# Indoor Air Quality Monitoring using Wireless Sensor Network

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*Abstract*—**Indoor air quality (IAQ) is a term describing the air quality of a building; especially it refers to the health and comfort of building occupants. It refers to the nature of the conditioned air that circulates throughout space/area, where we work and live in. IAQ can be affected by microbial contaminants (mold, fungus) which largely depend on temperature and humidity condition of a room, gaseous pollutants (including carbon monoxide, carbon dioxide, volatile organic compounds etc) and dust particles or aerosols. These pollutants can induce adverse health effects to building occupants. To avoid such adverse effects, an air quality monitoring system is utmost required. This paper aims to develop a wireless solution for indoor air quality monitoring. The proposed solution is to measure the environmental parameters like temperature, humidity, gaseous pollutants, aerosol/Particulate Matter to determine the environmental health of an indoor space. It also represents that in terms of Air Quality Index (AQI) and gives environmental information as input for controlling HVAC (Heating, Ventilation and Air Conditioning) system in a smart building. A toolkit has been developed to view the live air quality data of deployed regions in the form of numbers and graphs.**

***Keywords-air quality; gas sensor; aerosol monitoring; Air Quality Index***

## I. INTRODUCTION

Air pollution under the roof is a growing problem nowadays. As individual spend 90% of their time in indoors (schools, offices, institutions, commercial facilities), IAQ is the most influential factor for people health, comfort and safety. Indoor Air pollution causes the health problems known as Sick Building Syndrome (SBS) and Building Related Illness (BRI) [1]. The symptoms of SBS do not fit the pattern of any particular illness. It is very difficult to trace to any specific source, and relief from this symptoms occurs upon leaving the building. However, symptoms associated with Building Related Illness (BRI) are not relieved after leaving the building. BRI are caused by microbial contamination or specific chemical exposure that can result in allergy. The quality of indoor air depends upon a number of factors including the concentration of various gaseous and particulate pollutants. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources [2]. High temperature and humidity levels can also increase concentrations of some pollutants. Using ventilation to dilute contaminants, indoor pollutant source control and air filtration are the major methods of maintaining good IAQ in most of the buildings. Carbon monoxide (CO) sources inside a house are cooking activities, tobacco smoke or any kind of incomplete combustion. It is colorless, odorless, tasteless air pollutant, hence impossible to detect without sensory devices. It reduces the oxygen carrying capacity of the blood. This occurs because CO binds more readily to hemoglobin than does oxygen and results in the formation of Carboxyhemoglobin (COHb), which leaves less hemoglobin available for transferring oxygen around the body. EPA (Environmental Protection Agency of US) set an 8-hour primary standard for CO at 9 parts per million (ppm) [3]. Carbon dioxide ($CO_2$) is a colorless and odorless gas. It is a normal constituent of the atmosphere at 330-400 ppm. It's concentration in indoor air gives a good indication of air ventilation rate of an air conditioned building. SBS symptoms associated with $CO_2$ include headache, fatigue, eye burning and irritation in nose and respiratory tract. Particulate matter also known as aerosol is a complex mixture of extremely small particles of a number of components, including organic chemicals, smoke, soot, dust, salt, acid droplets, metals, and soil. There are two categories of particles i.e. inhalable coarse particles, such as those found near roadways and dusty industries, are larger than 2.5 micrometers and smaller or equal to 10 micrometers in diameter. Fine particles such as those found in smoke and haze, are 2.5 micrometers in diameter and smaller. The size of particles is directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller can pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious adverse health effects. PM10 can increase the number and severity of asthma attacks, cause or aggravate bronchitis and other lung diseases, and reduce the body's ability to fight infections, especially for the "sensitive populations" including children, the elderly and those suffering from asthma or bronchitis.

Rest of the paper is organized as follows: the section II represents some related works in the field of environment monitoring, section III gives an architectural view of the proposed indoor air quality monitoring system with a detailed discussion; section IV represents observations and findings; section V tells the challenges faced during project execution and section VI concludes with future work plan.

