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MOBILE & WIRELESS HEALTH

Indoor Air Quality Assessment Using a CO_2 Monitoring System Based on Internet of Things

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Abstract

Indoor air quality (IAQ) parameters are not only directly related to occupational health but also have a significant impact on quality of life as people typically spend more than 90% of their time in indoor environments. Although IAQ is not usually monitored, it must be perceived as a relevant issue to follow up for the inhabitants' well-being and comfort for enhanced living environments and occupational health. Carbon dioxide (CO_2) has a substantial influence on public health and can be used as an essential index of IAQ. CO_2 levels over 1000 ppm, indicates an indoor air potential problem. Monitoring CO_2 concentration in real-time is essential to detect IAQ issues to quickly intervene in the building. The continuous technological advances in several areas such as Ambient Assisted Living and the Internet of Things (IoT) make it possible to build smart objects with significant capabilities for sensing and connecting. This paper presents the *iAirCO₂* system, a solution for CO_2 real-time monitoring based on IoT architecture. The *iAirCO₂* is composed of a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. In future, it is planned that these data can be accessed by doctors in order to support medical diagnostics. Compared to other solutions, the *iAirCO₂* is based on open-source technologies, providing a total Wi-Fi system, with several advantages such as its modularity, scalability, low-cost, and easy installation. The results reveal that the system can generate a viable IAQ appraisal, allowing to anticipate technical interventions that contribute to a healthier living environment.

Keywords AAL (ambient assisted living) · Enhanced living environments · Health informatics · IAQ (indoor air quality) · IoT (internet of things) · Smart cities

Introduction

Ambient Assisted Living (AAL) is an emerging multidisciplinary field aiming at providing an ecosystem of different types of sensors, computers, mobile devices, wireless networks and software applications for personal healthcare monitoring and telehealth systems [1]. Currently, different AAL solutions are having as basis several sensors for measuring weight, blood pressure, glucose, oxygen, temperature, location and position, and they generally use wireless technologies such as ZigBee, Bluetooth, Ethernet and Wi-Fi.

There is a lot of challenges in designing and implementation of an effective AAL system such as information architecture, interaction design, human-computer interaction, ergonomics, usability and accessibility [2]. There are also social and ethical problems such as the acceptance by the older adults and the privacy and confidentiality that should be a requirement of all AAL devices. In fact, it is also essential to ensure that technology does not replace the human care and should be used as an essential complement.

In the USA, indoor and outdoor air quality is regulated by Environmental Protection Agency (EPA). EPA found that indoor levels of pollutants may be up to 100 times higher than outdoor pollutant level and ranked poor air quality as one of the top 5 environmental risks to the public health [3].

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The problem of poor indoor air quality (IAQ) is of utmost importance affecting especially severe form the poorest people in the world who are most vulnerable presenting itself as a critical problem for world health such as tobacco use or the issue of sexually transmitted diseases [4].

High-quality research should continue to focus on the quality problems of indoor air to adopt legislation, inspection and creating mechanisms that act in real time to improve public health, both in public places such as schools and hospitals and private homes and further increase the rigorousness of the buildings construction rules. For this purpose, it is necessary to use mechanisms for monitoring in real-time to make possible the correct analysis of the quality of indoor air to ensure a healthy environment in at least spaces of public use. In most cases, simple interventions provided by home-owners and building operators can produce substantial positive impacts on IAQ such as the avoidance of smoking indoors and the use of natural ventilation are essential behaviours that should be taught to children through educational programs that address the IAQ [5].

Increase the IAQ is critical as people typically spend more than 90% of their time in indoor environments. Associations of higher indoor carbon dioxide (CO_2) concentrations with impaired work performance, increased health issues symptoms and poorer perceived air quality are well documented, and there is also an evident correlation between high levels of indoor CO_2 and high concentrations of other indoor air pollutants that are influenced by rates of outdoor-air ventilation [6]. On the one hand, when CO_2 level reaches 7–10%, a person will lose consciousness within a few minutes and may be at risk of death. On the other hand, a low concentration of CO_2 is harmless to humans; it can still cause dizziness and sleepiness leading to poor work performance [7]. These are reasons enough to monitor CO_2 and to provide notifications in real-time to improve occupational health and provide a safe and healthy indoor living environment. The concentrations of CO_2, the main greenhouse gas, are steadily increasing to 400 ppm, reaching new records every year since they began to be produced in 1984 [8].

