Smart Sensors in Smart Cities Collaborate for Indoor Air Quality

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Abstract This paper presents an example of collaboration between two different air quality monitoring systems, one developed for indoor usage, the other one used in some regions of Italy as an example of citizens' collaborative work for monitoring the air quality in smart cities. The exchange of information between the two systems (the inner one and the external one) allows making a weighted decision for improving the inner air quality. By evaluating both indoor and outdoor air quality levels, a reasoner decides the best policy to be automatically adopted to improve, or at least not worsen, the indoor air quality.

1 Introduction

The deployment of wireless sensor networks (WSN) in Smart City infrastructures has driven to large amounts of information being generated each day across a variety of domains by a plethora of applications, including environmental monitoring applications. In this context, the usage of embedded devices and existing internet infrastructures is essential for the Internet of Things (IoT) vision [1]. A Smart City is just based on the usage of large amounts of IoT devices, some of them used in monitoring systems that enable the management and the remote control of wide ranges of sensor networks and actuators, used for both indoor [2] and outdoor applications [3,4].

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Persons spend an estimated 90% of their time indoors, so that poor indoor air quality (IAQ) both decreases the comfort level and poses a substantial risk to public health [5]. As a matter of fact, poor air quality may induce short-term health problems, such as fatigue and nausea as well as chronic respiratory diseases [6]. In this paper, we present an example of collaboration between a prototype of indoor air quality monitoring system and an outdoor air quality system, available in some regions of Italy, in order to evaluate when and if an automatic action, such as opening a window, is required for improving the inner air quality. The proposed IAQ monitoring system is based on a multi-component platform integrated in an extremely versatile monitoring system consisting of heterogeneous environmental sensors installed in a closed environment (apartment, office, some areas of an industry, etc...) for various monitoring purposes. An ad-hoc developed middleware allows a reasoner (installed on the server where all data are collected) to get the data from the sensors and to take decisions according to policies established by the user. It is not goal of this paper to present the whole monitoring system; this paper only focuses on the decision of automatically opening or not a window according to the external air quality. As far as the authors know, it is the first time in Italy that an indoor monitoring system communicates with an outdoor system for an optimal policy of maintenance of the indoor air quality.

2 The Indoor Air Quality

The term Indoor Air Quality (IAQ) means different things to different people and there is no single accepted definition for it. There are no specific legislated standards for IAQ, although there are exposure standards set for a range of chemicals in industrial environments. IAQ is a measure/analysis of the air condition in closed spaces and it includes the phys-

Table 1: Typical indoor air quality definitions based on CO_2 level picked up by most industry standards

Air Quality	Recommendation	CO2 [ppm]
Excellent	Target value	0-600
Good	Optional ventilation/airing	600-800
Fair	Ventilation/airing recommended	800-1000
Mediocre	Contaminated indoor air Intensified ventilation/airing recommended	1000-1500
Bad	Heavily contaminated indoor air Intensified ventilation/airing necessary	1500-2100

Table 2: TVOC guidelines issued by the German Federal Environmental Agency.

Air Quality	Recommendation	TVOC [ppb]
Excellent	Target value	0-65
Good	Ventilation/airing recommended	65-220
Moderate	Intensified ventilation/airing recommended	220-660
Poor	Intensified ventilation/airing necessary	660-2200
Unhealty	Use only if unavoidable/intense ventilation necessary	2200-5500

