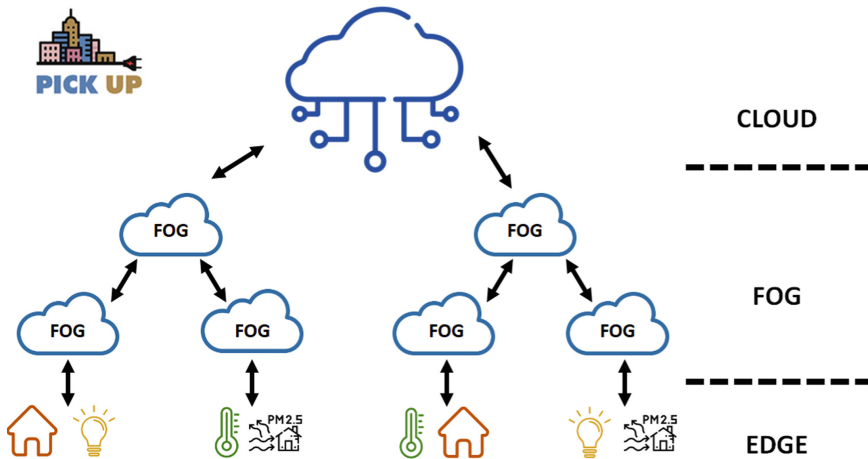


Fig. 1. Architectural model used for the experimentation (inspired to Open Fog Architecture).

Sensors-gateway communication is based on LoRaWAN protocol. Data transfer from each gateway to the cloud relies on TCP/IP protocol, adopting RESTful HTTP calls of information encoded according to LoRaWAN specifications. Each gateway is coupled with a Raspberry Pi 4 and an LTE router, composing the Fog node.

The adoption of Fog level does not require a continuous Ethernet connection: the services can run independently from the availability of Ethernet connection and can send the update to the Cloud only in case of availability. The use of smaller and less power demanding devices (i.e. switches, gateway, access point) installed close to the Edge level minimizes the latency needed to retrieve the data and processed them, since it is not needed the transfer of the data to the Cloud for processing. In fact, the Fog level has the objectives to guarantee data transfer from LoRaWAN gateways to the PickUP cloud, and to perform early elaborations and real-time data processing (i.e., data treatment and intelligence features) avoiding the latencies commonly experimented when relying on traditional cloud-based data processing.

The Raspberry Pi 4 was used for implementing the remote management features needed to monitor and maintain the nodes and the data collection state, whereas the router was needed for providing the internet connectivity to the Fog node by an LTE link. The Fog node is strongly based on the computational power provided by the Raspberry Pi 4, in charge of performing real-time analysis and of applying intelligent functionalities at node-level (e.g., those based on Artificial Intelligence/Machine Learning models). Fog node is designed to move computational tasks closer to where data is produced (i.e., from cloud towards sensors) in order to minimize latencies generated by the traditional approach and to tackle security leaks. Considering these objectives, the open source Eclipse ioFog was installed into the Raspberry Pi 4 to create a distributed Edge Compute Network (ECN), to run any microservice on it dynamically, securely, and remotely. Thus, the Raspberry Pi 4 implements some key functionalities: the first task is the local storage of the information collected, since the data acquired by sensors are stored locally, processed and then sent, from time to time, to the cloud for long-term storage and more

refined processing. The others tasks consist in the information redundancy, since stored data are kept locally until the server receives them and in the system monitoring, since it is possible to connect to the node for checking whether the node features are working correctly and if data are flowing regularly from the edge layer. Furthermore, the Fog level has been used to implement, experiment and validate the application of collaboration features among end-nodes (e.g., nodes mutual recognition, node health state awareness and sharing of resources).

Cloud represents the third level of the infrastructure. It mostly consists of a so-called LoRa Server, that is a remote application hosted on cloud servers and implementing Gateway Bridge, Network Server and Application Server features needed to complete an overall LoRaWAN communication infrastructure. The LoRa Server is based on the open-source project called ChirpStack, and it was configured and customized according to the project's architecture peculiarities. It acts as proxy for all the messages coming from the hardware LoRaWAN gateway as the result of the collection performed by all the individual LoRaWAN sensors installed on the pilot sites.

The LoRa Server decodes in readable JSON format and forwards the information to other PickUP architecture elements to create the data lake and prepare the data for data analysis and prediction functionalities (Fig. 2).

| Direction | Time | Status | Device ID |
|-----------|------------|-------------|------------------|
| Downlink | 5:33:54 PM | JoinAccept | |
| Uplink | 5:33:54 PM | JoinRequest | 70b3d58ff1012bc8 |
| Downlink | 5:33:54 PM | JoinAccept | |
| Downlink | 5:33:54 PM | JoinAccept | |
| Uplink | 5:33:48 PM | JoinRequest | 70b3d58ff1012bc8 |
| Uplink | 5:33:41 PM | JoinRequest | 70b3d58ff1012bc8 |

Fig. 2. Dashboard of the ChirpStack LoRaWAN server.