## II. Related Work

Pillai et al. [4] represents the simplest air quality monitoring module based on CAN (Controller Area Network) protocol. Sensor nodes comprise of CAN controller and CAN transceiver. Each node is interfaced with VOC (Volatile Organic Compound) sensors, continuously monitoring environment and putting sensor data into CAN bus. One motor control node is also interfaced with the same CAN bus which is turning on alarm and switching on an exhaust fan whenever sensor data crossing predefined limit. An array of polymer/CB (Carbon Black) based chemiresistors connected to TelosB motes from Crossbow Inc. by a signal conditioning circuit made a wireless e-nose for distributed air quality monitoring applications developed by De Vito et al. [5]. Wireless e-nose setup was exposed in a controlled chamber to different concentrations of three kinds of terpene in humid air. The set-up was able to identify the principal terpene which is accounted for 81.05% of total variance, but not able to find out the other two. In acetic acid spill detection test sensors response were positively correlated with increasing acetic acid flow. Chengbo Yu et al. [6] measure temperature, soil temperature, dew point, humidity and light intensity in real time by wireless sensor network working on ZigBee technology [7]. Sensor nodes deployed in greenhouse send data to sink node by multi-hop. Sink node connected with GPRS/CDMA can provide remote control and data download service. Data received by sink node periodically can be seen by running greenhouse management software. Their system had been tested in a 300 $m^2$ greenhouse in ChongQing Agriculture Demonstrate Center of China for more than one month and helped in monitoring proper growth of delicate vegetables. Indoor air quality (IAQ) monitoring system based on ZigBee wireless sensor network implemented with the TI CC2430 ZigBee chip is described by Ching-Biau Tzeng et al. [8]. In their proposed system, a temperature, relative humidity and carbon dioxide ($CO_2$) sensing module were integrated with each sensor node, which was placed in different indoor environment to monitor the IAQ parameters. The data acquisition was carried out by running a data logger program. The test result shows that not only CO2, the proposed system can be used for detecting some harmful gases too.

## III. Architecture of Indoor Air Quality Monitoring System

Figure 1 shows the architecture of the proposed monitoring system. The Indoor Air Quality monitoring system is designed and developed to obtain data of various air quality parameters; gases (CO, $CO_{2)}$, aerosols (PM2.5, PM10) along with other parameters like temperature and humidity.

### A. *Hardware Module*

Waspmote from Libelium [9] is used as the basic wireless sensing module that comprises of both processing and wireless communication module. The mote is having ATmega1281 as its microcontroller and Xbee module from Digi as the ZigBee based wireless communication module operating at 2.45 GHz.