ical, chemical and microbiological characterization of the air within and around buildings and structures, especially as it relates to the health and comfort of the building occupants. In the past, Carbon Dioxide (CO_2) was accepted as the main indicator for indoor air quality because the human beings were considered the main pollutant sources. Today, many other sources that emit pollutants different from human bioeffluents have been taken into account. In fact, many new materials and products used in indoor environments are responsible for the increase in indoor pollution concentration, especially Volatile Organic Compounds (VOCs), which contain carbon with a vapor pressure high enough to vaporise from materials and surfaces into the indoor air at room temperatures, a process known as "off-gassing". They include alkanes, aromatics, aldehydes, ketones, alcohols and ethers, which can be usually present in indoor air (Total VOC, TVOC). High levels of indoor particulates can also be an indicator of poor air quality. Due to the lack of fresh air, air circulation, and air filtration, the level of contaminants can be higher in some parts of a semi-enclosed space. In pursuit of higher energy efficiency, mechanical ventilation and circulation are necessary to manage the indoor air quality. CO_2 in the air is measured in percentage or ppm (parts per million) and is, however, the most important indicator of indoor air quality [7]. Typical indoor CO_2 concentrations range between 700 and 2000 ppm (approximately 3657 mg/m^3) but can exceed 3000 ppm (5486 mg/m^3) during the use of unventilated appliances [8]. To keep the CO_2 concentration at a maximum of 0.15% (1500 ppm), an average of 25 m^3 / h of new air per person must be added (for example, even more if you are practicing a sport). According to DIN EN ISO 15011-2 standards, the ventilation rate per person is about 30 m^3 / h for a house, about 20 m^3 / h for a nursery, and 35 m^3 / h for the master bedroom. The oxygen supply necessary for our metabolism is only 10% of the new air flow needed for the exchange of air containing CO_2 and harmful substances. Tables 1 and 2 represent the typical CO_2 [1] and TVOC [2] levels, respectively [9]. Outdoor environmental monitoring allows to know the status of the air quality, the water quality, the level of pollutants, and so on. At the moment, there are only a couple of significant maps in real time for the quality of the air in the world: i) the World Air Quality Index ([3]), which has the merit of standardizing the air quality indexes of the various countries (which are almost all different), making them comparable to each other, and ii) the map named "Che aria tira (CAT[4])?" (What air does it blow?) for Italy. CAT is the only real-time map of air quality in our country; it is made with fixed stations not belonging to the Regional Agency for Environmental Protection (ARPA -Agenzia Regionale per la Protezione Ambientale). CAT is an open source project of Active Citizenship and Citizen Science that aims at building a self-monitoring network of air quality, where citizens, associations / organizations or other institutions can build their own environmental monitoring unit and share data online on the platform created by the project. At the moment, CAT provides the values of PM2.5 and PM10 derived from 72 fixed monitoring stations in 6 provinces and 33 municipalities in Italy.

3 The Monitoring System

The monitoring system we developed, shown in Figure 1, is logically divided in three parts: 1) a complex Wireless Sensor Network (WSN), constituted by a variety of heterogeneous sensor subnetworks, each one with its own monitoring

[1] `https://ams.com/environmental-sensors`
[2] `https://www.repcomsrl.com/wp-content/uploads/2017/06/Environmental\_Sensing\_VOC\_Product\_Brochure\_EN.pdf`
[3] `https://airnow.gov/index.cfm?action=aqibasics.aqi/`
[4] `http://www.cheariatira.it/`