Data from the Edge sensors are collected by the gateways on the Fog level and then sent through the Internet to the Gateway Bridge using the UDP protocol. Network Server manages the state of the LoRaWAN network, administers and monitors the activation of LoRaWAN sensors and manages inbound and outbound messages flows. Finally, the Application Server provides WEB and API interfaces to manage applications, gateways and devices registration, thus enabling advanced configurations and facilitating maintenance operations for the system administrators team. It can also process uplink data and

forward them to one or multiple configured integrations. The software platform Senseioty was used to provide a cloud dashboard for the visualization of both the last available measurement and the time-series. Figure 3 shows an example of the user-interface.

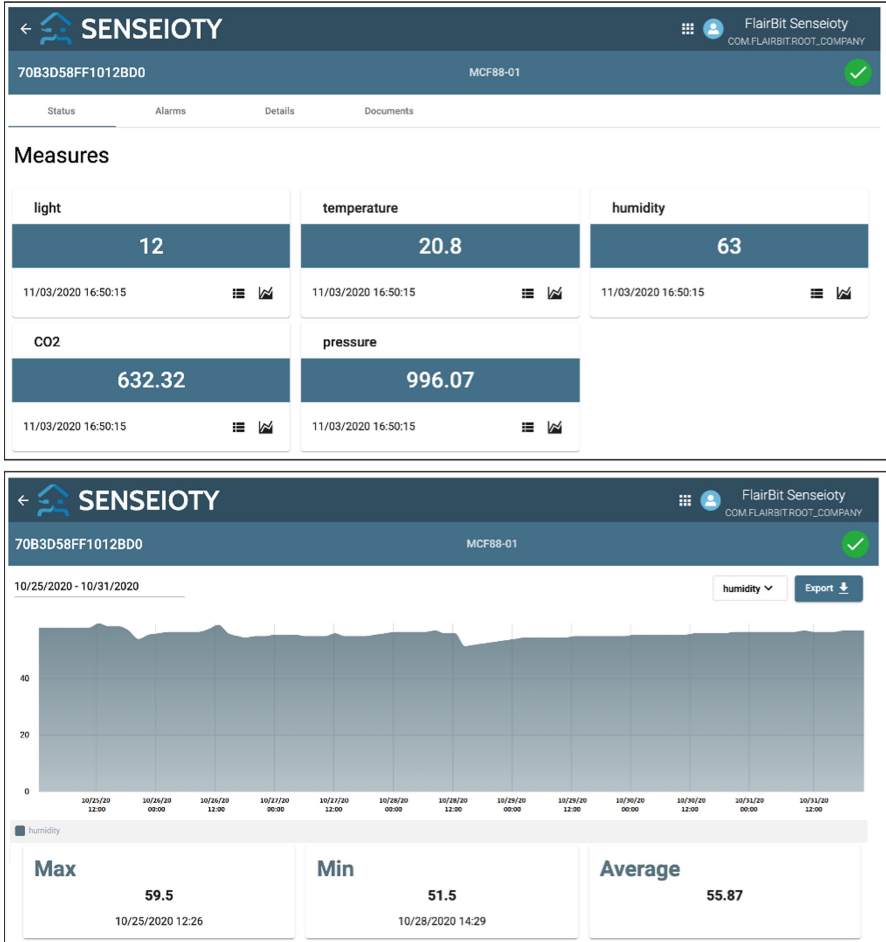


Fig. 3. Dashboards for (top) real time measurement and (bottom) time-series as provided by Senseioty platform.

In this way, it is possible to integrate the LoRa Server with external applications to build added-value business services. For example, as part of the PickUP project, some mobile applications have been developed to allow users of the police station and the school to monitor the comfort of their rooms by viewing the data processed on dedicated management and analysis dashboards (Fig. 4), and to provide feedback on their well-being (Fig. 5). The availability of these feedbacks represented a key requirement for implementing Demand-Response algorithms based on Artificial Intelligence, which

were developed as additional service within the project and the details of which can be found in Bianco et al. [23].