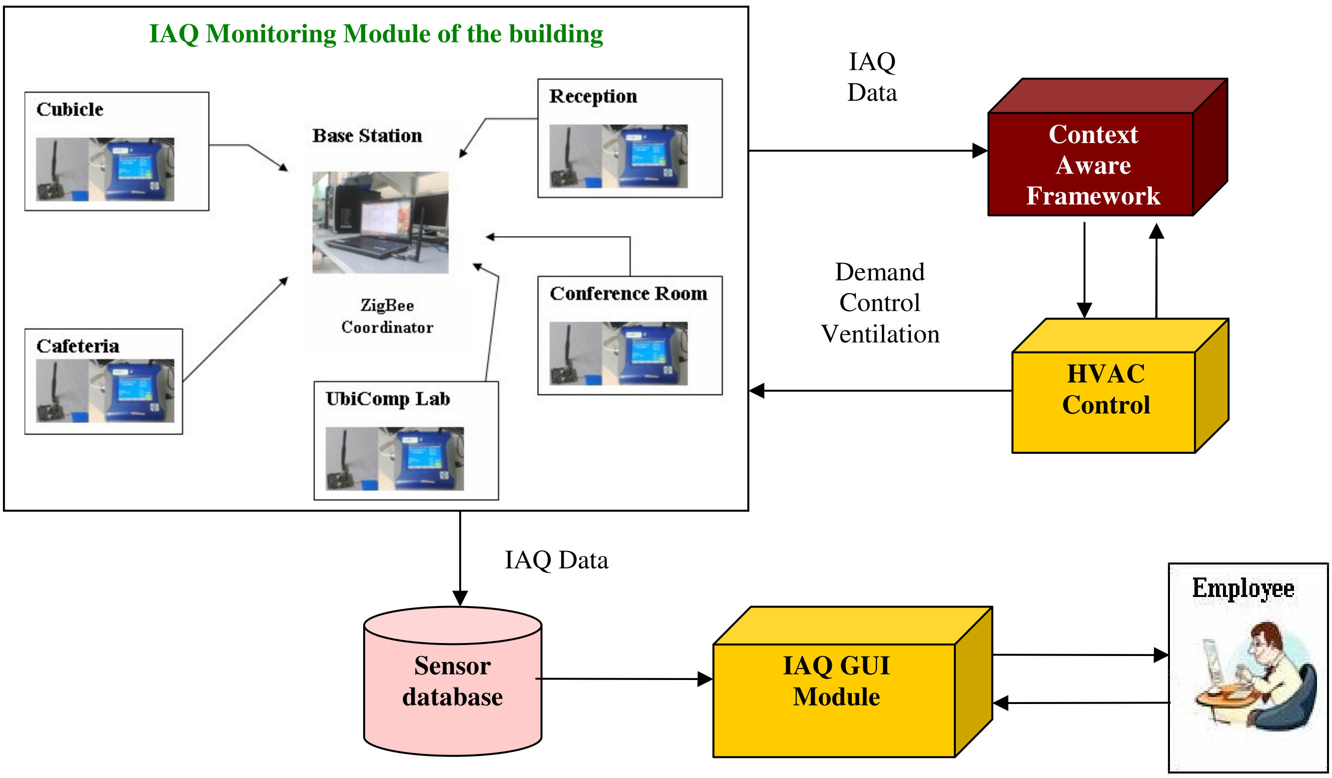


Figure 1. Architecture and Sub systems of proposed Indoor Air Quality Monitoring System

Waspmotes with gas sensor boards [10] as shown in Figure 2 have been used for indoor environment monitoring.

Libelium Waspmote with Gas Sensor Board

DUSTTRAK DRX 8533 Aerosol Monitor from TSI Inc.

Figure 2. Hardware used for Indoor Air Quality Monitoring System

Choosing of load resistance, gain of signal conditioning, configuration of gas sensor module and RF Xbee module has been done as per Libelium technical documentation [9, 10]. TGS 2442 and TGS 4161 have been used for measuring Carbon monoxide (CO) and Carbon dioxide ($CO_2$) respectively. These gas sensors are working on the principle of resistive heating. The gas sensing layer is formed of Tin-dioxide ($SnO_2$). When a metal oxide crystal such as $SnO_2$ is heated at a certain high temperature in air, oxygen is adsorbed on the crystal surface with a negative charge [11]. Then donor electrons in the crystal surface are transferred to the adsorbed oxygen, leaving positive charges in a space charge layer. Thus, surface potential is formed to make a potential barrier in electron flow resulting in increase of sensor's electrical resistance. In the presence of a deoxidizing gas, the surface density of the negatively charged oxygen decreases, so the barrier height is reduced. The reduced barrier height decreases sensor resistance. The relationship of sensor resistance to gas concentration is linear on a logarithmic scale for certain range of gas concentration (from a few ppm to thousand of ppm). DustTrak DRX Aerosol monitor Model 8533 as shown in Figure 2 from TSI Incorporated is chosen for real time dust monitoring. It can simultaneously measure aerosols of PM1.0, PM2.5, PM4.0 and PM10.0. The DUSTTRAK DRX desktop monitor is a battery operated, data-logging, light-scattering laser photometers that gives real-time aerosol mass readings [12]. It has a measurement range of 0.001 to 150 mg/m3. This aerosol monitor is connected to base station PC via LAN (Local Area Network). It is proposed to develop an interface to mote for wireless transmission of aerosol data.