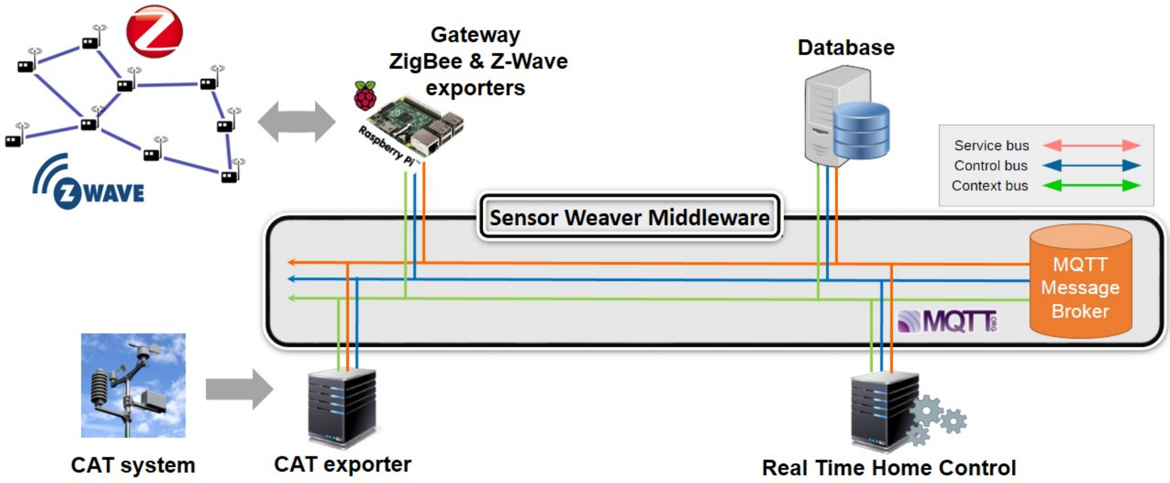
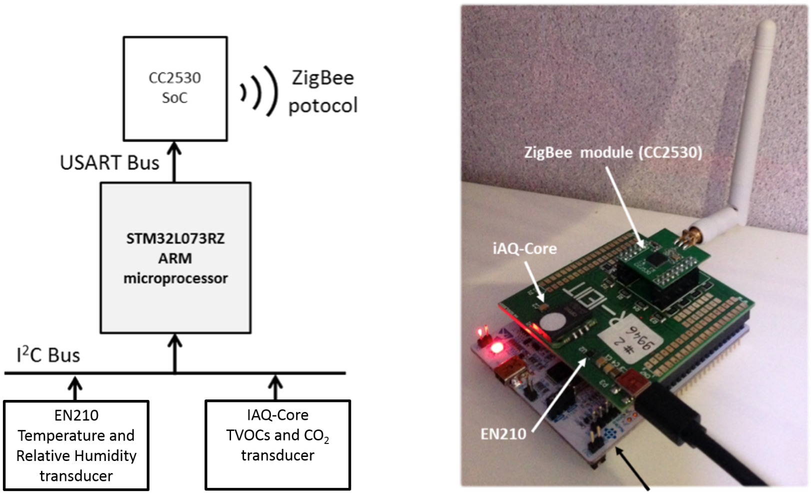


Fig. 1: Monitoring system architecture

peculiarities and communication protocol, 2) a secure communication platform for the exchange of sensors data and for the control of the actuators in a distributed sensor network environment (middleware); it offers a simple and technology independent abstraction layer for representing both sensors and actuators, and 3) a set of real-time applications. In this work, a real time application related to the indoor air quality has been considered. As already stated, one element of our global monitoring network is the prototype of IAQ platform, which provides the values of air temperature, humidity, and air quality in terms of ppm CO_2 and ppb TVOC. The configuration of this platform is very versatile both in terms of hardware and software. In fact, in addition to replacing the commercial sensors currently present, for example to improve the performance of the platform itself, it is also possible to increase the functionality of the platform by introducing additional transducers for monitoring the concentration of other pollutants or particulates. This platform belongs to the ZigBee subnetwork [10], while the window open/close actuator (WA) belongs to the Z-Wave subnetwork. The middleware communication platform we developed is called *Sensor Weaver* [11]; it uses the MQTT protocol and the publish / subscribe communication paradigm, building three types of communication buses for three different types of messages: i) Service Bus: messages related to the availability of sensors / actuators and their relative characteristics; ii) Context Bus: messages related to communications generated by sensors / actuators; iii) Control Bus: messages that control functions offered by sensors / actuators. Figure 1 shows the monitoring system architecture.