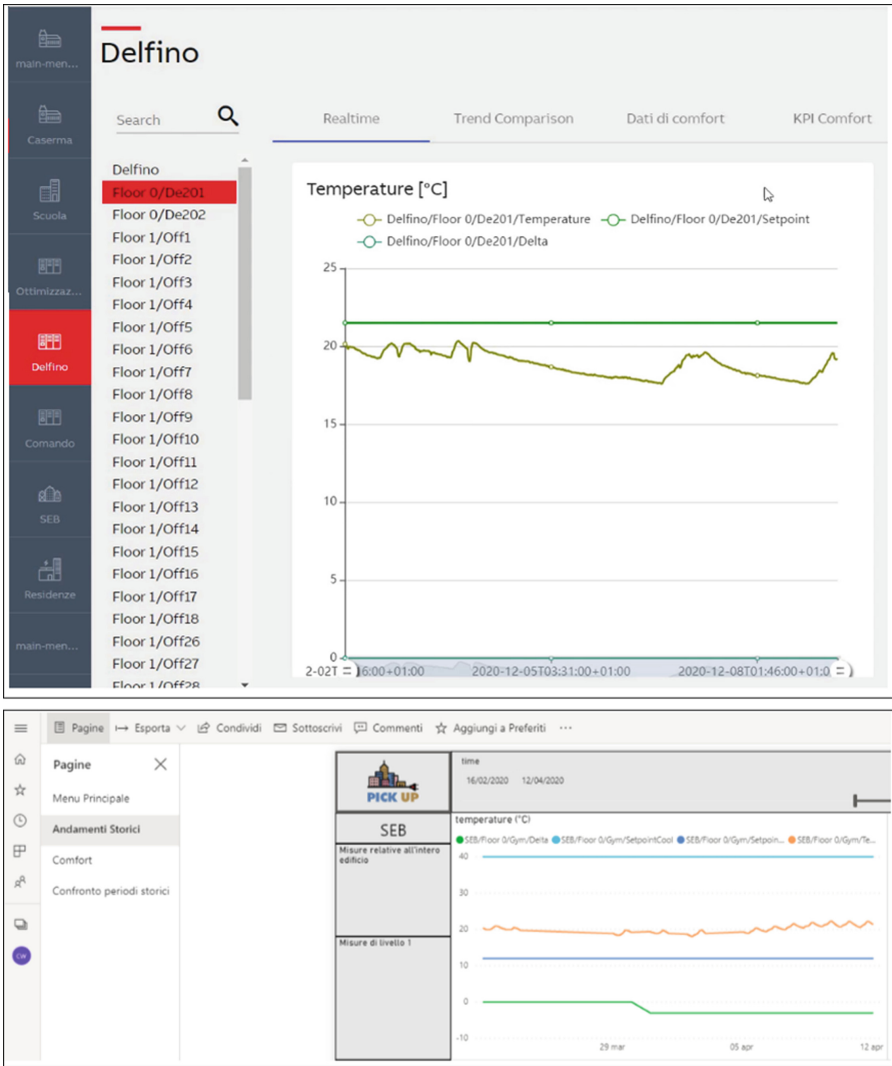


Fig. 4. Screenshots of the (top) real-time and (bottom) historical dashboards developed for the end-users.

Position: Control room

Which is your feeling about temperature?

What icon best describe your clothing?

What icon best describe your work?

Leave a comment

Send my opinion

Fig. 5. Snapshot of the interface of the mobile application to retrieve feedbacks from end-users.

The dashboards were implemented to provide a graphical interface to visualize collected data enabling both historical and real-time analysis. These dashboards are user-dedicated tools providing access to different types information. They are made available through the use of two different technologies according to their scope: for real-time analysis they are based on Angular JS, whereas for historical time-series they are based on Power BI.

The end-nodes used to monitor air quality are on the shelf, and they have been chosen to answer the need of the network to be fully operational on the long-term basis and to guarantee efficient and effective LoRaWAN communication. The selected end-nodes for internal well-being monitoring were powered by a 3.6 V lithium battery assuring an annual lifetime, whereas end-nodes for outdoor environment were powered by embedded solar power. The proposed architecture based on LoraWAN allows the use of multiple end-nodes with one gateway, does not require cabled infrastructure and only a TCP/IP connection is needed to connect gateway and server. The low-cost of each device contributes to keeping the capital cost for the overall architecture under control and distributed throughout a multiannual temporal scale.

Moreover, the use of commercial devices allows the reusability and replicability of the proposed solution in other different sites. The adoption of open hardware (and open source) solutions has been evaluated and adopted for trials in a controlled environment as in the case of Arduino-based sensors as well as Raspberry PI-based LoRaWAN gateways that have been approached even though they are not presented.

3.1 Police Station Building Setup

An experimental activity was carried out inside the building of the Clelia Corradini police headquarters in Savona (PS, hereafter) focused on the usage of LoRaWAN technologies for monitoring indoor well-being. Considering the overall architecture described above, the following levels have been adopted for this site: i) for the Edge layer, six internal sensors have been installed (three ERS-sound devices by ELSYS (Elektroniksystem i Umeå AB), and three MCF-LW12VOC devices by Enginko srl) for monitoring level of light, air temperature, relative humidity, noise level, motion detection, atmospheric pressure, CO₂ and VOC.