### *B. Data Acquisition Module and IAQ Toolkit*

Base station or ZigBee coordinator receives data at a regular time interval from the deployed ZigBee end nodes. 5 nodes were placed in 5 different places as shown in Figure 3.

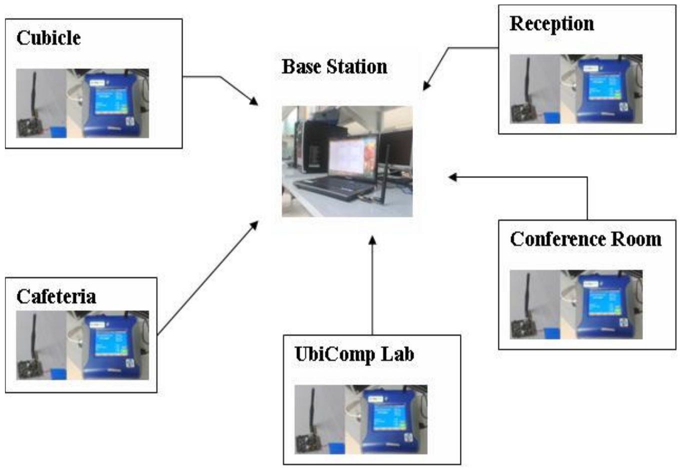


Figure 3. Star network formed by wsn nodes and placement of aerosol monitors

Each location is mapped to mote's MAC id. Data acquisition module is built using JAVA, which receives data from serial port and parse the data packet. A GUI is developed to show live data coming from motes of each location at every one-minute interval and parameter trend is shown in graph as given in Figure 4.

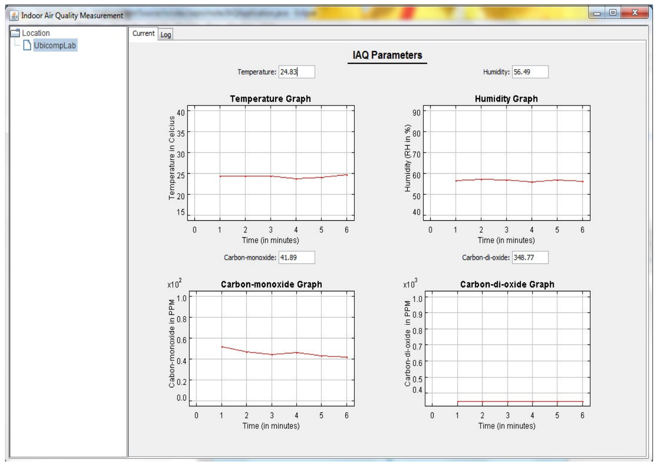


Figure 4. Screenshot of mote GUI showing live IAQ data

Options are given to user to see historical data of each place in form of graph with mean, max and average value of each parameter. Aerosol monitors are kept at remote locations as shown in Figure 3. Users can observe real time aerosol data from a remote place via aerosol module of IAQ toolkit. These dust monitors are directly connected to host PC via LAN. Client PC can talk to aerosol monitor via TCP/IP by a set of predefined commands. Figure 5 is showing the screen shot of the aerosol GUI through which user can operate the machine remotely. Open source Java swing component library SteelSeries [13] is extensively used to show live aerosol data.