3.1 The Multi-component platform for IAQ

The programmable components installed give the user the ability to customize measurement protocols and to process the data collected. As a matter of fact, our IAQ platform can be considered as a smart sensor node. The transducers used are a temperature and relative humidity transducer (ENS210, AMS) and an air quality transducer (iAQ-Core, AMS); moreover, a NUCLEO-L073RZ development board (STM32 Core Board, STMicroelectronics), which installs the STMicroelectronics STM32L073RZ ARM microprocessor, and a module (WaveShare Electronics) for the implementation of the ZigBee wireless communication protocol based on the CC2530 System-on-Chip (SoC) (Texas Instruments) are also part of the platform. The EN210 transducer provides air temperature values in the operative range [-40, 100] °C with a resolution of 0.2 °C, while the relative humidity values are provided in the range [0, 100]% with a resolution of 3.5%. The iAQ-Core transducer detects a broad range of reducing gases associated with bad air quality providing a signal that is translated into CO_2 concentration in the range [450, 2000] ppm or TVOC concentration in the range [125, 600] ppb. Figure 2a shows a block diagram of the platform structure highlighting its main components. The communication between the STM32L073RZ ARM microprocessor and the transducers EN210 and iAQ-Core has been implemented using the I2C (Inter Integrated Circuit) protocol, while the UART (Universal Asynchronous Receiver-Transmitter) protocol has been used to exchange data between the microprocessor and the CC2530 SoC.
The integration between the various components was obtained by developing an ad-hoc electronic integration board on which the components EN210, iAQ-Core and the ZigBee module were positioned. The board also supports the I2C and UART communication buses in addition to the 3.3V power supply line for the transducers and the ZigBee module. Figure 2b shows the prototype of the IAQ platform, highlighting its individual components and the fully assembled integration board. The firmware allows the autonomous



(a) Block diagram highlighting components and communication protocol

(b) The realised prototype

Fig. 2: The platform for indoor air quality monitoring

and automatic management of the various phases of the acquisition / processing / transmission protocol of the data supplied by the platform. In particular, the defined protocol includes: i) the measurement of temperature, relative humidity and the evaluation of CO_2 and TVOC concentrations every 10 s; ii) the processing of raw data from the transducers in order to determine the levels of the physical quantities monitored; iii) the transmission to the ZigBee module of the data packets. A data packet is generated and sent when the reporting timer expires and, at the same time, the variation of at least one of the monitored parameters undergoes a threshold level, defined by the user. This allows the coordinator to simply receive the messages from the nodes, without pulling them continuously. Moreover, the network coordinator provides connectivity to the middleware through the gateway.

4 The Interaction with the CAT Outdoor System

It is possible to interact with the outer CAT system via an HTTP-based API in order to retrieve the latest readings from the fixed stations, as well as the historical data. To retrieve the latest readings, a POST request is sent to the CAT server with a JSON body containing an SQL query. The response contains a JSON object with the requested information. The information that can be retrieved are the latitude/longitude of the monitoring station, the PM2.5 and PM10 readings, the timestamp of those readings and the device-id (other, more descriptive, information is also available). For instance, a body like:

```
{"stmt":"select d.geo, d.pm25, d.pm10, d.
   last_update, d.deviceId from device d
   where active = true"}
```

requests the most recent readings about all active devices. It is also possible to request data from a specific device with a query like:

```
{"stmt":"select d.geo, d.pm25, d.pm10, d.
   last_update, d.deviceId from device d
   where d.deviceId='<device-id>' and
   active = true"}
```

In this case, the response contains a reading from the specified single device:

```
{ "cols": [ "geo", "pm25", "pm10", "
   last_update", "deviceid" ],
  "rows": [
     [[ 11.0789829, 43.8927226 ],
      1.31, 1.41,
      1534303056465, "<device-id>"]
  ]
}
```

Note how attribute `cols` describes the meaning of the fields contained in attribute `rows`. The middleware provides a high-level interface through which its users can

- publish streams of information as *data feeds* (e.g., readings from a given sensor);
- subscribe to (e.g., request to receive) data feeds;
- offer to perform a service (e.g., perform some actuation on a device);
- request to perform a service.