The six end nodes were installed in meaningful places of the building, taking into consideration police station's daily activities; ii) the Fog layer integrated an indoor LoRaWAN gateway (Conduit MTCDDT series by Multi-Tech Systems, Inc.) with a Raspberry Pi 4 and a Router 3/4G model RUT955 by Teltonika Networks (Fig. 6). The end nodes were set up to provide a data stream every 10–30 min (the former for ELSYS sensors, the latter for MCF88 sensors), compliant with the European constraints of duty-cycle to be applied to LPWAN transmission [24]. All nodes used the Over the Air Activation (OTAA) method for joining the network.

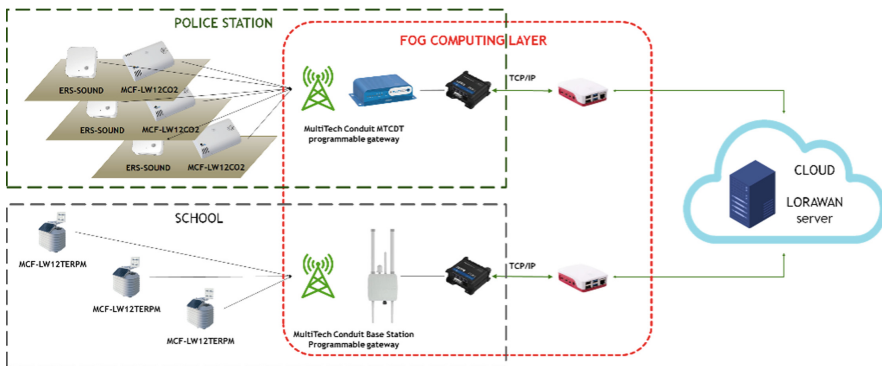


Fig. 6. Schematic diagram of the IoT network implemented for the (top left) Clelia Corradini police station and the (bottom left) Colombo-Pertini school.

3.2 School Building Setup

At the school's building Colombo-Pertini of Savona (SC, hereafter) an experiment focused on outdoor air quality monitoring has been performed. LoRaWAN technology was exploited to implement an infrastructure for outdoor environmental monitoring. Taking into consideration the presented architecture, the levels involved into this pilot site consist of: i) for the Edge, three MCF-LW12TERPM devices by Enginko srl, were installed for outdoor air quality monitoring, specifically consisting in observations of air temperature, relative humidity, atmospheric pressure and concentration of PM₁, PM₁₀ and PM₂₅; ii) regarding the Fog, an outdoor LoRaWAN gateway (Conduit IP67 base

station by Multi-Tech Systems, Inc.) integrated with a Raspberry Pi 4 and a Router 3/4G model RUT955 by Teltonika Networks were exploited (Fig. 6). The sampling time of the end-nodes was set to 30 min, to satisfy the constraints of the European duty cycle for LPWAN [24]. OTAA method was used by the end nodes to join the network also in this case.

An end-node and the Fog node were installed on the roof of the school Colombo-Pertini (A letter in Fig. 7) whereas the other two end-nodes were positioned in via Caboto (B letter in Fig. 7) and in via Manzoni (C letter in Fig. 7) at an aerial distance of 52.9 m and of 133 m from the Fog node, respectively.

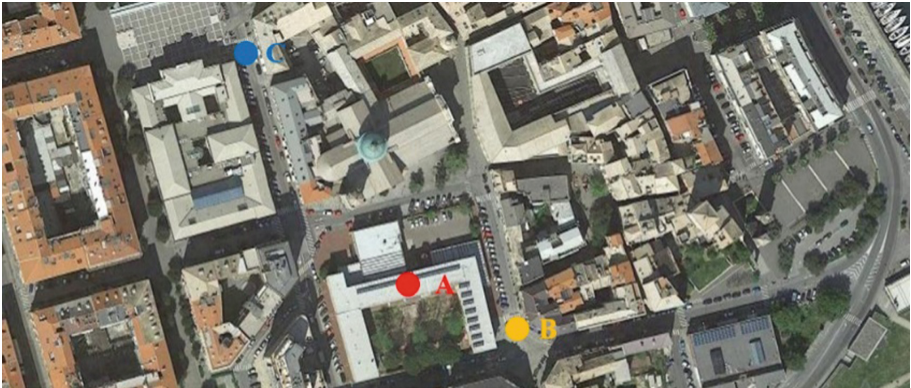


Fig. 7. Map of the end-nodes and Fog node installation on the roof of school Colombo-Pertini (A letter) and the end nodes of via Caboto (B letter) and via Manzoni (C letter).

