Development of an IoT-based System for Real Time Occupational Exposure Monitoring

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***Abstract*—A large number of air pollutants have known or suspected harmful effects on human health and the environment. The objective of CAPFEIN (CAPteur de FormaldEhyde INtelligents) project funded by the French National Research Agency is to develop smart system enabling to estimate personal air pollution exposure of employers working in closed environment. In this paper, the development of an Internet of Things-based real time occupational air pollution exposure monitoring system is described. The system combines user indoor location provided by a wireless indoor positioning device with real time pollutants concentrations provided by a multi-pollutant sensing unit deployed in each indoor microenvironment. The system was tested for real time occupational exposure assessment to formaldehyde and CO_2 air pollutants. The system provides accurate and real time occupational exposure assessment. The real time and continuous monitoring capability makes it possible to better predict worker health risks and protect them from occupational overexposure to air pollution.**

Keywords-Air quality; sensor networks; Internet of Things; personal exposure; real time monitoring.

I. INTRODUCTION

The human health consequences of air pollution are considerable. The world health organization (WHO) estimates that 800 000 people per year die from the effects of air pollution [1]. In addition to posing a serious public health problem, poor indoor air quality impacts worker productivity. Human exposure was defined as the interface between humans and the environment; the impacts of air pollution on an individual's health are related to their exposure concentrations in the different locations in which they spend time. In general, occupational environment is a space which worker exposure can be assessed with difficulty. Two fundamental information are necessary to estimate personal exposure; the concentration of pollutant in different environments and individual time activity. Last, recent development in communication and information technology allows occupational exposure monitors to be ubiquitous and part of everyday activities without significantly impact personal daily function. Real time environmental sensing is the integration of different micro environmental detection sensors with data communication device into one system, in which the data acquired can be used for further processing and visualization [2][3]. Ubiquitous sensing enabled by Wireless Sensor Network (WSN) technologies offers the ability to measure, infer and understand environmental indicators. A WSN consists of autonomous sensor nodes that sense some physical phenomena in their surroundings and transmit the sensed data to a centralized unit, through single or multi-hop connectivity. WSNs have gained more significance as the foundation infrastructure for a new and interesting technology era: the Internet of Things (IoT). IoT can be represented as a main enabling factor of promising paradigm for integration of several technologies for communication solution. As defined by European Research Cluster on the Internet of Things (IERC) [4] IoT is "A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network". IoT has emerged to be attractive in many applications such as, health care, target tracking and surveillance. This paper proposes the implementation of an IoT-based real time occupational exposure monitoring system using multi-pollutant sensors nodes to measure air pollutants concentrations in different indoor microenvironments and wearable tags for real time indoor personal tracking. The remainder of this paper is organized as follows. In Section II, the related work and an overview of previous personal exposure monitors are discussed. Section III, Presents an overview about air pollution monitoring in the context of occupational exposure assessment Section IV, describes the architecture and implementation of an IoT-based real time occupational exposure monitoring system and provides experimental results. Finally, Section V reports our conclusions.

II. RELATED WORK

Several wearable systems for personal monitoring have been developed and tested [5]-[13]. WearAir is a low-cost Volatile organic compounds (VOCs) sensor embedded T-shirt indicates VOCs levels with light-emitting diodes (LEDs) [5]. However, because WearAir does not have real

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time locations recording module, the exposure measures cannot be connected to personal activity context directly. Recently, several studies and projects in literature take advantage of global positioning system (GPS) receivers as a tool for people tracking combined with air quality sensors. In Negi et al. [6], a wearable monitor with real-time and continuous personal monitoring was developed to measure concentrations of total hydrocarbons and total acids in real-time, and send the data to a cell phone using wireless communication. The same approach is used in Brown et al. [7]. Adams et al. [8] developed a particulate matter (PM) exposure monitoring system. The system includes a portable GPS receiver to track individual time and location, and air quality sensors to record temperature and PM exposure level. Rudman et al. [9] implemented "THE eGS SYSTEM" project on measuring air quality using a carbon monoxide CO sensor associated with GPS receiver. Recent project such as N-SMARTS [10] integrates CO, NO_2 and SO_2 sensors with GPS-embedded phone into a single pack, using Bluetooth as the communication support between sensors and smartphone. Area's Immediate Reading (AIR) project [11] uses real time portable GPS-air monitoring devices. Individual air pollutants exposure are measured and transmitted to the network database center. Common Sense [12] developed a portable handheld device that measured CO, NO, O_3, temperature and humidity data associated with GPS location using mobile phone chip. These data were uploaded to a database server through GPRS [12]. GPS receivers have been applied successfully in human exposure studies [6]-[12] but there are limits to the general applicability of this technology. The main problem when using GPS devices is the poor coverage of satellite signal inside buildings or near certain materials such as body panels and metals decreases its accuracy and makes it unsuitable for indoor location estimation. GPS spatial resolution is around 3 m in outdoors and 5 m inside buildings [13]. Furthermore, these wearable systems may not be used to detect all air pollutants or as a multi-pollutant monitors, due to sensor size, weight and cost constraints. These approaches are limited to a number of air pollutants where its concentrations can be measured using small integrated sensors. It is for these reasons that there is an urgent need to develop a real time occupational exposure monitoring system for the indoor environments integrating more accurate real time indoor positioning system and multi-pollutant sensors nodes.