In order to integrate the CAT system with our middleware, we developed a ”CAT exporter” software module that is responsible for interacting with the CAT system by periodically performing HTTP requests and publishing the obtained data as middleware data feeds. Any interested client module is then able to receive readings from a specific outdoor air monitoring station by subscribing to the corresponding data feed.We performed HTTP requests to the CAT system and hence we obtained the related data feed every 240 seconds. A "ZigBee exporter" module performs a similar function with respect to the devices on the ZigBee network. The exporter collects indoor sensor readings and publishes them as data feeds on the middleware. It also offers a service to operate the window opener device. This actuator is a Z-Wave flush shutter device that is ideal for controlling the motors of blinds, rollers and windows. Interaction with the ZigBee network and coordinator node is hidden inside the implementation of this module, which interacts with the other modules via the middleware interface. A third "Client" module acts as a data consumer and reasoner. This module subscribes to the data feeds for indoor air quality sensing, and to the relevant data feeds for outdoor air quality sensing (the latter is chosen based on user location and closest outdoor sensing devices). Based on indoor air quality data, it determines when ventilation is appropriate and, based on outdoor air quality data, it decides whether or not to actually open the window by requesting the corresponding service. The reasoner follows several simple rules shown in algorithm 1. Algorithm relies on four thresholds: two for the indoor CO_2 concentration estimated by our IAQ prototype, one for the PM10, and one for the PM2.5, the last two thresholds being imported from the CAT system. According to CO_2 values reported in Table 1, we defined 750 ppm and 600 ppm as thresholds for opening (th_o) and closing (th_c) windows, respectively. For what concern PM10 ($limit_{PM10}$) and PM2.5 ($limit_{PM2.5}$) thresholds, we consider the Italian legislative limit, set to 50 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively. The windows will be opened if the indoor CO_2 concentration exceeds the opening condition threshold and, at the same time, the outer PM10 and PM2.5 values are under the respective limits. On the contrary, the windows will be closed whether CO_2 concentration falls below the closing condition threshold or PM10 and PM2.5 values exceed the respective limits.

Algorithm 1 Decision Rules ($th_o, th_c, limit_{PM10}, limit_{PM2.5}$)

while 1 **do**
  if state == CLOSED **then**
    if $CO_2 >= th_o$ && $PM10 < limit_{PM10}$&&$PM2.5 < limit_{PM2.5}$ **then**
      state = OPEN
  else if state == OPEN **then**
    if $CO_2 < th_c || PM10 >= limit_{PM10} || PM2.5 >= limit_{PM2.5}$ **then**
      state = CLOSED

5 Experimental Setup

In order to evaluate the potentialities of the proposed monitoring system, we conducted preliminary experiments in some indoor environments at the Research Area of the National Council of Research (CNR) located in Pisa (Italy). In particular, we installed the IAQ platform prototype in an office that measures about 26 m^2 and hosts three workstations (Room A). Figure 4 shows the map of the indoor environments; the IAQ platform has been positioned 1 meter high, in the middle of the Room A, while the network coordinator is in Room B. We collected sensing data for three days (September 25-26-27, 2018) and the resulting TVOC, CO_2, temperature and relative humidity time-series are shown in Figure 3. A perfect time correlation between the TVOC and CO_2 signals can be observed. This behavior is due to the transducing method used by the iAQ-Core sensor: the CO_2 or TVOC concentrations are estimated by applying a specific algorithm to the same signal, that is the resistance variation of a single MOX (Metal Oxide) integrated sensor. PM10 and PM2.5 concentrations collected by CAT system in the same days are also reported in Figure 3. The indoor CO_2 concentration exceeded the threshold for opening the windows (th_o) three times, as highlighted in the inset of Figure 3, where an enlarge view of the data is shown. Therefore, after verifying the outdoor air quality data, the reasoner decided to actuate ventilation by opening the window of the room A, as shown in the inset of Figure 3, where the grey regions indicate the window opening times.