4 Results and Discussion

Diagnostic services and identification of anomalies are key factors to determine the well-being of people both for indoor and outdoor application, as the case of thermo-hygrometric comfort for public buildings or the anomalous concentration of air particulate matter in an urban district. Pandemic status has also clearly enlightened the need to closely monitor indoor occupancy.

To this aim, a continuous monitoring of the variables of interest has been set-up in both scenarios and the capability of the Fog node to analyze the observation in near-real-time was exploited to generate alarm in case of observed anomalies (i.e., values exceeding thresholds) or sensor's fault and to provide feedback to actuators, when available. The proposed IoT infrastructure has the role to provide real-time data from heterogenous sensors that constituted the backbone of a more complex architecture constituted of a prevision module and an action module. The prevision module uses the acquired data to forecast power consumption and perceived comfort exploiting the use of Neural Network algorithm, whilst the action module is responsible for acting on available heat pumps or for tuning of thermostatic valves and air conditioning system. Once an issue is detected, such as temperature over or below thresholds depending on the season in a room, an alarm

is issued via TCP/IP and/or Wifi to the monitoring dashboard. If the problem persists for more than 30 min, automatically the action module will act on the thermostatic valves to increase or decrease the temperature interfacing with the existing respective control units or remote terminal units (RTU). In case of failure, a fault alert is issued via TCP/IP and/or Wifi to the monitoring dashboard and an e-mail and a SMS are sent to the persons in charge of control.

The same procedures have been set-up in case of CO₂ or VOC values exceeding the thresholds, in this case the system will automatically act on the heating, ventilation and air conditioning system (HVAC) to ventilate the room.

Table 1 summarizes the thresholds used to generate alarm for each monitored parameter on the basis of legislation in force.

Table 1. Threshold used to generate alarm for each monitored parameter on the basis of legislation in force.

| Parameter | Threshold | Legislation |
|----------------------------------|-------------------------|--|
| Room temperature in summer | 26 °C | American Society of Heating, Refrigerating and Air-Conditioning Engineers, (ASHRAE) Standard 55–2017 |
| Room temperature in winter | 20 °C | American Society of Heating, Refrigerating and Air-Conditioning Engineers, (ASHRAE) Standard 55–2017 |
| Indoor carbon dioxide | 1000 ppm | National Institute for Occupational Safety and Health (NIOSH) Recommendation |
| Indoor volatile organic compound | 500 ppb | U.S. Environmental Protection Agency recommendation |
| Daily outdoor PM10 | 50 $\mu\text{g m}^{-3}$ | 2008/50/CE directive |
| Daily outdoor PM25 | 20 $\mu\text{g m}^{-3}$ | 2008/50/CE directive |
| Indoor light | 500 lx | UNI EN 12464–1 2011 |
| Average sound | 80 dB | Italian legislation number D.Lgs.81/2008 |
| Average peak | 140 dB | Italian legislation number D.Lgs.81/2008 |

4.1 Evaluation of the LoRaWAN Network

For each aforementioned scenario and for each IoT packet received by the implemented Fog node, all the parameters related to the quality of the radio transmission were stored. Specifically, the strength of the received signal (RSSI), the signal-to-noise ratio (SNR) as well as the information content of the node (payload) and date and time of receipt of the packets were stored.

The implemented network envisaged the use of the Adaptive Data Rate algorithm, which automatically allows to maximize communication efficiency by reducing the energy consumption of the nodes. As performance metrics, packet delivery ratio (PDR),

RSSI and SNR were used, acquired during three months of continuous monitoring (from January to April 2021). RSSI and SNR values were directly provided by the gateway as metadata for each received message, whereas PDR is defined as the ratio between the number of packets received and the number of packets transmitted. Table 2 summarizes the results in terms of PDR and highlights how the developed network was effective for a continuous monitoring of citizen well-being in both indoor and outdoor scenarios.

Table 2. Packet delivery ratio during three months of continuous monitoring.

| Sensor type | Position | Packet received | Packets transmitted | PDR [%] |
|---------------|-----------------|-----------------|---------------------|---------|
| MCF88 indoor | PS control room | 4147 | 4202 | 98.69 |
| MCF88 indoor | PS meeting room | 4132 | 4136 | 99.90 |
| MCF88 indoor | PS entrance | 3973 | 4019 | 98.85 |
| ELSYS | PS meeting room | 11752 | 11969 | 98.18 |
| ELSYS | PS control room | 11974 | 12159 | 98.48 |
| ELSYS | PS entrance | 7811 | 7962 | 98.10 |
| MCF88 outdoor | SC via Caboto | 4079 | 4226 | 96.52 |
| MCF88 outdoor | SC roof | 4123 | 4245 | 97.12 |
| MCF88 outdoor | SC via Manzoni | 4133 | 4225 | 97.82 |

RSSI values provided as metadata by the gateway for each transmission and for each end-node for the PS site, showed, as expected, better results for the end-node located in the proximity of the Fog node (i.e., the devices installed at the second floor in the meeting room), with respect to the end-nodes installed at the entrance or in the control room at the second floor. RSSI values ranging between -30 dBm and -40 dBm were observed for the end-nodes closest to the Fog node, and a drop in the received power down to -70 dBm and -120 dBm was observed for the other nodes. This behavior is clearly ascribable to the presence of obstacles, especially the walls in the building which are responsible for a not negligible contribution to the path loss.

