Real-Time Indoor Carbon Dioxide Monitoring Through Cognitive Wireless Sensor Networks

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***Abstract*—In recent years, indoor air quality has become an important health and safety concern, as more energy efficient and air tight buildings are built and the existing buildings age. Clean air is essential for good health, and this is especially true when it comes to indoor air. However, many work environments lack proper detection mechanisms to identify health risks for occupants. Wireless *ad hoc* sensor networks have the potential to alleviate this problem. This paper presents a real-time cognitive wireless sensor network system for carbon dioxide monitoring at a complex indoor environment. The system aims to monitor and detect the concentration of carbon dioxide in a real-time basis and provide overall air quality alerts in a timely manner. Moreover, the system coexists with minimum interference with other systems in the monitoring area. A prototype is designed to show the enhanced real-time data transmission. Experiments are conducted to validate and support the development of the system for real-time monitoring and alerting.**

***Index Terms*—Wireless sensor networks, indoor air quality monitoring, real-time monitoring, carbon dioxide monitoring.**

I. Introduction

INDOOR Air Quality (IAQ) refers to the quality of the air within and around buildings and structures. It is an issue of great importance since it relates directly to the health and comfort of building occupants. Common issues associated with IAQ include improper or inadequately maintained heating and ventilation systems as well as contamination by construction materials (glues, fibreglass, particle boards, paints, etc.) and other chemicals. Moreover, the increase in the number of building occupants and the time spent indoors directly impact the IAQ [1]. Air quality can be expressed by the concentration of several pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), tobacco smoke, perfume, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3). Some of these pollutants can be created by indoor activities such as smoking and cooking. IAQ problems are more prevalent in indoor infrastructures such as houses, offices and schools [2]. Consequently, the development of an accurate system for IAQ monitoring is of great interest.

Manuscript received June 2, 2015; revised August 17, 2015; accepted September 1, 2015. Date of publication September 17, 2015; date of current version December 22, 2015. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada and in part by an ORF-RE Grant. The associate editor coordinating the review of this paper and approving it for publication was Dr. Santiago Marco.

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Digital Object Identifier 10.1109/JSEN.2015.2479647

Wireless Sensor Networks (WSNs) can be an ideal solution to this problem as they generally consist of inch scale and low cost nodes that can integrate sensing, data processing, packet formation as well as wireless transmission. Therefore, the potential of an easily deployed and inexpensive WSN consisting of tens to thousands of these nodes has attracted a great deal of attention. Moreover, an efficient IAQ monitoring system should integrate ad hoc principles. The monitoring units should be able to operate unattended and they can join or leave the network according to the application needs.

Another important aspect is the network coexistence. Nowadays, buildings have many wireless devices and most of them transmit in the unlicensed bands. An IAQ system should be designed in a way to minimize, or preferably not interfere at all, with any existing networks in the monitoring area. The IAQ monitoring network deployment must have a minimal impact on the existing infrastructure and be designed to operate autonomously for an extended period of time.

In this work, we present a real-time carbon dioxide (CO_2) monitoring system for a complex indoor environment. The system is implemented through a WSN. Each node in the network has two antennas and follows cognitive networking techniques to minimize the interference with other systems in the monitoring area. The routing protocol of the packets from the source towards the control room follows opportunistic routing principles [3]. Hence, the nodes can join or leave the network depending on the needs of the application while there is no pre-existing infrastructure. The system is deployed at the University of Toronto.

The major contributions of this paper are as follows:

- A prototype that monitors the carbon dioxide concentration in a room is designed. The prototype consists of two main modules: The sensor unit, which is commercially available and the radio module, which is designed within our group.
- An information processing framework is proposed. The framework outlines the main principles to detect outliers in the sensor data, form packet with minimum overhead and calibrate the sensor nodes periodically.
- A real-time monitoring system is presented. The system is evaluated through experiments at a complex indoor environment at the University of Toronto. The system successfully reports CO_2 concentration of four rooms to the system administrator on time through a Graphical User Interface (GUI) that is also developed.

The routing protocol and simulation results have already been presented in [4]. In this work, we focus on the hardware implementation and the system evaluation through experiments. We also compare the experimental and the simulation results as well as the proposed system with a system without cognitive and opportunistic principles. The proposed system performs better in terms of packet delay.

The rest of this paper is organized as follows: In Section II, the relevant related works are reviewed. Section III describes the design requirements and constraints. Section IV outlines the system architecture. Experiments and results are presented in Section V and the conclusions are brought in Section VI.

II. Related Work

WSNs are a promising solution for a number of monitoring applications [5], such as building monitoring [6] and highway bridges [7]. Environmental condition monitoring in homes have been examined in [8]. The authors proposed a framework to monitor temperature, humidity and light intensity, which is based on a combination of pervasive distributed sensing units, information system for data aggregation, and reasoning and context awareness. The reliability of the sensing information is encouraging.

Recently a number of systems have been proposed for carbon dioxide monitoring. In [9], a remote carbon dioxide concentration monitoring system is developed. The system reports geological CO_2, temperature, humidity and light intensity of the outdoor monitoring area. Similarly, in [10] an urban CO_2 monitoring system is presented. The system operates outdoor at an urban area around 100 square kilometres.

Indoor and outdoor air quality monitoring through a WSN is presented in [11]. Each node has an array of sensors and it is connected to the central monitoring unit either hardwired or wirelessly. Indoor environment can pose different challenges to a monitoring system. In [12], a real-time indoor air quality monitoring system is proposed. The system has seven sensors monitoring seven different gases. In [13], a system with aggressive energy management at the sensor level, node level, and network level is presented. The system detects Volatile Organic Compound (VOC) and CO and saves energy through context-aware adaptive sampling. A low-power ZigBee sensor network to monitor VOC pollution levels in indoor environments is proposed in [14]. The network consists of end device sensors with photoionization detectors and routers.