III. AIR QUALITY MONITORING

A. *Real time occupational exposure monitoring model*

The proposed model estimates occupational exposures by combining the information on the measured concentration of pollutants, the movements of a worker in various microenvironments and the time duration a worker spent in each microenvironment. In order to protect the occupational safety and health, Time-Weighted Average Individual Exposure E_{TWAI} (Represents the allowable average individual air pollution exposure for a given period of time in relation to guidelines values duration) is updated periodically and compared with the $E_{TWAI\ Limit}$ based on guidelines values and country regulations. In case of exceeding individual exposure limits, the alert management unit triggers the appropriate action (warning, ventilation, ask worker to take a break time, etc…) to ensure personal health and risk prevention. An overview of real time occupational exposure monitoring model is shown in Figure 1, where C_{MEj} is air pollutant concentration in microenvironment j and Ej is individual exposure to air pollutant in microenvironment j.

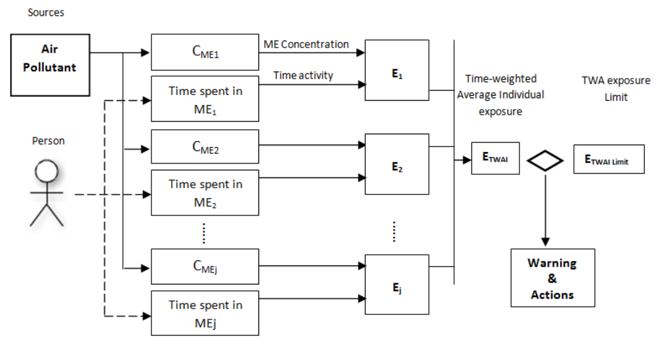


Figure 1. Conceptual model for real time occcupational exposure monitoring

B. *Formaldehyde*

The classification of formaldehyde as a known human carcinogen by IARC is based on previous studies of workers exposed to formaldehyde [14]. Additional health effects of exposure to formaldehyde include respiratory and eye irritation and contact dermatitis. Formaldehyde is a major industrial chemical for numerous industrial processes. It has three basic industrial uses: as an intermediate in the production of resins, as an intermediate in the production of industrial chemical and as a bactericide or fungicide. Formaldehyde is present in consumer and industrial products as preservatives or bactericides (e.g., shampoos, hair preparations, deodorants, cosmetics and mouthwash).

Several international safety and occupational health organizations proposed guideline and reference values of formaldehyde exposure by inhalation. Indoor guideline values are classified according to duration of exposure as shown in Table I.

TABLE I. GUIDELINE VALUES FOR FORMALDEHYDE IN INDOOR AIR

Duration	Value (µg. m^{-3})	Source
30 min	100	Australia -Japan-Norway-U.K.-WHO
2 H	50	AFSSET France
8 H	33	USA
	50	Canada
	120	Singapore-Korea
24 H	50	Poland
	60	Norway

A guideline value of (100 µg m^{-3}, 30 min) was defined as a safe concentration as regards the carcinogenic effect of formaldehyde in the human organism [15]. France discusses guideline value of the order of 50 µg m^{-3} for a 2h exposure [16]. Long-term exposure values in indoor guidelines are based on 8h and 24h time duration, guideline values between 33 µg m^{-3} and 120 µg m^{-3} are proposed for 8h exposure. In Poland and Norway guideline values of 50 µg m^{-3} and 60 µg m^{-3} are respectively proposed for 24h exposure.

C. Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is a good indicator of proper building ventilation and indoor air exchange rates. Consequently, it is measured in buildings to determine if the indoor air is adequate for humans to occupy the building. CO_2 is considered to be a potential inhalation toxicant and a simple asphyxiate [17]. This is why the concentration of CO_2 in indoor air is a criterion on which regulations for building ventilation are based. In France, the current regulatory and normative limit values usually vary from 1000 to 1500 ppm.

IV. System Design and evaluation

We introduce the architecture of an IoT-based real time occupational exposure monitoring system in Sec. A. We then discuss the implementation of the system in Sec. B. Sec. C provides experimental results.

A. System architecture

The architecture of an IoT-based real time occupational exposure monitoring is shown in Figure 2. Indirect estimates of exposure may be made by combining measurements of pollutant concentrations at fixed sites with information on personal real-time indoor coordinates. The workplace is divided into microenvironments. Each microenvironment is equipped with a multi-pollutant sensors node, for measuring air pollutants concentrations, and a positioning system (zone locator and wearable tag) to identify in real time worker's localization. Pollutants concentrations and real time personal coordinates data are remotely collected in a data center in which data are processed and made available to users. IoT is implemented as a network of interconnected "things" (Tags and multi-pollutant sensors nodes), each of which can be addressed using unique id and communicates based on standard communication protocols.

1) Wireless Sensor Network

Wireless sensor network can be divided into two parts: air pollution sensors nodes for real time indoor air pollutants concentrations and indoor positioning system for real time personal tracking.

a) Multi-pollutant sensor node: Indoor air pollutants concentrations are measured using the concept of microenvironments [18]. The workplace is decomposed into microenvironments; air pollutants concentrations are measured using a multi-pollutant sensors node placed in each homogeneous microenvironment. Each node monitor the indoor air quality and sends periodically and wirelessly a message *<Node_Id, C_{p1}, ... C_{pn}, t>* , which contains the node identifier, pollutants concentrations C_{pn} and the measured time t through the gateway to a central storage system in which data are processed.

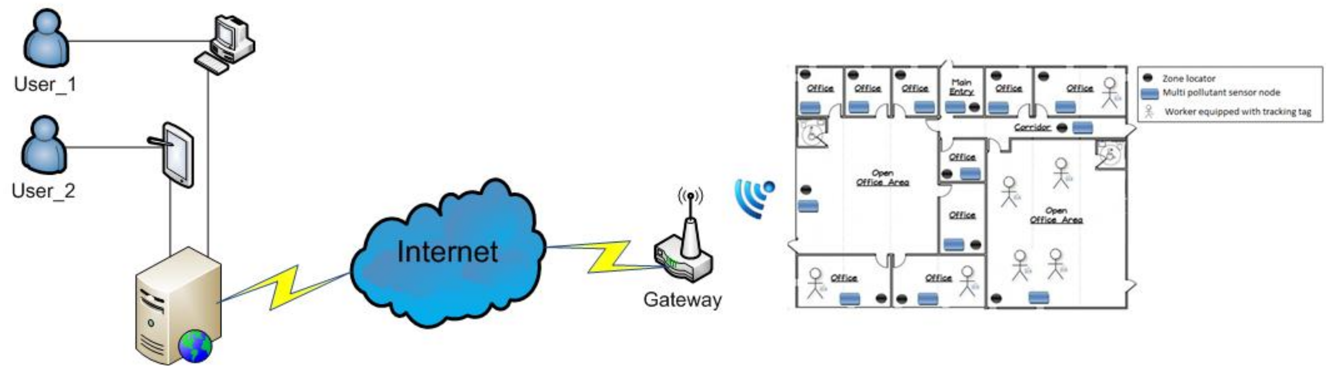
b) Indoor positioning system: To measure a personal indoor air pollution exposure, locations and time spent in each location are two critical factors. Zone locator combined with wearable tag is used as a solution to provide worker's time activity information. Each employee wears a tag with a unique Id. The tag sends periodically a message contains its Id and the location_Id provides by the zone locator *<Tag_Id, Location_Id>* through the gateway to a central system.