The concept of the "smart city" has recently been introduced as a strategic device to encompass modern urban production 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 [9]. Nowadays, cities face interesting challenges and problems to meet socio-economic development and quality of life objectives and the concept of "smart cities" correspond to answer to these challenges [10]. The smart city is directly related to an emerging strategy to mitigate the problems generated by the urban population growth and rapid urbanisation [11]. The most relevant issue in smart cities is the non interoperability of heterogeneous Technologies. The Internet of Things (IoT) can provide interoperability to build a unified urban-scale ICT platform for smart cities [12]. The smart city implementation will cause impacts at distinct levels on science, technology, competitiveness and society, but also will cause ethical issues. The smart city needs to provide access to accurate information, as it becomes crucial when such information is available at a fine spatial scale where individuals can be identified [13]. IoT has a relevant potential for creating new real-life applications and services for the smart city context [14].

This paper presents a solution for CO_2 real-time monitoring based on IoT architecture. To create a low-cost system, only one type of indoor air pollutant was chosen. CO_2 was selected since it is easy to measure and it is produced in quantity (by people and combustion equipment). Thus, it can be used as an indicator of other pollutants, and therefore of the IAQ in general. The solution is composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. The *iAirCO$_2$* is based on open-source technologies and is a totality Wi-Fi system, with several advantages compared to existing systems, such as its modularity, scalability, low-cost and easy installation. The data is uploaded to a SQL SERVER database using. NET Web Services and can be accessed using a smartphone application or the Web portal. This system is based on an ESP8266 microcontroller with built-in Wi-Fi communication technology as communication and processing unit and incorporates a CO_2 sensor as sensing unit.

The paper is structured as follows: besides de introduction (Section 1), Section 2 presents the related work and Section 3 is concerned to the methods and materials used in the implementation of the sensor system; Section 4 demonstrates the system operation and experimental results, and the conclusion is presented in Section 5.

Related work

Various IAQ monitoring solutions are available in the literature and this section presents some of the related work.

A battery-free sensor that is capable to monitor IAQ in real-time that consists of three main components: an entirely passive ultra-high frequency (UHF) smart tag for communication with a UHF radio frequency identification (RFID) reader, a smart sensing module with ultra-low power sensors and a microcontroller unit (MCU), and an RF energy harvester is proposed by [15].

Several IoT architectures for IAQ monitoring that incorporate open-source technologies for processing and data transmission and microsensors for data acquisition, but also allows access to data collected from different sites simultaneously through Web access and/or through mobile applications in real-time, are proposed by [16–22].

Ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, CO_2, VOC, temperature and humidity monitoring system is proposed by [16]. It incorporates a smoothing algorithm to prevent from temporary sensor errors, and an aggregation algorithm to reduce the network traffic and power consumption. The prototype sensor module is based on the Raspberry Pi. It is not a low-cost solution for IAQ regarding the components costs.

A Wireless Sensor Network (WSN) for IAQ supervision developed using Arduino, XBee modules and microsensors (temperature, humidity, carbon monoxide, CO_2 and luminosity), for storage and availability of monitoring data in real-time using an Android Application and a Web portal is proposed by [17, 18]. The solution is composed by one gateway and several sensors nodes. The gateway receives the data from the sensor nodes using ZigBee protocol, and it uses Ethernet and Web Services for data communication for enhanced occupational health. Its purpose is reducing the burden of symptoms and diseases related to sick buildings. However, this solution has a complex installation architecture regarding the nodes and coordinators configuration.

A complete wireless solution for IAQ monitoring based on IoT architecture composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting is proposed by [19]. This solution is based on open-source technologies, and the data collected by the system is stored in a cloud IoT analytics platform named Thingspeak. Although, this solution does not provide an integrated management system for building supervision, as the Web portal is based on the ThingSpeak analytics service. The *iAirCO₂* provides an integrated Web portal for building supervision which leads to a more quick intervention on the building to increase the IAQ in real-time.

A simplified ZigBee WSN system for IAQ monitoring applications based on the Arduino platform which incorporates low-cost CO_2, VOC, and temperature and humidity sensors is presented by [20]. However, similar to the previous solution [19], this system based on the Arduino platform doesn't provide any mobile computing solution for IAQ evaluation neither analytics.

An IAQ supervision system for AAL is proposed by [21]. This solution proposes a hybrid IoT/WSN architecture approach for real-time monitoring of temperature, humidity, carbon monoxide, CO_2 and luminosity. The solution is based on open-source technologies such as Arduino platform and ZigBee. The proposed gateway is wirelessly connected to the Internet using the ESP8266 module for data communication. However, it is an expensive and time-consuming solution to install and configure, and it costs a significant amount of money than *iAirCO2*. The *iAirCO2* provides several advantages in scalability and in-home installation because it is only necessary to configure the Wi-Fi connection and it is not necessary to configure the sensor nodes and coordinators.

The iDust is a real-time particulate matter exposure monitoring system and decision-making tool for enhanced healthcare based on an IoT architecture. It was developed using open-source technologies and low-cost sensors. It provides a Web portal for data consulting and alerts that can be used by the building manager to plan interventions for enhanced IAQ [22]. Despite the advantages presented in the iDust, this system does not monitor CO_2 levels, which is assumed as the most significant parameter to be collected for IAQ assessment.