RSSI values measured by the gateway collocated on the roof of the school showed better performance for nearby nodes with respect to those installed in the neighboring streets of via Manzoni and via Caboto, due to the proximity between node and gateway, obtaining comparable values for the other two neighboring stations.

Measured SNR values showed, on average, positive values for all indoor nodes, ranging from 5 dB to 10 dB, although an increase of negative values were observed during the last weeks of monitoring for both devices installed in the control room, maybe due to variations in room usage in relation to the evolving pandemic scenario.

On the other hand, SNR values provided by the gateway installed on the school demonstrated that the chosen locations are suitable for monitoring the air quality of the area, since positive values were obtained, in the range between 0 dB and 10 dB considered as optimal for LoRaWAN transmission [25].

4.2 Evaluation of Indoor Occupancy

The implemented network allowed the provision as a service information about the occupancy for the rooms in which the end-nodes were installed at PS, at the entrance, in the meeting room and in the control room located at the second floor of the building.

The monitoring of the estimated occupancy in those rooms was strategic, especially in the pandemic situation, since it allowed to organize spaces according to their use and in a future perspective has provided fruitful insight for potential building renovation. Occupancy assessment is a key element for both the implementation of energy efficiency strategies and the correct evaluation of the occupants' comfort conditions [26, 27]. Indeed, data acquired during the experimentation can be used to further reduce the consumption of energy by air conditioners, lighting systems, IT infrastructures and other systems inside the PS. The data ensure suitable conditions of comfort when users actually occupy the premises in accordance with their specific needs and the type of activity they are carrying out.

Sound measurements provided by the end-nodes were used to infer about the occupancy of the chosen rooms. The time series of sound pressure levels provided by the end-node installed at the entrance of the PS during three months of continuous monitoring evidenced a clear pattern with low values (below 50 dB) during nighttime (between 01 am and 07 am) and high values (up to 60 dB) during the day. A clear cycle on daily and weekly basis can be also observed in the time-series of the sound pressure levels acquired by the end-node installed in the control-room from November 2020 and April

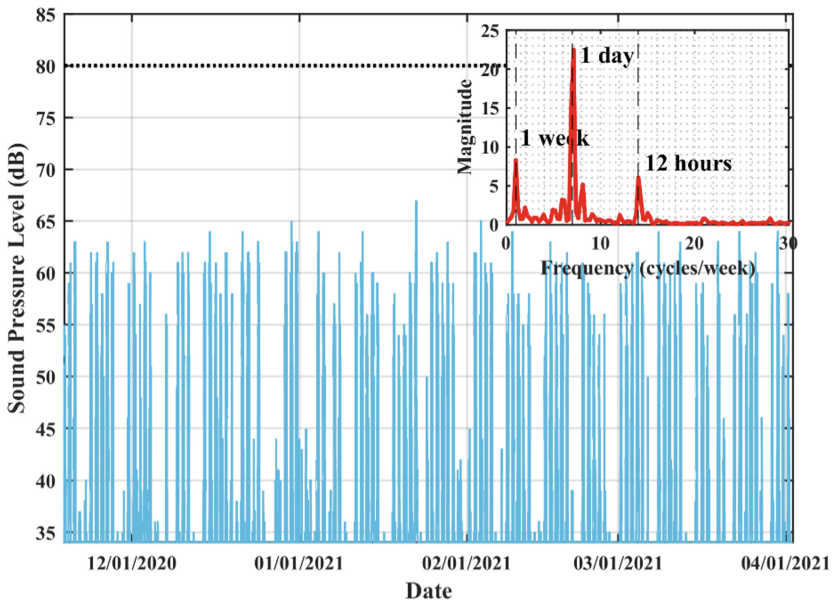


Fig. 8. Time series of sound pressure levels acquired in the control room of “Clelia Corradini” PS between November 2020 and April 2021. The upper right box in the figure shows the result of the spectral analysis performed on the overall time series. Horizontal dotted line marks the threshold used to generate the alarm.

2021, as evidenced by the spectral analysis performed on the time series (Fig. 8). Very low values, close to the instrumental limit, were observed during night (between 7 pm and 7 am) and during Friday evening, Saturday and Sundays with very few exceptions (Fig. 8).