2) Data Center: central system

Data center is the server of whole system. It stores and processes the data. This is the central system which integrates three software components: multi-pollutant sensors node and wearable tag configuration function, data collection function and data management system. Data collection process is based on the event-driven paradigm. Data management is the process of real time displaying air pollutants concentrations and indoor positioning coordinates generated respectively by the multi-pollutant sensors nodes and wearable tags, synchronizing and combining data, storing the data into a database, and then archiving the data for later analysis. In case of exceeding individual exposure limits the central system trigger in real time the appropriate action (Warning, ventilation, ask worker to take a break time etc…) to ensure risk prevention and to avoid any personal health.

B. System implementation

In this section, a worker exposure to formaldehyde and CO2 in workplace scenario was developed and tested. In our architecture, the system design and implementation is divided into three phases: multi-pollutant sensors node implementation, indoor positioning system implementation, and the central system, includes web services for data collection and data management, implementation. As shown in Figure 3, multi-pollutant sensors node is an integrated platform for air quality sensing, which is constructed from combination of an Olimex PIC32-MAXI-WEB board [19] and microchip MRF24WG0MA IEEE 802.11 b/g Wi-Fi transceiver module [20] and environmental sensors including SHT11 temperature and relative humidity sensor [21], T6613C CO2 sensor [22] and Grove-HCHO formaldehyde sensor[23]. The Olimex PIC32-Maxi-Web is a microcontroller network development board based around a 32-bit microcontroller PIC32MX795F512L and featuring a color touch screen LCD and extension connectors for external module like Wi-Fi module and environmental sensors.



Central system

Figure 2. System architecture

A Wireless network is built by the combination of node Wi-Fi module in the Olimex PIC32 board and a sink node constructed by configuring the Wi-Fi gateway. Each node reads connected sensors values and sends periodically a message *<Node_Id, T, H, C_{CO2}, C_{HCHO}, Date, Time>* to the central system through the Wi-Fi network.

RF code wearable tag and zone locator are used for real time personal tracking. As shown in Figure 4, the IR signals used to locate people are combined with RF signals, which perform synchronization and coordination in the positioning systems and increase the system coverage area. In each located place or microenvironment, one or more room detectors (zone location) are fixed and continually transmitting a unique identification IR signal *Location_Id*. Each personal wearable tag hears the room detectors signals and transmits the microenvironment id *(Location_Id* is the same id as *Node_Id)* combined with the unique *Tag_Id* to the central indoor receiver (Gateway) using RF communication. The tracking and location information data are transmitted periodically to the central system via internet. By estimating the location of the tag taken along with the person, the indoor positioning system can locate persons in its coverage area with microenvironment accuracy.