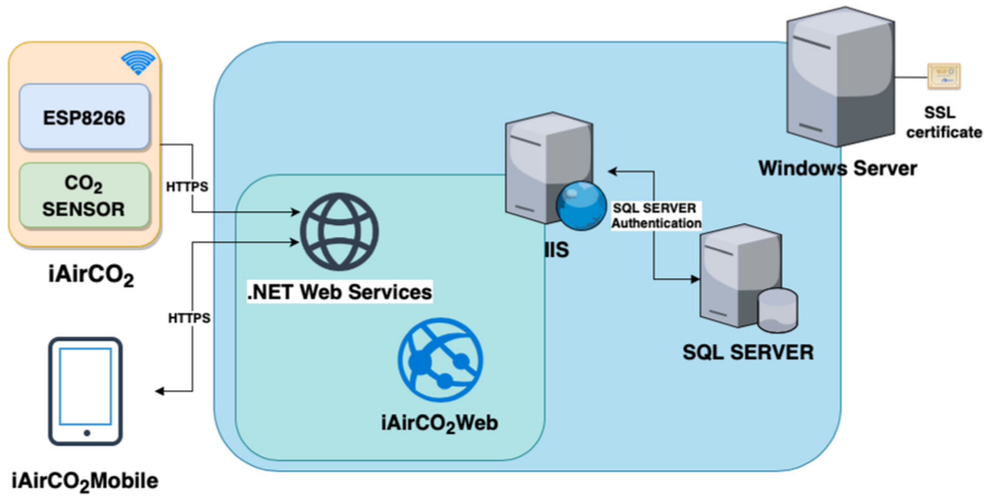
IAQ monitoring is a significant requirement for global health. Therefore, the development of low-cost and open-source monitoring systems for IAQ supervision is a trending topic. Due to the quality and relevant contribution of several existing solutions [23–27], a summarised comparison review is presented in Table 1.The excessive levels of CO_2 inside classrooms is a problem known and studied for several years [25, 28–31]. Through the use of real-time monitoring and availability of data, occupational health risk situations can be

Table 1 Summary of similar researches on IoT platform for real-time IAQ monitoring

	MCU	Sensors	Architecture	Low-Cost	Open-Source	Connectivity	Data Access	Easy Installation
Wang, S. K et al.[27]	Arduino	Temperature, Relative Humidity, CO_2	WSN	√	√	ZigBee	Desktop	×
P. Srivatsa and A. Pandhare [23]	Raspberry Pi	CO_2	WSN/IoT	√	√	Wi-Fi	Web	×
F. Salamone et al. [24]	Arduino UNO	CO_2	WSN	√	√	ZigBee	×	×
S. Bhattacharya et al. [25]	Waspmote	CO, CO_2, PM, Temperature, Relative Humidity	WSN	×	√	ZigBee	Desktop	×
F. Salamone et al. [26]	Arduino UNO	Temperature, Relative Humidity, CO_2, Ligth, Air velocity	IoT	√	√	ZigBee / BLE	Mobile	×

MCU: microcontroller; √: apply; ×: not apply.

Fig. 1 *AirCO₂* system architecture: connection diagram and security methods used



detected and assertively intervened. The *iAirCO$_2$* system aims to provide a useful tool for management enhanced living environments of smart cities. The benefits for health, comfort and productivity of good IAQ conditions can be improved by decreasing the pollution load while the ventilation remained unchanged [32].

Materials and methods

Considering the IAQ impact on health, the authors developed a reliable, cost-effective system that can be easily configured and installed by the average user for enhanced living environments. It was selected a low-cost but very reliable CO_2 sensor and a microcontroller with native Wi-Fi support. In this section will be discussed in detail the hardware and software that make up the system as well as its construction cost.

The authors developed an utterly wireless solution using the ESP8266 module which implements the IEEE 802.11 b/g/n networking protocol. This microcontroller with built-in Wi-Fi capabilities is used both as the processing and communication unit.

The collected data is uploaded to the SQL SERVER database using. NET Web Services. This solution provides a Web portal developed in ASP.NET denominated *iAirCO$_2$Web* and a mobile application developed in SWIFT for the iOS operating system named *iAirCO$_2$Mobile* for data consulting.

The *iAirCO$_2$Web* 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 *iAirCO$_2$* prototype and to support the network requests from the *iAirCO$_2$Mobile*.

The *iAirCO$_2$Web* is directly connected to the SQL Server database using SQL Server authentication. To provide security for the Web Services used and to provide access only to authenticated clients, the requests messages are encrypted and signed using HTTPS. The Web Services are authenticated using an SSL (Secure Sockets Layer) certificate. In order to guarantee security, the server uses a valid X.509 certificate. The *iAirCO$_2$* system architecture is shown in Fig. 1.

