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A Cost-Effective Wireless Sensor Network System for Indoor Air Quality Monitoring Applications

Sherin Abraham, Xinrong Li*

Department of Electrical Engineering, University of North Texas, Denton, Texas, 76203, USA

Abstract

Indoor air pollution has become a serious issue affecting public health. An indoor air quality monitoring system helps in the detection and improvement of indoor air quality. The monitoring systems presently available are very expensive. In this paper, we present a low-cost indoor air quality monitoring wireless sensor network system developed using Arduino, XBee modules, and micro gas sensors. The system that we have developed is capable of collecting six air quality parameters from different locations simultaneously. We have also developed a linear least square estimation-based method for sensor calibration and measurement data conversion. The performance and usefulness of the system are demonstrated by comparing measurement results of our system and a professional-grade air quality measurement device.

Keywords: Arduino; environmental monitoring; indoor air quality; micro gas sensors; wireless sensor network.

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1. Introduction

Indoor air pollution has been consistently ranked by the US Environmental Protection Agency (EPA) and its Science Advisory Board to be among the top five environmental public health risks[1]. Average person spends an estimated 90% of their time indoors so that poor indoor air quality (IAQ) poses a substantial risk to public health. Poor air quality may cause increased short-term health problems such as fatigue and nausea as well as chronic respiratory diseases, heart disease, and lung cancer. It is estimated that annual costs and productivity losses in US is $10 to $20 billion related to sick building syndrome, which is defined to describe acute health and discomfort effects that appear to be linked to poor indoor air quality and the time spent in a building[1,2].

There are a number of factors that complicate the IAQ issue. First, most of the existing air quality measurement devices are designed for professionals. Such systems are expensive and beyond the reach of average users. Second, poor air quality is extremely difficult for human beings to feel or sense; thus, most people cannot tell whether or not indoor air quality is bad. For the same reason, most people do not realize that some of our daily activities degrade indoor air quality. On the other hand, a variety of simple and common sense measures may help prevent and solve

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* Corresponding author. Tel.: +1-940-891-6875 ; fax: +1-940-891-6881.
E-mail address: xinrong@unt.edu

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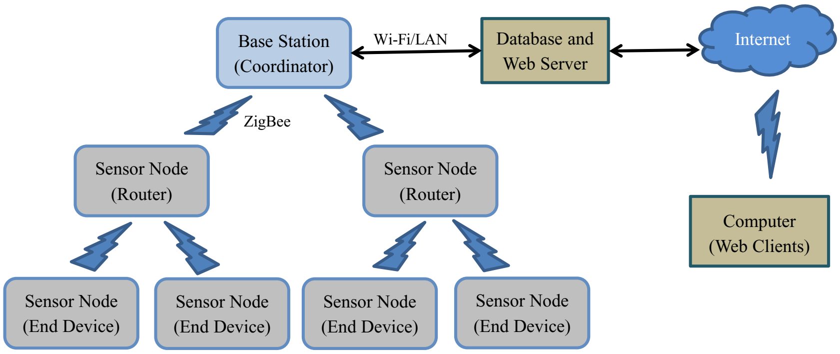

Fig. 1. Overall system architecture of wireless sensor network system for indoor air quality monitoring.

many indoor air problems. A recent study shows that realizing the current level of indoor air quality motivates people to alter their behavior and perform activities to improve air quality[3]. Third, most people think indoor air quality is better than outdoors, while studies indicate that indoor levels of pollutants may be two to five times higher than outdoors[1,3]. Excessive use of air freshener and chemical household cleaning products may instead degrade indoor air quality. Therefore, there is an imminent need for a widely-accessible IAQ monitoring system that can provide intuitive sense of air quality conditions in indoor environments.