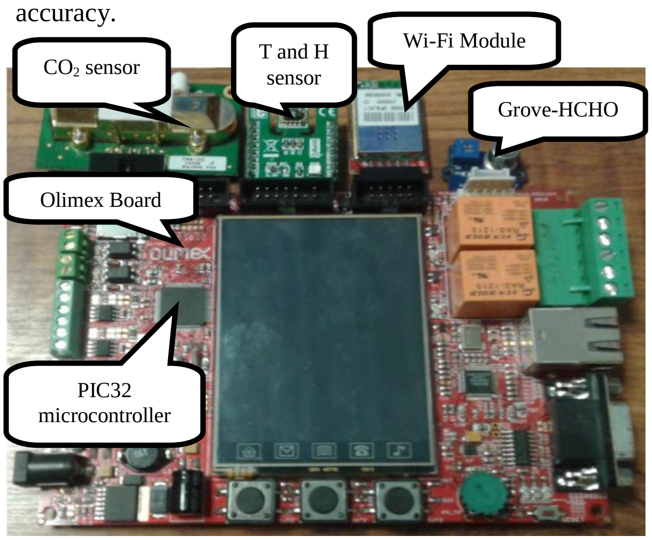


Figure 3. Multi-pollutant sensors node demonstration

Figure 4. Overview of the indoor positioning system

The central system is a back-end server that stores gathered data and provides those data for several services. The supervisor can remotely configure the measurement period of the multi-pollutant sensors node and the wearable tag. A web application includes web server and web interface, which is constructed based on PHP compliant Apache web server with MYSQL database was implemented in the central system side. Received data are stored into the MYSQL database in the following form: *<Node_Id, T, H, C_{CO2}, C_{HCHO}, Date, Time>* and *<Tag_Id, Location_Id, Date, Time>* respectively for air pollutants concentrations and indoor personal location. Personal indoor locations have been combined with real-time air pollutants concentrations using an occupational exposure assessment algorithm in order to calculate time-weighted average individual exposure $E_{TWAi.}$ Figure 5 shows the flowchart of the algorithm. Occupational exposure estimation process would be triggered by one of these two events: (1) The reception of new air pollutants measurement or (2) A change in a person's physical location. In the first case, the process detects all workers locations *<Tag_Id, Location_Id>* and combines location data with the newest air pollutants concentrations. Then, the process updates each individual air pollutant concentration $C_i(t_n)$ with the new received air pollutant concentration $C_j(t_n)$ where j is the microenvironment j where participant is located. In this case the time spent in the microenvironment is $T_i = t_m - t_{last}$ where t_m is the new air quality measurement time and t_{last} is the last event trigger time. When a new worker location is received, the process receives *<Tag_Id, new_Location_Id>* message from worker's tag and updates the individual air pollutants concentrations $C_i(t_n)$ with the last received air pollutants concentrations $C_j(t_{n-1})$. In this case, the time spent

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in the microenvironment is $T_i = t_{mo} - t_{last}$ where t_{mo} is the time when new location event is received.

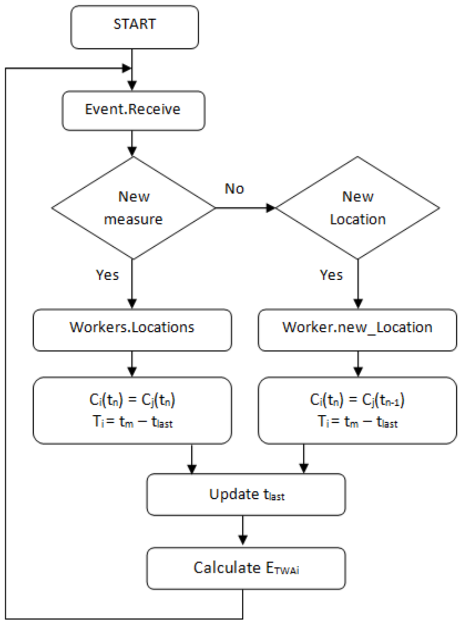


Figure 5. Flowchart of real time occupational exposure assesment process

Finally the process updates t_{last} and calculates the time-weighted average individual exposure E_{TWAi} for each worker in real time bases on mathematical model to make the link between individual air pollutant concentration C_i and exposure time duration T_i.

$$E_{TWAi} = \frac{\sum_{n=1}^{k} C_i(t_n) * T_i}{Period\ of\ exposure} \qquad (1)$$

Where k is the number of event trigger during the exposure period.

C. Results and discussion

Poor ventilation and air quality inside indoor workplaces are leading causes of serious illness and loss of productivity in these workplaces. Continuous monitoring of air pollution is therefore an essential part of health and safety that could make a significant impact. We demonstrated that the IoT-based real time occupational exposure monitoring could provide effective monitoring of personal air pollution exposure at these sites. Figure 6 and Figure 7 show the levels of formaldehyde and CO2 monitored by multi-pollutant sensors nodes in 4 microenvironments: office_1, office_2, open office area and copy room. Formaldehyde and CO2 concentrations are taken every 5 minutes between 8:00AM and 12:00AM. As shown in Figure 6 and Figure 7 the levels of formaldehyde and CO2 are very high in copy room. Insufficient ventilation and photocopier was often found to be the cause. A good air quality was detected in the open office area.

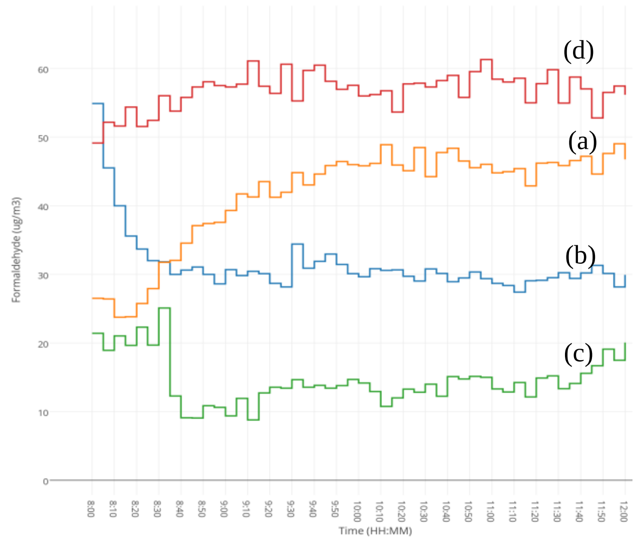


Figure 6. Formaldehyde levels in (a) office_2 (b) office_1 (c) open office area (d) copy room