This system consists of 2 components, an ESP8266 Thing Dev (Sparkfun) microcontroller and an MHZ-19 CO_2 sensor developed by Winsensor. Figure 2 represents the prototype developed by the authors.

A brief introduction of each component is shown below:

- ESP8266 is a Wi-Fi chip with integrated antenna switches, RF balun, power amplifier, low noise receive amplifier, filters and power management modules. It supports 802.11 b/g/n protocols, Wi-Fi 2.4 GHz, WPA/WPA2. It has an integrated low power 32-bit MCU and an integrated 10-bit ADC. It has a standby power consumption of

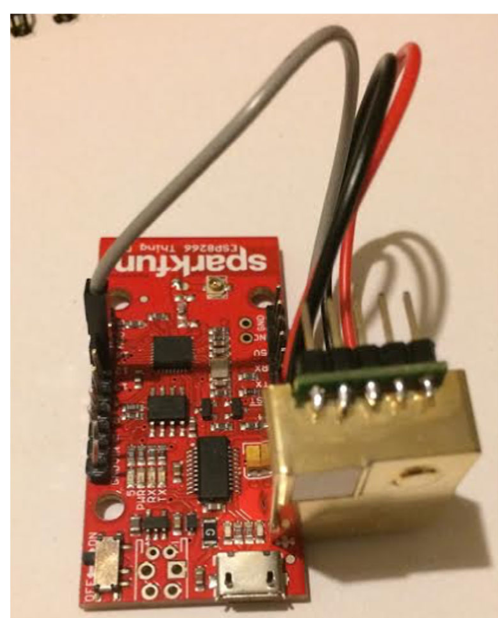


Fig. 2 *iAirCO$_2$* hardware prototype

Table 2 *iAirCO$_2$* system cost

Part	Cost
ESP8266	10.39USD
MHZ-19	22.90USD
Cables and Box	8.59USD
Total	41.88 USD

<1.0 mW (DTIM3) and it can operate at temperature range -40C ~ 125C [33].

- MH-Z19 NDIR (non-dispersive infrared) is a CO_2 sensor; it is non-oxygen dependent with a built-in temperature sensor for temperature compensation. It has a digital output and analogue voltage output. This sensor can operate at 0~50 °C temperature and 0~95% humidity. It has a measurement range of 0~2000 ppm, a lifespan higher than 5 years and an average current consumption lower than 10 mA. The MH-Z19 has a 3.3 V interface level and a PWM and UART output signal.

Competing systems are more expensive than *iAirCO$_2$* and they do not gather data in real time. This system is a suitable low-cost solution for enhanced living environments that cost around 41,88 USD. Table 2 describes the cost of the system.

The CO_2 sensor is connected to a PWM input of the ESP8266, which is the power source. The connection diagram is shown in Fig. 3. The MHZ-19 CO_2 sensor provides three connection types: analogue, PWM and I2C.

The ESP8266 Arduino Core brings support for the ESP8266 chip to the Arduino environment and supports several libraries to communicate using Wi-Fi. The Arduino Core enables the use of Arduino functions and libraries directly on ESP8266. This system is implemented using the Arduino Core with the Arduino IDE. The sensing activity is updated in every 15 s and stored in the SQL SERVER database.

The end user can configure this system. The system is by default a Wi-Fi client. If it is unable to connect to the Internet, the system will turn to hotspot mode. Then the user can connect to this Wi-Fi network and configure the credentials (Fig.4).

This functionality provides a significant advantage. As this is a turn-key solution, the system can be easily installed by the owner, that makes it more competitive and commercially interesting and attractive.

The iOS application is denominated *iAirC0$_2$Mobile* (Fig.5). This mobile application (app) was developed with SWIFT programming language in XCODE IDE, and it is compatible with iOS 9 and following versions [34]. This app has three essential features as it permits not only real-time consulting of the last data collected, receive real-time notifications to advise the user when the air quality is defective but also to configure the CO_2 levels for the alert. The end user can access the data from the mobile app after logged in. This app provides not only easy access to IAQ data in real time but also allows the user to keep the parameters history and providing a history of changes. The system helps the user to analyse in a precise and detailed way the air quality behaviour. The map view feature allows the user to check in real time the latest data collected by *iAirCO$_2$* including location.

Discussion and results

Dwelling, construction, heating, and ventilation types influence air permeability changes. It is estimated that two-thirds of commercial/services buildings with natural ventilation are extremely airtight, and the remaining third tend to be leakier.