4.3 Evaluation of Thermo-hygrometric and Light Comfort

Indoor comfort is strictly linked to the psychophysical conditions of individuals, but the analysis of thermo-hygrometric and light status of the room can provide additional insights for implementing optimization policies.

While the thermo-hygrometric comfort is ruled by the standard ISO 7730 dealing with the ergonomics of thermal environments, the analytical determination and interpretation of thermal well-being by calculating indices and local thermal well-being criteria, visual comfort is not quantitatively measurable. It may depend on the color rendering of the light sources and the balance in the distribution of luminance.

End-nodes able to measure pressure, atmospheric temperature, relative humidity and light level were installed in some selected rooms of police station, namely the entrance, the meeting room and the control room. The aim was to provide a tool for improving the level of comfort to the people occupying the room in an automatic way by acting on the existing heating and illumination remote control units.

The time series of air temperature presented well marked diurnal cycles and clearly allowed the identification of issues related to the air-conditioning or heating of the rooms. For instance, the Fog node reported strong anomalies in the meeting room between late June and September 2020, when temperature exceeded 30 °C, and several alerts were reported in the first two weeks of December 2020, when less than 15 °C were recorded (Fig. 9a). Relative humidity values during the whole period of monitoring (December 2019-April 2021) spanned from 10% to 80%, thus no alert messages were issued for humidity.

Light observations followed the diurnal cycle. During winter months values close to 0 between 7 pm and 8 am were collected for the meeting room (Fig. 9b) and the same trend was observed for the control room, whereas in the main entrance darkness was observed only for three hours between 4 am and 7 am. During summer, the hours of light increased and darkness was observed between 10 pm and 6 am of the following day in the meeting room (Fig. 9b). The different day-length throughout the season is also clearly evidenced by the spectral analysis performed for winter and summer months (upper right box in Fig. 9b).

Light levels in the main entrance and in the control-room show more variability with darkness only between 5 am and 6 am.

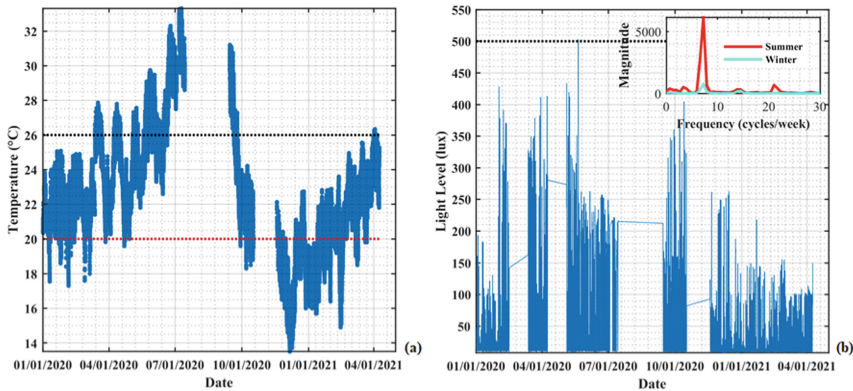


Fig. 9. Time series of (a) air temperature acquired in the meeting room of “Clelia Corradini” police station with horizontal black and red dotted line showing the thresholds used for summer and winter, respectively, and (b) light level acquired in the meeting room of “Clelia Corradini” police station with the upper right box showing the result of the spectral analysis performed on the timeseries of winter and summer months with black horizontal dotted line showing the used threshold.

4.4 Evaluation of Air Quality

The multiple sources of indoor air pollution are typically divided, based on their nature, into chemical, physical and biological pollutants; they come partly from the outside (outdoor air pollution, pollen), but many are produced from internal sources. The main internal sources of pollution are represented by: occupants, presence of dust, existing structures, building materials and systems like air conditioners, humidifiers and plumbing systems, among others.

CO₂ and VOC measurements were considered as indicators for indoor air quality evaluation since carbon dioxide concentration increases as the number of people present in a confined space increases and in the absence of adequate ventilation.

To evaluate the outdoor air quality the chosen parameters were PM₁, PM₁₀, and PM₂₅ since they are air pollutants and their levels are strictly linked with fossil fuels for automotive and heating.

Real-time analysis of CO₂ and VOC concentrations in the selected rooms, allowed to quickly intervene in case of malfunctioning or need of tuning of the air ventilation control system of the room when VOC values were over 500 ppb and/or CO₂ exceeded the threshold of 1000 ppm, that is commonly considered the limit over which people begin to get headache. In the three months of monitoring, no anomalies were detected and the dynamic of CO₂ concentration was very similar for the entrance and the meeting room and followed a diurnal cycle with values between 350 ppm and 650 ppm. In the control room the values are generally lower than 300 ppm with peaks up to 650 ppm in agreement with an irregular occupancy of the room. On the contrary VOC data were greater in the control room than in the entrance and in the meeting room. In the control room values varied between 400 and 500 ppb, with several episodes over 800 ppb detected by the Fog node. In the other two rooms VOC spanned between 400 and 500 ppb, and only in few episodes, the exceeding of the limit of 500 ppb occurred at the entrance and

in the meeting rooms in winter months and were suddenly detected by the Fog node (Fig. 10a).