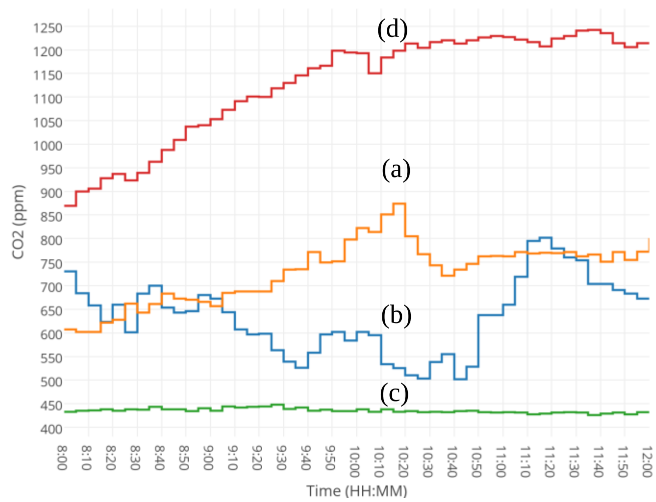
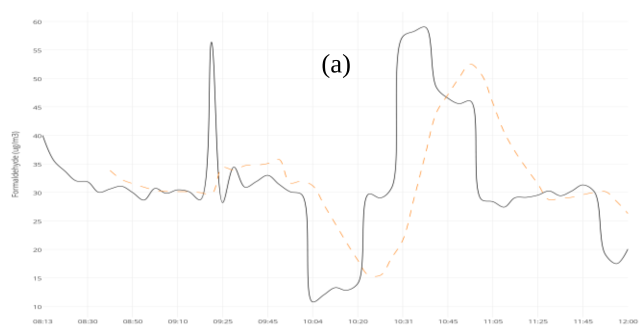


Figure 7. CO_2 levels in (a) office_2 (b) office_1 (c) open office area (d) copy room

Figure 8 shows the real time occupational exposure levels and ETWAi (with 30 min averaging time) to formaldehyde and CO2. The levels of personal formaldehyde and CO2 exposure increase sharply every time when the worker entered the copy room.



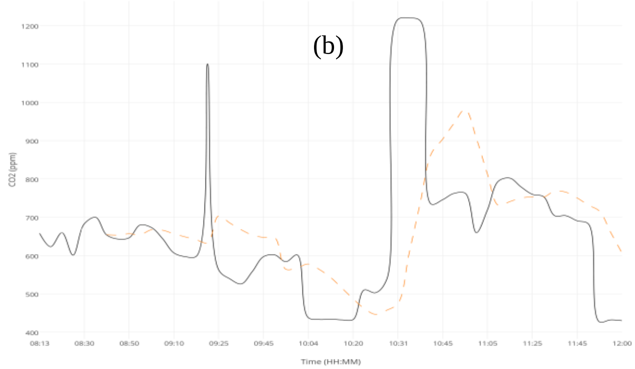


Figure 8. Personal exposure levels and E_{TWAI} to (a) formaldehyde and (b) CO_2

As shown in Figure 8, the $E_{TWAI\ Limit}$ of CO_2 fixed to 1000 ppm was exceeded a couple of times during the experiment period and alert message was sent to the occupational health and safety administration.

V. CONCLUSION

High level of air pollution can cause health problems for workers. Quantifying human exposure to air pollutants in real time is a challenging task as worker time-activity patterns effect exposure to air pollution over time and space. Also, the variation of ambient pollutants concentrations in space and time make the quantification difficult. The development of an IoT-based real time occupational exposure monitoring for real time workers health and safety monitoring will help to be able to see high level workers exposure and their relation to specific microenvironments, sources and work tasks. The measurement of time, location and concentration allows the determination of worker's time weighted average exposure. This novel indoor monitoring approach allows real time analysis of occupational air quality problems and making decision and action with regard to pollutants concentrations control policies and worker health protection. This approach can be extended to other type of pollution monitoring such as noise pollution.

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