For testing purposes, a laboratory of a Portuguese university was on-site monitored, and one *iAirCO$_2$* module was used. Fig. 6 represents the *iAirCO$_2$* installation scheme for performing the experiments carried out by the authors. The system was placed to monitoring the laboratory environment

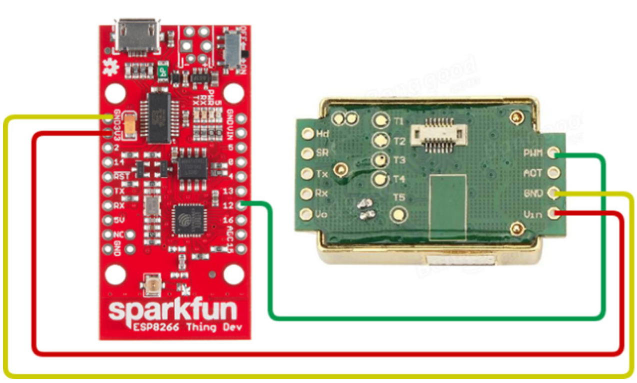


Fig. 3 *iAirCO$_2$* hardware connection diagram

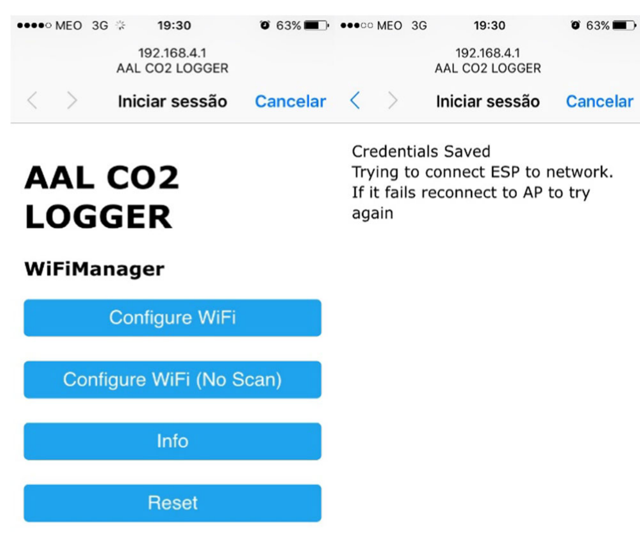


Fig. 4 *iAirCO$_2$* system network configuration process

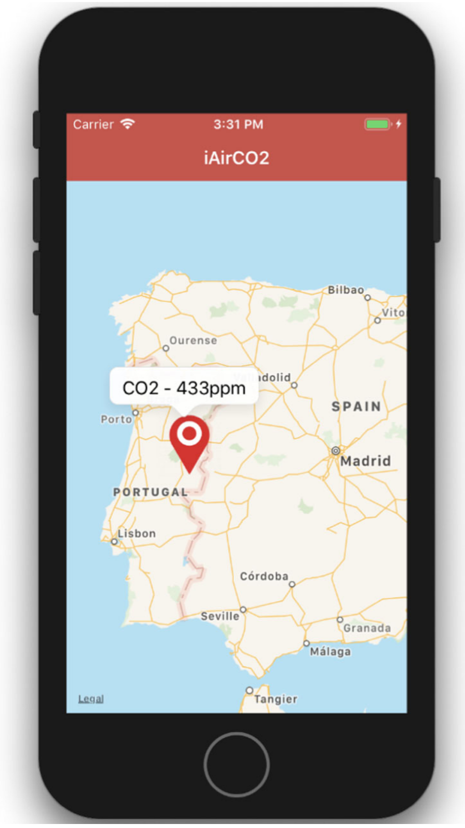


Fig. 5 *iAirCO$_2$Mobile* application map view

(identified with "X" in Fig. 6). The router was positioned in the corridor at a distance of about 13 m. As in most buildings, the space monitored is naturally ventilated, without any dedicated ventilation slots on the facades. Natural ventilation is performed through uncontrolled infiltration and door and windows opening.

The module is powered by a 230 V–5 V AC-DC 2A power supply. CO_2 data was collected for two months which showed that under certain conditions air quality values are significantly lower than those considered healthy for standards. The tests conducted show the system capability to analyse in real-time the IAQ, the potential to planning interventions to ensure safe healthy and comfortable conditions, but also to identify multiple situations or habits that affect the IAQ negatively.

The *iAirCO$_2$* data is represented in graphics and numerical formats, and are consulted using a Web browser or smartphone application. A sample of the data collected by *iAirCO$_2$* is shown in fig. 7; it represents the CO_2 sensor data measured in ppm.

The graphics displaying the air quality data provides a better perception of the monitored parameters behaviour than the numerical format. On the other hand, the Web and smartphone software also provides easy and quick access to collected data; this tool enables more precise analysis of parameters temporal evolution. Thus, the system is a powerful tool for analysing IAQ and to support decision making on possible interventions to improve productivity and a healthy indoor environment.

Abundant scientific evidence shows that CO_2 is the single most important climate-relevant greenhouse gas in Earth's atmosphere. High external charges naturally lead to higher indoor concentrations due to the contribution of internal sources (human metabolism and combustion equipment) [35, 36].