6 Conclusions

The integration of two different air quality monitoring systems is proposed as an example of IoT application in a Smart City. One system is a platform designed for indoor environments and it is included in a wide monitoring network; the other one is CAT, an open source network for monitoring the outdoor air quality in a collaborative way, implemented in some regions of Italy. Data communication among the various sensors of the inner monitoring wireless network takes place via the developed middleware, which also allows a reasoner (installed on a server where all data are collected) to access the sensing data and to take decisions about opening or closing a window, according to the external air quality. The fused information between the two systems allows taking a weighted decision for improving the inner air quality and, as a consequence, the wellness of the occupants. As a future work, we plan to include other parameters, such as temperature and humidity, in the reasoning decisions relevant to the air quality of the inner environment, in order to implement a personalization of the environment. Readers interested in learning about the air quality in Europe are invited to read [12].

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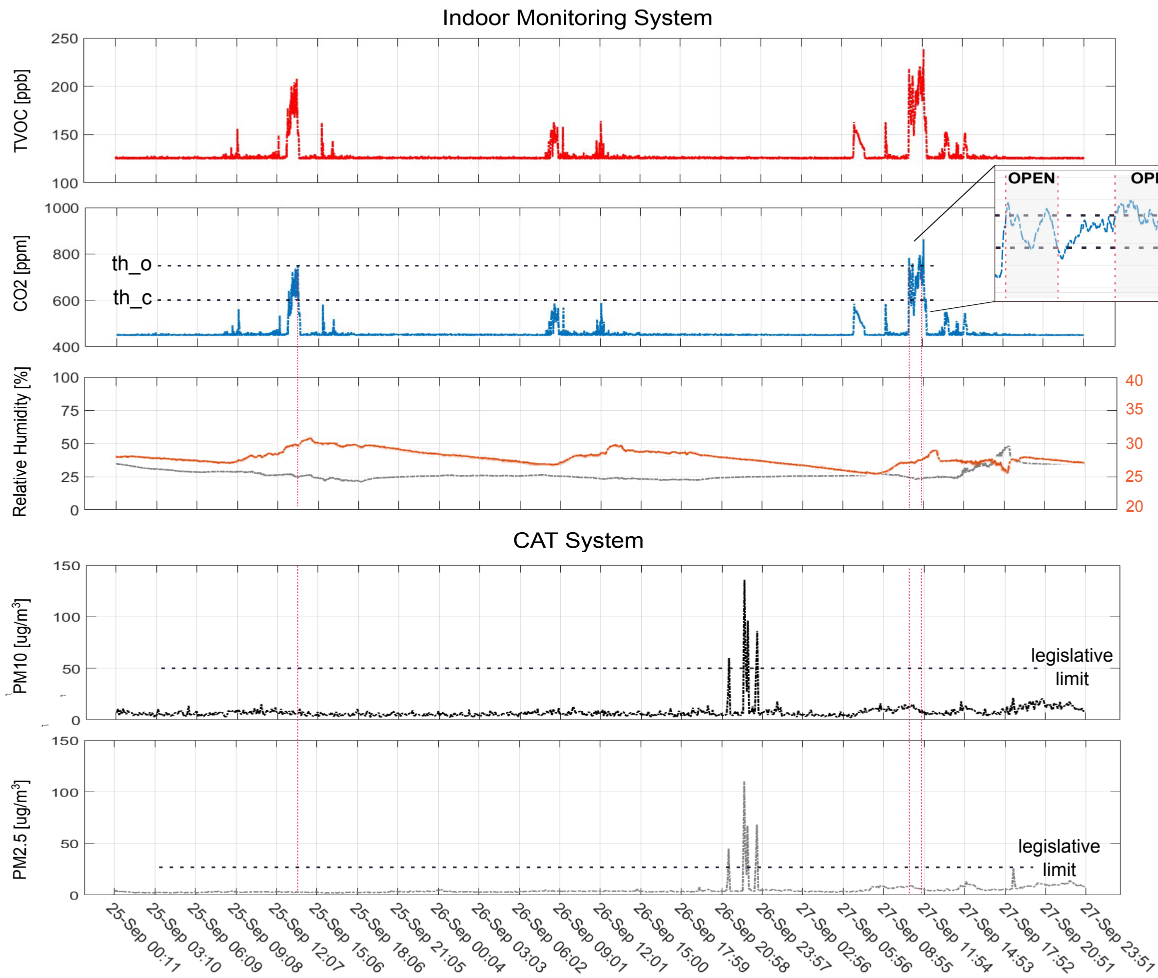