Regular indoor air monitoring is typically confined to smoke and carbon monoxide (CO) detectors with binary detection results to trigger an alarm. Some advanced HVAC (heating, ventilation, and air conditioning) systems use carbon dioxide (CO2) sensors to control ventilation. However, neither binary CO detectors nor CO2 sensors are adequate measures of indoor air quality as a plethora of indoor air pollutants affect public health. On the other hand, the expensive professional-grade commercial air quality measurement systems are normally used by professionals for walk-through or spot test only when a problem has been reported. The divided spaces of large buildings exhibit vastly different microclimate conditions, which necessitate simultaneous distributed monitoring with many sensor nodes to accurately characterize the spatiotemporal dynamics and correlation properties of the air quality conditions throughout the building. The commercial air quality measurement systems are not designed for such purposes. Therefore, a cost-effective, widely-accessible, distributed IAQ system is needed for real-time monitoring in large buildings.

In this paper, we present a low-cost wireless IAQ sensor network system developed using Arduino, XBee modules, and micro gas sensors. The system that we have developed is capable of collecting six air quality parameters from different locations simultaneously. We have also developed a linear least square-based method for sensor calibration and measurement data conversion. The performance and usefulness of the system are demonstrated by comparing measurement results of our system and a professional-grade air quality measurement device.

The rest of the paper is organized as follows. In Section 2, the overall system architecture is described. Then, in Section 3, the design of sensor node is presented in details. A least-square estimation-based calibration method is presented in Section 4. Some sample experimental measurement results are presented in Section 5 to demonstrate the usefulness of the design. Finally, the paper is concluded with a summary in Section 6.

2. Wireless Sensor Network System Design

The overall system architecture of wireless sensor network system that we employ in this development is shown in Fig. 1, which is similar to the one we developed earlier[4]. The main components of the system include sensor node, base station, and the database and web server as shown in the figure. The base station receives measurement data from distributed sensor nodes periodically, then the data is forwarded to a database server for storage and management. A web server can be implemented to provide convenient web interface for users to access the data and to manage the sensor network system remotely[4]. In this paper, we focus only on the development of sensor node while the development details of base station, database and web server, and web interface are left for another publication.

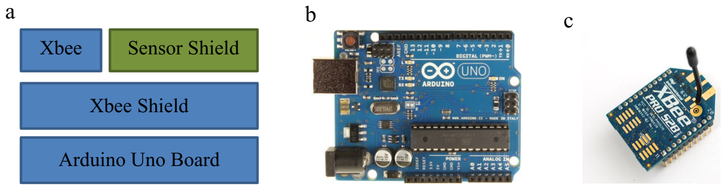

Fig. 2. (a) Functional block diagram of sensor node, (b) Arduino Uno microcontroller board, and (c) Digi XBee module.

The wireless communication and mesh networking capability of the sensor node is implemented using the Digi XBee module[7]. The XBee module implements the IEEE 802.15.4 radio and ZigBee networking protocol and it has become very popular for rapid prototyping of wireless sensing and actuation systems. The IEEE 802.15.4 standard specifies the physical and medium access control layers for low data-rate wireless personal area networks[5]. ZigBee is a low-cost, low-power, wireless mesh networking standard built upon 802.15.4[6].

The XBee module can be configured into three types of devices: coordinator, router, and end device. Coordinator has the capability to control the entire network. Router can relay messages in a tree or mesh network topologies. End device can only communicate with the coordinator or the router. There can be only one coordinator in a network; the number of router or end device is not limited. Theoretically, a coordinator device can support a network of up to 65,536 nodes, which is only limited by the 16-bit network addresses of individual nodes. The XBee modules on sensor nodes are configured as either router or end device, while the XBee module on base station is configured as coordinator. Then, all of the XBee modules within the network work together to form a mesh network topology using the ZigBee protocols.

3. Sensor Node Design

The sensor node that we developed is equipped with multiple sensors, a processing unit, and a wireless communication and mesh networking module as shown in Fig. 2. The processing unit is the Arduino Uno, an open-source microcontroller development board based on Atmega328. Wireless communication is achieved by using the XBee module as discussed in Section 2. Sensor shield is designed to integrate multiple sensors with their conditioning circuits and the shield is directly plugged into the standardized expansion headers on the Arduino board.