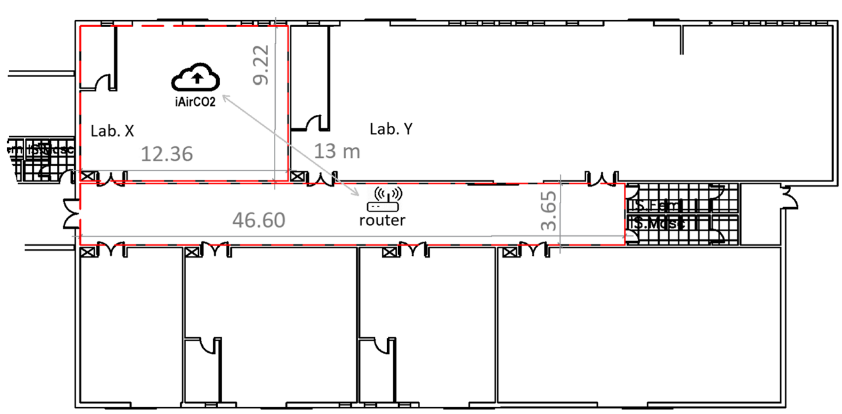
It is a need to control the concentration of CO_2 in an effective way. The first step will be to monitor it. Pollutants fluctuations records in real-time enables planning interventions for CO_2 concentration reduction.

The *iAirCO$_2$* is also equipped with a powerful alert manager that notifies the user when the air quality is poor. Based on values from literature, the maximum and minimum health quality values are predefined by the system, but the user can also change these values for specific purposes on the notification system (Fig.8).

When a value exceeds the defined threshold, the user will be notified in real time by e-mail, SMS or smartphone notification. The user can also check the notifications history using the Web portal (Fig. 9).

The data collected by the *iAirCO$_2$* system is analysed before being inserted into the database. If the data exceeds the defined thresholds, the user receives a notification. This function enables the user to act in real time ensuring indoor

Fig. 6 *iAirCO$_2$* installation scheme used in the experiments



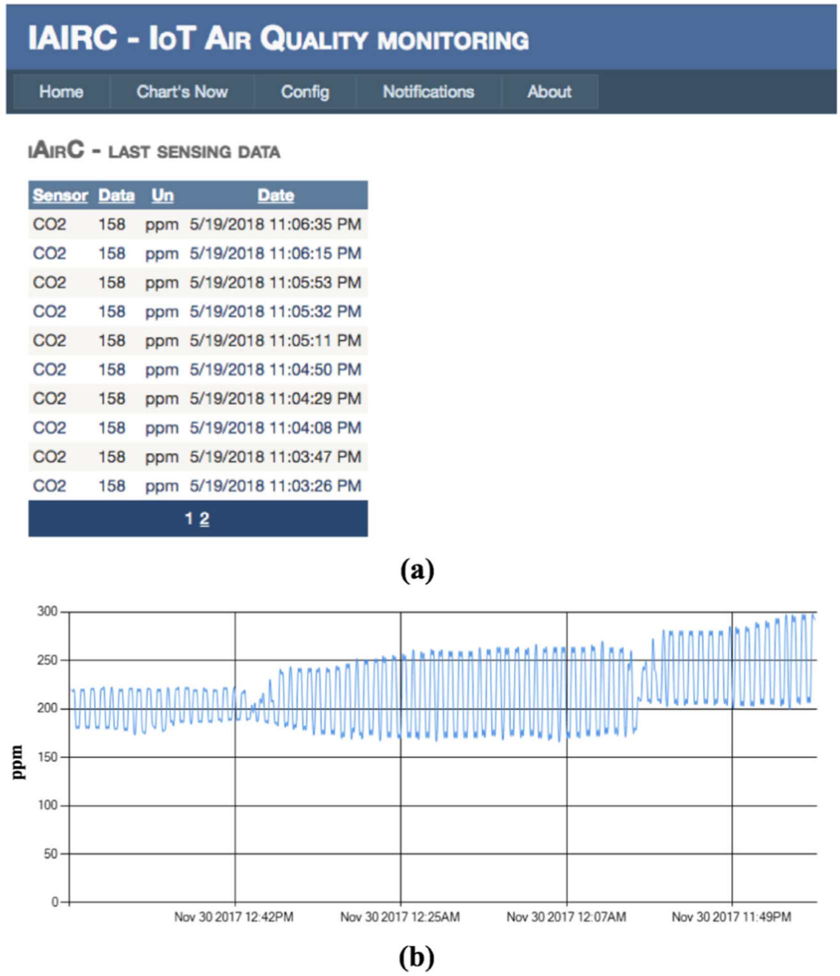


Fig. 7 Results of CO_2 concentrations monitored during the tests: (a) Web Application Table History; (b) Web Application Graphic View

ambient proper ventilation. The notification system architecture is shown in Fig. 10.