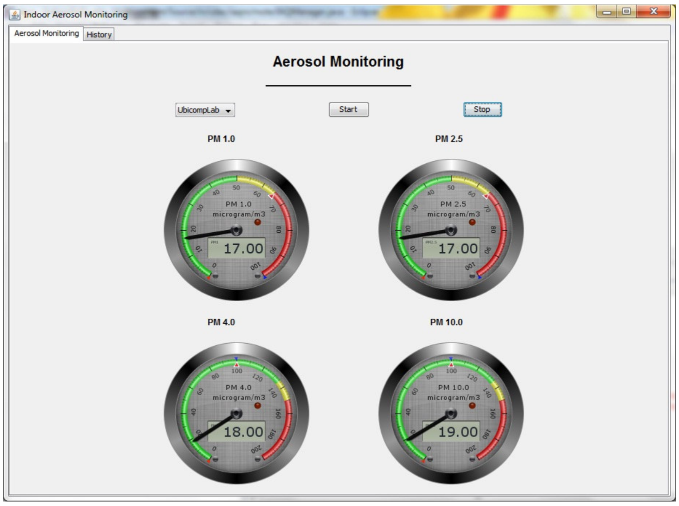


Figure 5. Screenshot of Aerosol GUI showing live aerosol data

Along with sensor information, Air Quality Index (AQI) is also calculated of an indoor place. AQI is a number used by government agencies to characterize the quality of the air at a given location. Computing the AQI requires an air pollutant concentration from a monitor or model. The function used to convert air pollutant concentration to AQI varies by pollutant to pollutant, and is different in different countries [14]. Air quality index values are divided into ranges, and each range is assigned with a descriptor and a color code. Standardized public health advisories are associated with each AQI range [15]. Calculation of AQI has been done as per (1) given by EPA (US Environmental Protection Agency) [15]. It gives an overall idea about the condition of air of a certain place.

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} (C_P - BP_{Lo}) + I_{Lo} \qquad (1)$$

Where $I_P$ = the index for pollutant p
$C_p$ = the round concentration of pollutant p
$BP_{Hi}$ = the breakpoint that is greater than or equal to $C_p$
$BP_{Lo}$ = the breakpoint that is lesser than or equal to $C_p$
$I_{Hi}$ = the AQI value corresponding to $BP_{Hi}$
$I_{Lo}$ = the AQI value corresponding to $BP_{Lo}$

As per EPA, the AQI is divided into six levels of health concerns [15] as described in Figure 6.

| Air Quality Index (AQI) Values | Levels of Health Concern | Colors |
|---|---|---|
| *When the AQI is in this range:* | *...air quality conditions are:* | *...as symbolized by this color:* |
| 0 to 50 | Good | Green |
| 51 to 100 | Moderate | Yellow |
| 101 to 150 | Unhealthy for Sensitive Groups | Orange |
| 151 to 200 | Unhealthy | Red |
| 201 to 300 | Very Unhealthy | Purple |
| 301 to 500 | Hazardous | Maroon |

Figure 6. Color Code and Descriptor of AQI as per EPA

The purpose of AQI is to make users understand what effect it can have on habitat's health. 24 hours average of PM2.5, 24 hours average of PM10 and 8-hour mean of CO have been taken into consideration. Among AQIs of these three parameters the maximum one will be the Air Quality index of that location. AQI along with responsible pollutant, date and time of measurement and location must be mentioned in the AQI report as per EPA. It has been implemented as shown in Figure 7.