The microcontroller on Arduino Uno is the 16 MHz Atmega328. It belongs to the Atmel 8-bit microcontroller family with advanced RISC architecture. Its features include 32 KB flash memory with read-while-write capabilities, 1 KB EEPROM, 2 KB SRAM, 23 general purpose I/O lines (GPIO), 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts, serial programmable UART, a byte-oriented 2-wire serial interface, SPI serial port, 6-channel 10-bit A/D converter, programmable watchdog timer with internal oscillator, and five software selectable power saving modes.

Several factors like cost, power consumption, space utilization was considered for the design of the module. We have put the sensors in two separate sensor shields so as to make the sensor node compact and handy. Hence, two types of sensor shields are designed which have different sensors with necessary interfacing circuit. The Type I sensor shield has the CO2, VOC (volatile organic compounds), and the temperature and humidity sensors while the Type II sensor shield has the CO, Ozone, and the temperature and humidity sensors. The temperature and humidity sensor is placed on both types of the shields to observe if the output of gas sensors depended on the humidity and temperature variations. The sensor node with Type I sensor shield is shown in Fig. 3.

The CO2 sensor MG811 is a chemical sensor. The range of CO2 concentration it can detect is 350-10000 ppm (parts per million). It works based on the solid electrolyte cell principle. When the sensor is exposed to CO2 gas, chemical reactions occur in the cell producing an electromotive force. The surface temperature of the sensor needs to be high enough for these reactions to take place. Hence, a separate heating circuit is used to heat the sensor to the required temperature[10]. As the output voltage of the sensor is very low (100mV -600mV), it needs to be amplified in order to improve the accuracy of measurements. It also requires an external heating supply as its power requirements cannot be satisfied by the microcontroller. Therefore, it becomes essential to develop a signal conditioning and heating circuit for this sensor.

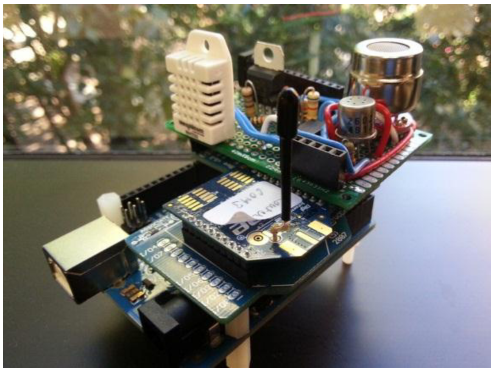

Fig. 3. Sensor node with CO2, VOC, and temperature and humidity sensors.

The VOC sensor TGS2602 is a heating semiconductor sensor. It consists of a sensing layer composed of metal oxide material such as tin dioxide or zinc dioxide. The sensing layer is formed on the alumina substrate of the sensing chip along with an integrated heater[11]. The conductivity of sensor increases when it is exposed to detectable gases. The change in conductivity produces an output signal corresponding to the gas concentration. TGS2602 is highly sensitive to low concentrations of gases like ammonia, hydrogen sulfide and toluene. Its detection range is 1-30 ppm. Low power consumption, long life, simple circuit, small size and high sensitivity to odorous gases are some of the advantages of this sensor. Since the output of sensor is in the range of 0 V to 5 V, special amplification circuitry is not required. A separate heating circuit is required for the betterment of the sensor performance.

The CO sensor MQ7 is also a heating semiconductor sensor similar to the VOC sensor[12]. It is highly sensitive to CO and has long stable life. The CO detection range of this sensor is 20-2000 ppm. The required measurement voltage source is 5 V, but the required heating voltage level needs to be alternated between a high voltage of 5 V (for 60 s) and a low voltage of 1.4 V (for 90 s). Therefore, a special switching power source needs to be designed for heating. The output signal measurement is made across a load resistor after every heating cycle of 2.5 min.