The real-time notification system provides several advantages when the purpose is achieving effective changes for enhanced living environments. In one hand, the notification messages promote behaviour changes. In fact, these messages alert the user to act in real-time providing measures to improve building IAQ. On the other hand, this real-time feature allows the building manager to recognize patters when recurrent unhealthy events are detected, and implement adjustments to prevent them to occur.

The *iAirCO₂* has advantages when compared to other systems. It is easy to install and configure due to the use of wireless technology and its small size (about 5.5 cm × 2.5 cm × 2.5 cm depth). Also, it is equipped with a smartphone and Web application to provide access to the recorded data at any time from anywhere.

The *iAirCO₂* provides entirely solution for data analysis and notifications. It is a support tool for building interventions planning. It can be shared with medical teams to help with diagnostics. Individuals spend most of the time indoors, therefore, it is necessary to monitor the CO_2 level to change habits and even to plan ventilation interventions for a healthier living environment and productivity improvement. This system makes a significant contribution compared to existing air quality monitoring systems due to its low-cost of construction, installation, modularity, scalability and easy access to monitoring data in real time through the Web application.

The *iAirCO₂* system uses the ESP8266 for both processing and Internet connectivity; it offers several advantages regarding system cost reduction, but also improves processing power because the ESP8266 has an 80 MHZ CPU, while the Arduino UNO used in several IAQ monitoring solutions has only a 16 MHZ CPU. The use of the ESP8266 has another important feature: it makes to the end user easyly to configure the Wi-Fi network to which *iAirCO₂* is connected.

The *iAirCO₂* prototype CO_2 sensor selection was carefully conducted in order to create not only a low-cost but also a reliable IAQ supervision system. Besides, an industrial level CO_2 sensors can be incorporated in the *iAirCO₂* for enhanced accuracy.

In the future, the main goal is to make technical improvements to the prototype including the development of additional relevant notifications methods to notify the user when the

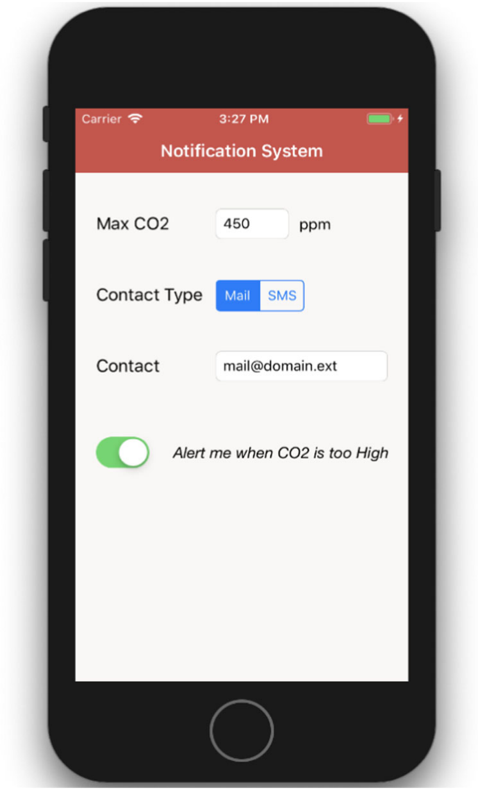


Fig. 8 Notification configuration process

quality of indoor air has serious deficiencies such as smartwatch compatibility. Improvements to the system hardware and software are planned to make it much more appropriate for specific purposes such as hospitals, schools and offices. The authors also plan to test other messaging protocols and data communication technologies, such as MQTT and LoRa respectively. It will be implemented device management protocols such as Mobile Alliance's Device Management (OMA DM) and Lightweight Machine-to-Machine (OMA LwM2M) for enhanced device management and configuration.

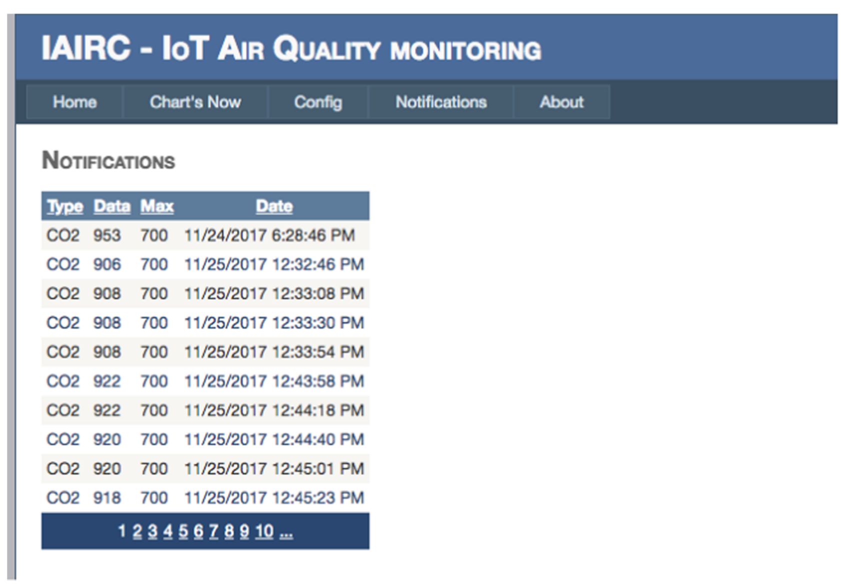
Most of IAQ monitoring solutions require professional installers. The *iAirCO*$_2$ system can be installed by a typical user; this contributes to keep the low-cost of this IoT solution. The notification system allows users to act in real time to significantly improve IAQ through the ventilation or deactivation of pollutant equipment.