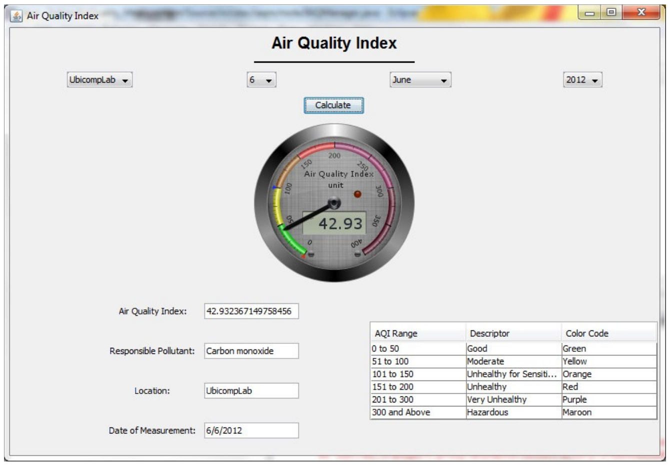


Figure 7. Screenshot of AQI module showing Air Quality Index Report

### *C. Demand Control Ventilation for Building HVAC System*

For similar day-to-day activities, people exhale $CO_2$ at a predictable rate depending on age and activity level. As a result, $CO_2$ concentration can be used as a good indication of human occupancy in a closed building. Occupants will not only produce $CO_2$, they will also generate odor, sweat, bio effluents etc that in turn will make poor IAQ. Lack of fresh air can make building occupants uncomfortable, drowsy even sick. Building codes specify that a minimum amount of fresh air from outside must be brought in to ensure a good IAQ. To comply with, often ventilation system operates at a fixed rate e.g. 15 cfm (cubic feet per minute) per person based on assumed occupancy. Sometimes much more fresh air brought inside than what is necessary. This air must be conditioned, result in higher energy consumption. In humid climates, excess ventilation can result in uncomfortable IAQ and can increase fungal growth [16]. To avoid the problem of over or under ventilation, HVAC system can use Demand Control Ventilation (DCV) technique as per occupancy based on $CO_2$ concentration. To provide adequate ventilation for an acceptable indoor air quality, ASHRAE standard 62-2001 [17] requires that the outdoor air ventilation rate should be based on the occupancy of indoor space. Ventilation rate should be modulated over the base rate when 700 ppm inside/outside $CO_2$ concentration differential exists. This is done to maintain target cfm/person ventilation rates based on actual human occupancy [18]. $CO_2$ based DCV does not affect the capability of building ventilation system; it just controls the operation in tune with occupancy and thus save energy. In literature [18], achievable energy saving using DCV is estimated from \$0.05 to \$1 per square foot annually. The highest pay back is expected in highly dense spaces where degree of occupancy is variable such as conference halls, meeting rooms, shopping malls, auditoriums etc. Here we propose a similar technique for IAQ control. Depending upon actual occupancy ($CO_2$ concentration), ventilation rate will be modulated to maintain IAQ and comfort level of the occupants. Developing such control algorithm is our future work plan.

### *D. Context Aware Framework*

Context Aware Framework [19] (CAF) is ontology based middleware developed as a part of our Ubiquitous Computing project. It works as a generic middleware between the sensors and applications. Sensor provides sensor information about entity (person, place, object etc) and makes it available in CAF. Applications can subscribe for interested context / environmental parameter and get notified whenever there is any change in subscribed context. Applications and sensors are connected to each other through CAF in a loosely coupled way. CAF is used in IAQ monitoring to collect the sensor data and make it available for various applications. DCV, which is a HVAC control application, runs as a service for smart home. DCV can subscribe to CAF for any change in IAQ parameters. WSN motes and aerosol monitors send IAQ data of each location to the base station, which is connected to a computer. IAQ data is published to CAF in XML format using Publish API. Rules for AQI can be defined in the CAF to know the current state of IAQ and actions to be taken if any. A sample set of rules added in the Context Rule base for Air Quality Index are listed in the Table 1.

TABLE I. CONTEXT RULES FOR AIR QUALITY INDEX

| AQI_Low | AQI_High | State | Action |
|---|---|---|---|
| 0 | 50 | Good | DCV based on occupancy |
| 51 | 100 | Moderate | -- do -- |
| 101 | 150 | Unhealthy for sensitive group | Increase ventilation rate, send sms |
| 151 | 200 | Unhealthy | Maximum ventilation rate, send sms & e-mail |
| 201 | 300 | Very Unhealthy | Send alarm to all occupants to leave the place immediately |
| 301 | 500 | Hazardous | -- do -- |

Trigger points can be set to send alerts to HVAC control applications. If occupants wish to get personalized alerts, they can make use of SMS and Email services that are built along with the Context Aware Framework

## IV. OBSERVATIONS AND FINDINGS

Experiments were performed to test the sensitivity of gas sensors. Two motes along with gas sensor boards were covered with a bell-shaped glass vessel and parameters like CO, $CO_2$ were observed for some time. Then a candle was burnt in the covered place by the vessel avoiding outside air contact. Due to lack of oxygen, flame of the candle died down within 2-3 minutes. Mostly CO, smoke, soot and water vapour was formed. A sudden rise in concentration of CO was observed as shown in Figure 8. After some time when it is diluted to air, CO concentration came down to previous state.