The Ozone sensor MQ131 is also a heating semiconductor sensor[13]. The sensitive material in this sensor is tin oxide. Its composition and working principle is the same as explained for the VOC sensor. It is highly sensitive to Ozone and it is also sensitive to Chlorine and Nitrogen Dioxide (NO2). The Ozone detection range of this sensor is 10-1000 ppb (parts per billion). Long life, low cost, wide range of sensitivity of Ozone is some features of this sensor. The sensor requires a measurement voltage source of less than 24 V and a heating voltage source of 5 V. To meet the heating power requirements of the sensor, a heating circuit has to be designed.

The temperature and humidity sensor RTH03 is a digital sensor and it is compact with low power consumption and long-term stability. The sensor is pre-calibrated and it can be connected directly to the digital input and output pins of a microcontroller without any additional interfacing circuitry. The output signal from RTH03 is a 40-bit data with temperature and humidity measurements in proper engineering units.

4. Least-Square Method for Sensor Data Calibration

Among the five sensors that we have integrated into sensor shields, the temperature and humidity sensor RTH03 is a digital sensor that outputs a 40-bit measurement data in proper engineering units of temperature in °C and relative humidity in percentage %. The sensor is shipped pre-calibrated. However, the other sensors, the CO2 sensor MG811, the VOC sensor TGS2602, the CO sensor MQ7, and the Ozone sensor MQ131, have the output signal as voltage level, instead of a measurement in gas concentration units. As a result, the sensors need to be calibrated.

It is very costly to acquire appropriate equipments for calibration of micro gas sensors such as special chamber for maintaining the gas concentration at fixed levels, a source for generating the gas, and a reference instrument for measuring the actual gas concentration[8]. As a result, as described in this section, we developed a simplified sensor calibration method that does not require measurements at any predefined fix levels.

Table 1. Linear conversion model parameters estimated from measurement data using the LS estimation method.

Parameters	CO2 Sensor	VOC Sensor	CO Sensor
model	Eq. (1)	Eq. (4)	Eq. (4)
a	0.3618	1.3813	0.017
b	-472.47	-1555.9	-36.14
unit of $y[n]$	ppm	ppb	ppm

To perform calibration, the sensor node is placed in a clear plastic sealed container of size 24 × 13.1 × 16.8 inches, together with the sensor probe of a professional-grade air quality measurement system, the GrayWolf Direct Sense IAQ 610[9]. The GrayWolf system is capable of detecting VOC, CO2, CO, Ozone, temperature, relative humidity and dew point. Then, the gas concentration inside the sealed container is varied by injecting the particular type of gases of interest. The collected data from the sensor under test is then calibrated against the data from the GrayWolf system using the least-square based method that is described below. Since the proposed calibration method does not depend on measurements at any predefined gas concentration levels, when compressed gas source is not available, different gas concentration conditions can be created by various approaches. For example, incomplete combustion of paper produces CO, CO2 and other volatile compounds. Perfume, brewed coffee, air freshener, and household cleansing products are among the typical sources of the VOC.

We employ the following linear conversion model for the CO2 sensor MG811 since the voltage output signal of the sensor decreases as the CO2 concentration level increases:

$$y[n] = a(5000 - v[n]) + b, \tag{1}$$

where $y[n]$ and $v[n]$ are the measurement data in ppm and mV units at the time step n, respectively, and a and b are the unknown parameters that need to be estimated. When a set of N measurement data $v[n]$, $1 \leq n \leq N$, are available, the signal model can be represented in the vector form as

$$\mathbf{y} = \mathbf{H}\theta, \tag{2}$$

where $\mathbf{y} = [y[1], y[2], \ldots, y[N]]^T$, $\theta = [a, b]^T$, and $\mathbf{H}$ is the observation matrix with the n-th row $\mathbf{h}[n] = [(5000 - v[n]), 1]$. Also, we define the N measurement data from GrayWolf system as $\mathbf{x} = [x[1], x[2], \ldots, x[N]]^T$. Then, the unknown model parameters, a and b in (1), can be derived using the linear least-square (LS) estimation method:

$$\begin{aligned}\hat{\theta} &= \arg\min_{\theta}(\mathbf{x} - \mathbf{H}\theta)^T(\mathbf{x} - \mathbf{H}\theta) \\ &= (\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{x}.\end{aligned} \tag{3}$$