Conclusion

One of the best indicators of the IAQ conditions is the CO_2 level. It is emitted in large quantities and is relatively easy to measure. CO_2 is a useful quantitative indicator of human presence in a room. Also, it can be used as an indirect indicator of high concentrations of other pollutants. Consequently, it becomes an indicator of the degradation of the IAQ as a whole. The CO_2 level data is useful in providing support to a clinical analysis performed by health professionals. We spend about 90% of our lives in indoor environments. Only IAQ monitoring makes it is possible to perceive accurately the ventilation conditions that influence the occupant's health. It provides the data to plan interventions to decrease the CO_2 levels if needed.

This paper had described an IoT architecture for CO_2 real-time monitoring composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. The results obtained are auspicious, representing a significant contribution to CO_2 monitoring systems based on IoT. In the one hand, the monitored data can be particularly valuable to offer support to a medical diagnosis by clinical professionals as the medical team might analyse the history of IAQ parameters of the ecosystem everywhere the patient lives.

Fig. 9 Notification history table



Type	Data	Max	Date
CO2	953	700	11/24/2017 6:28:46 PM
CO2	906	700	11/25/2017 12:32:46 PM
CO2	908	700	11/25/2017 12:33:08 PM
CO2	908	700	11/25/2017 12:33:30 PM
CO2	908	700	11/25/2017 12:33:54 PM
CO2	922	700	11/25/2017 12:43:58 PM
CO2	922	700	11/25/2017 12:44:18 PM
CO2	920	700	11/25/2017 12:44:40 PM
CO2	920	700	11/25/2017 12:45:01 PM
CO2	918	700	11/25/2017 12:45:23 PM

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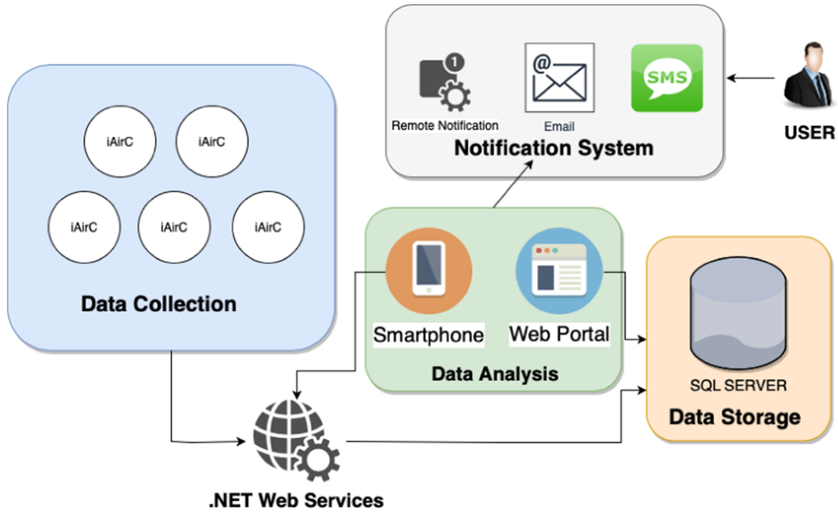

Fig. 10 *iAirCO$_2$* notifications architecture

It can be related to the records with health complications. On the other hand, it is possible to detect poor air conditions, and at a very early stage, intervention plans can be set up for enhanced occupational health.

When comparing to existing systems, it is advantageous due to the use of low-cost and open-source technologies but also due to its easy installation. The system has advantages both in installation and configuration, due to the use of wireless technology for communication. Also, it was developed to be compatible with all domestic house devices and not only for smart houses or high-tech houses.

In the future, it is expected to introduce new monitoring products to create an ecosystem for IAQ as well as the development of a platform that allows data sharing in a secure way to health professionals to support medical diagnostics. The authors are planning software and hardware improvements to adapt the system to specific cases such as hospitals, schools and industry. We believe that systems like this will contribute to enhanced living environments but also be an integral part of the daily human routine.

Compliance with Ethical Standards

Conflicts of Interest The authors declare no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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