The analysis of the particulate evidence similarities among the three sites, with a clear monthly periodicity and a less evident cycle of 24 h due to the dynamic of urban traffic (Fig. 10b). PM1 values reached up to about $85 \mu\text{g m}^{-3}$, PM10 values were commonly less than $200 \mu\text{g m}^{-3}$ and PM25 less than $100 \mu\text{g m}^{-3}$ but both PM10 and PM25 showed some peaks up to $350 \mu\text{g m}^{-3}$ and $120 \mu\text{g m}^{-3}$, respectively, in December 2020 and in late February 2021 presumably linked with the Christmas holidays and the easing of anti-pandemic restrictions, respectively (Fig. 10c).

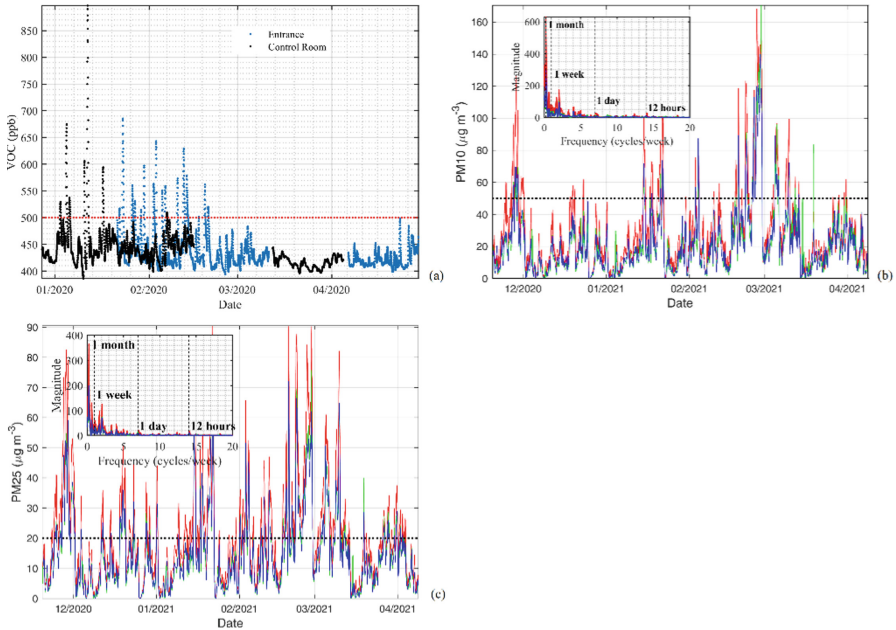


Fig. 10. Time series of: (a) VOC acquired in the control room of the “Clelia Corradini” police station with horizontal red dotted line showing the used threshold; (b) PM10 and (c) PM25 acquired in the streets adjacent to the “Colombo-Pertini” school with horizontal black dotted line showing the used threshold.

5 Conclusions

Comfort can be defined as a sensation perceived by a user within a given domestic or working environment as well as during outdoor activities, which states the perceived level of well-being. Environmental well-being may concern three different sensory domains: the thermo-hygrometric, the visual, and the acoustic comfort. Furthermore, in addition to the assessment of comfort in a strict sense, it is important to evaluate the well-being of the citizens in terms of air quality-related parameters being directly correlated to respiratory-olfactory well-being.

To this aim, an IoT network has been designed and operated in the framework of the regional project PickUP in the premises of the Clelia Corradini police station and of the Colombo-Pertini school in Savona.

Edge node was constituted of environmental sensors with LoRaWAN capability and all acquired data were managed by a Fog node aiming at monitoring and improving the perceived comfort of people living in the urban district of the police station and the school. Specifically, the availability of a Fog node based on Raspberry Pi 4 allowed the detection in near real time of anomalies and issues related to air-conditioning, heating or a lack of proper ventilation of the rooms as well as the exceeding of thresholds in case of poor air quality both indoor and outdoor.

Results evidence the capability of the proposed network to monitor in the long-term citizen well-being and to quickly activate the proper actuators in case of need, if available. The presented infrastructure is easily replicable in any urban district, since it employs low-power and low-cost Edge and Fog nodes, and it is scalable, thus it is easy to integrate new sensors. Also, the related dashboard and services provided as monitoring tools can be easily adapted.

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