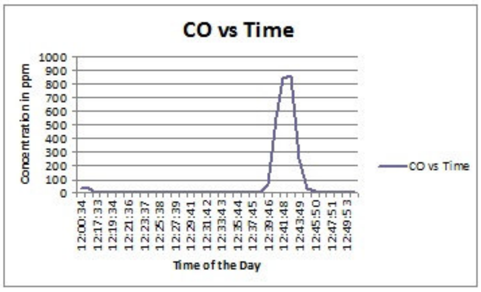


Figure 8. Rise in CO concentration due to candle burning

A field trial had been done by putting both TGS2442 (CO) and TGS4161 ($CO_2$) in a domestic environment. Initially motes with sensor boards were kept in a non-air conditioned room from noon 13'O clock to evening 17:30. Then the same was exposed to open air on the roof. Slight decrease in concentration was found for both gases. $CO_2$ concentration vs. Time of measurement graph is plotted as shown in Figure 9.

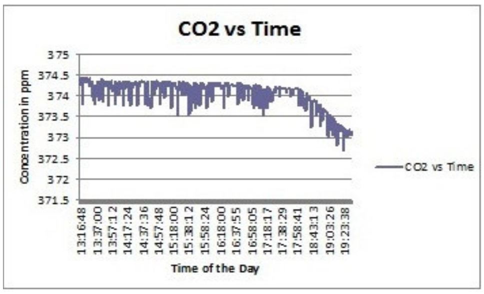


Figure 9. Without A/C and open-air measurement of $CO_2$ concentration

Rise in concentration of CO observed in kitchen during cooking time is also plotted in graph as shown in Figure 10.

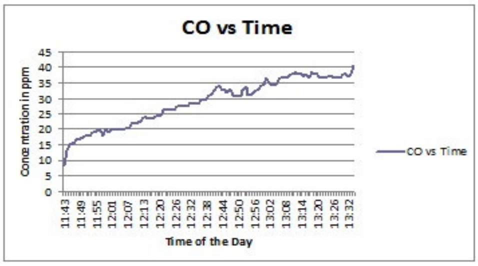


Figure 10. CO concentration increases in kitchen during cooking time

## V. CHALLENGES FACED

Metal oxide sensors like TGS4161 and TGS 2442 are based on the principle of resistive heating. They consume a lot of energy from the battery of wireless mote, which is detrimental to network lifetime. Motes are to be put in sleep mode to save the battery life. The effect of temperature and humidity are to be taken into consideration while measuring various gas concentrations. Each gas sensor is unique in behavior although the gas sensed is same. Therefore, it becomes essential to calibrate every sensor before interfacing the same to the mote. Calibration of sensor is to be carried out in laboratory by exposing the sensors into various concentration of the gas with a fixed temperature (25$^{o}$C) and humidity (50% RH) condition [20].

## VI. CONCLUSIONS

Commercially available WSN motes, gas sensors and dust monitors were used for air quality monitoring in real time. A sensor data acquisition module and a toolkit were developed in Java. It collects the raw sensor data, parse, extract the IAQ information and save them in sensor database. IAQ parameters are published in Context Aware Framework so that HVAC control application can get the information by subscribing to interested IAQ parameters. Air Quality Index was calculated to know the health impact of air pollution on the habitat. Experiments were carried out by using the developed indoor air quality monitoring system under different environmental conditions. The system behaved as per the actual situation and collected enough amounts of real time air quality data. In order to maintain good indoor air quality index, we aim to develop a DCV system for smart building in which control algorithm for HVAC will keep air pollutants in limit. It is expected to increase occupant's comfort level with energy savings.

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