Similarly, the linear conversion model for the voltage output signal of the VOC sensor TGS2602 is defined as

$$y[n] = av[n] + b, \tag{4}$$

since the voltage output signal of the sensor increases as the gas concentration level increases, and the same LS estimation method as presented above can be used to derive the unknown parameter values. The same linear model shown in (4) is used for CO sensor MQ7. The Ozone sensor MQ131 has already been integrated into the Type II sensor shield, but the sensor is yet to be properly calibrated when appropriate measurement data become available, and it is left as a future work for us.

5. Experimental Results

To calibrate the gas sensors, we first use one set of measurement data obtained using both the GrayWolf and the IAQ sensor node that we have developed to derive the linear conversion models for CO2, VOC, and CO sensors, following the method described in Section 4. The derived model parameter values are shown in Table 1, and the results after applying the derived conversion models are shown in Fig. 4 for all three gas sensors.

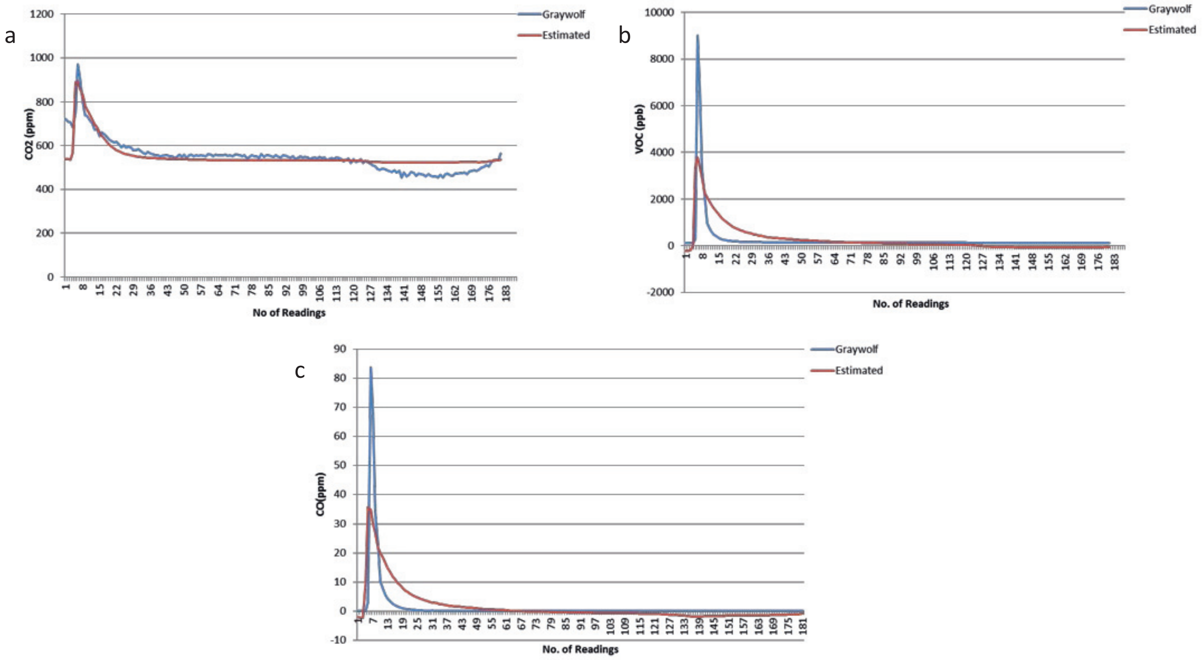

Fig. 4. The LS modeling results for (a) CO2 sensor, (b) VOC sensor, and (c) CO sensor. The derived model parameter values are shown in Table 1.