Fig. 3: Timeseries reporting three workdays of measurements. From top to bottom: TVOC, CO_2, temperature and relative humidity registered by IAQ platform, PM10, PM2.5 measured by CAT system.

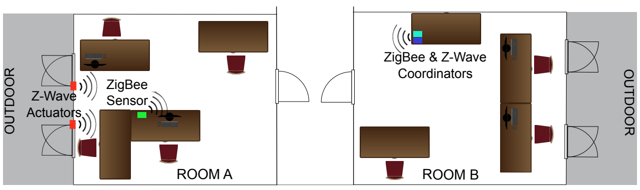

Fig. 4: Map of indoor environments where the ZigBee subnetwork has been deployed

References

1. Barsocchi, P., Cassara, P., Mavilia F., Pellegrini ,D. "Sensing a City's State of Health: Structural Monitoring System by Internet-of-Things Wireless Sensing Devices." IEEE Consumer Electronics Magazine 7, no. 2 (2018): 22-31.
2. Barsocchi, P. "Position recognition to support bedsores prevention." IEEE journal of biomedical and health informatics, 17(1), pp.53-59, 2013.
3. Bacciu, D., Chessa S., Gallicchio C., Micheli A., Ferro E., et al. "Smart environments and context-awareness for lifestyle management in a healthy active ageing framework." In Portuguese Conference on Artificial Intelligence, pp. 54-66. Springer, Cham, 2015.
4. Barsocchi P., Calabr A., Ferro E., Gennaro C., et al. "Boosting a Low-Cost Smart Home Environment with Usage and Access Control Rules." Sensors 18, no. 6, pp.1886, 2018
5. Crivello, A., Mavilia, F., Barsocchi, P., Ferro, E., Palumbo, F. "Detecting occupancy and social interaction via energy and environmental monitoring." International Journal of Sensor Networks, 27(1), 61-69. 2018.
6. Sherin A., Li X., "A cost-effective wireless sensor network system for indoor air quality monitoring applications." *Procedia Computer Science* ,vol. 34, pp. 165-171, 2014.
7. H.U. Wanner. "Sources of pollutants in indoor air", IARC Scientific Publications, 109, pp. 19-30 ,1993.
8. K. Arashidani, M. Yoshikawa, T. Kawamoto, et al. "Indoor pollution from heating Industrial Health", 34 (3), pp. 205-215, 1996.
9. ANSI/ASHRAE Standard 62.1/2 - 2016 "Ventilation for acceptable indoor air quality set"
10. Girolami, Michele, et al. "The integration of zigbee with the giraffplus robotic framework." International Joint Conference on Ambient Intelligence. Springer, Cham, 2013.
11. Barsocchi, P., Ferro, E., Fortunati, L., Mavilia, F., Palumbo, F. "EMS@ CNR: an energy monitoring sensor network infrastructure for in-building location-based services." In High Performance Computing & Simulation (HPCS), pp. 857-862. IEEE 2014.
12. Air Quality in Europe - 2018 Report, EEA Report N. 12/20118 published on October 29, 2018.