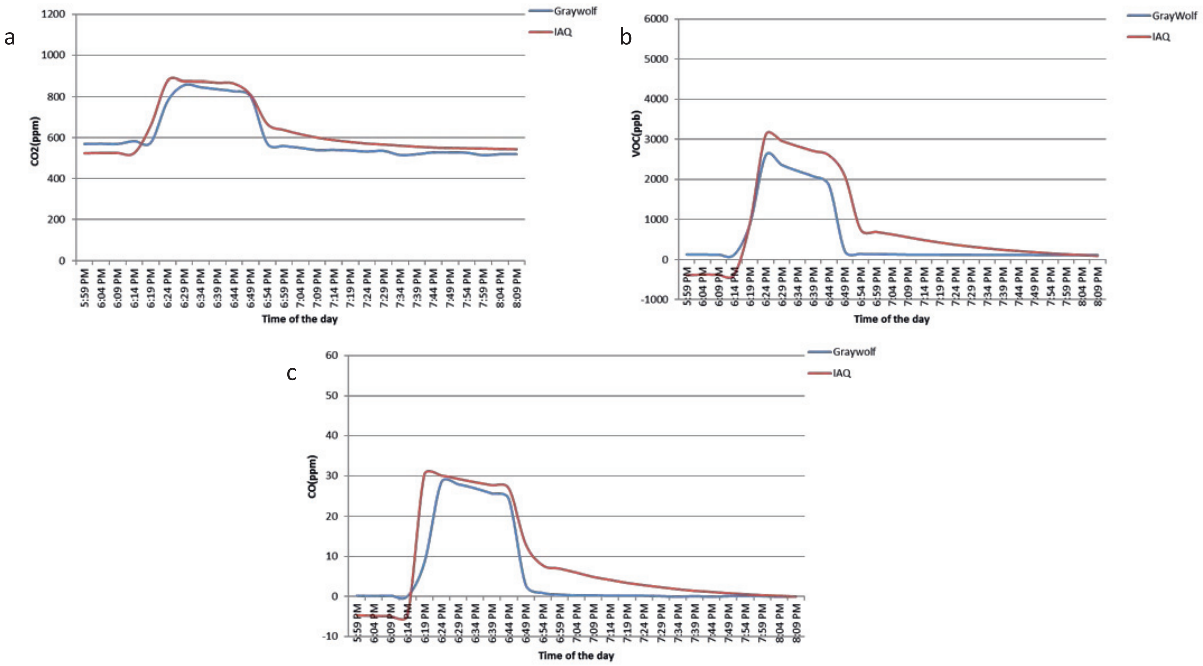

Fig. 5. Test results using the derived model parameters in Table 1 for (a) CO2 sensor, (b) VOC sensor, and (C) CO sensor.

Then, to test the usefulness of the derived conversion models, we apply the derived models to a second set of measurement data obtained using our own sensor system in a different gas concentration conditions and compare the results with the data obtained using the GrayWolf system in the same exact experiments. The comparison results are shown in Fig. 5. From the results, we can observe that the measurement results from both systems follow the same trend closely. However, further investigation is needed to arrive at more accurate calibration procedure.

It is observed that temperature readings from the sensor node module are higher and humidity readings are lower than the readings from the GrayWolf system. This is determined to be caused by the heat developed by the gas sensors on the shield[15]. It is also observed that the gas sensors are independent of slight temperature and humidity variations.

6. Summary and Conclusions

In this paper, we present a wireless sensor network system for indoor air quality monitoring applications. The system is developed using low-cost micro gas sensors that are commercially available in the market and an open-source microcontroller development platform Arduino. The mesh networking capability of the system is achieved by using a commercial off-the-shelf ZigBee module, which greatly simplifies the development of wireless sensor network system. A least-square estimation-based method is developed for calibration of micro gas sensors. Such a system is extremely useful in monitoring air quality conditions inside buildings to better understand the current status of air quality as well as to study the long-term impacts of poor air quality on public health.

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