In this work, we proposed a real-time monitoring system for carbon dioxide through a WSN with cognitive principles. The wireless units follow a cognitive networking technique to minimize the coexistence problem. The prototypes follow a dynamic routing approach, hence, they can join or leave the network at any time. A single sensor for carbon dioxide monitoring is used. Finally, the system is compared with a system without cognitive principles.

III. Design Requirements and Constraints

In this section, the application scenario will be briefly described, along with the system requirements and the challenges that are posed.

Designing a real-time indoor monitoring system is a complex and challenging task because many factors, such as the

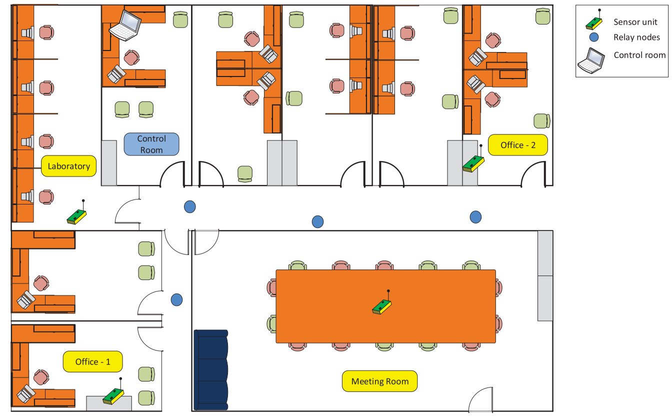


Fig. 1. An indoor CO_2 detection and monitor system deployed at the 7th floor of Bahen Centre for Information Technology at the University of Toronto. The sensor units have been deployed in four rooms: Office -1, Office -2, Laboratory and Meeting Room. The sensor units transmit the monitoring data to the control room through the relay nodes.

application scenario, monitoring target, network traffic, power consumption, overall cost, sensor coverage range, etc., have an impact on the system performance. Moreover, several performance measures, such as accuracy, packet latency, and energy consumption need to be considered. There is always a trade-off between these parameters. For instance, an accurate sensor unit might have higher energy requirements. On the other hand, an energy efficient duty cycle scheme with the nodes switching between monitor and sleep mode, might not provide sufficient and continuous monitoring of the network field.

A. Application Scenario

The design decisions can be optimized when the WSN is designed following the needs of a specific scenario. In this work, an indoor monitoring application for CO_2 in four offices is considered, as illustrated in Fig. 1.

The proposed system is deployed at a region of the 7th floor of Bahen Centre for Information Technology at the University of Toronto. We used the offices that are for researchers, visitors as well as a meeting room. All the offices and the meeting room do not have windows and are connected to the same ventilation system. During day time, each office has either one or two people working, while more people can come and stay in each room. The meeting room, can have between fourteen and eighteen people.

Many people spend most of their time every day in their offices. IAQ is very important for their health and it can also affect their performance. Generally, each person in a closed environment is a source of pollutants. An efficient IAQ monitoring system should detect any change in the air quality, alert the system administrator and trigger the necessary mechanisms, if available, such as automatic ventilation and fresh air, to improve performance and protect heath.

B. Requirements

The selection of the application can simplify the system design and optimization, but also imposes a number of requirements.

The first requirement involves the selection of the sensor type. There are three types of gas sensors: the Metal Oxide Semiconductor (MOS), the electrochemical, and the optical sensors. Each type has unique characteristics and the selection of the sensor is closely related to the overall power consumption of the system, accuracy, lifetime and cost.

The majority of the current available sensors belong to the MOS type. This is because they have fast response times and low cost along with a long lifetime. However, they have high power consumption and low sensitivity while they are sensitive to environmental changes. On the other hand, electrochemical sensors are less sensitive to environmental changes and have low power consumption, but they have higher cost and shorter lifetime. Optical sensors have long life time and low energy consumption, but their cost is significantly higher, they are more complex in order to integrate in a system and they can be damaged easily. A comprehensive study on the different types of sensors can be found in [12].

The second requirement is the selection of the number of sensors. The number is related to sensor reliability, coverage area and cost. In general, as the number of sensors increase, the system accuracy increases as well. However, the system deployment cost and the network traffic also increases. The placement of the sensors can also affect the system accuracy. The type of the air pollutant emission sources and a detailed study of the monitoring area can improve the sensor placement. Coverage optimization techniques exist in the WSNs literature, though well designed routing protocols and standards [15].

The third requirement is real-time data aggregation. The packets related to the CO_2 concentration should be delivered to the control room on time with a minimum delay. There is a maximum delay, after which the data are no longer useful. The routing protocol must be able to meet these packet delay requirements [4].

The forth requirement is the energy consumption of the sensor units. Most of the gas sensors have high power requirements. Moreover, they have initial startup period before they stabilize. They need a few minutes before they start to operate. Hence, a control scheme with multiple power on and off over time can not be considered an ideal solution. Finally, a number of other requirements such as reliable data transmission and remote control access can be an issue.

These are the minimum network requirements for the proposed system. For different monitoring applications, there might be additional and more specific requirements. The proposed infrastructure can be scaled to meet additional requirements. The sensor and the power source can be easily changed to meet the new requirements. For instance, if a solar panel replaces the battery that is used as power source and proper sensors are selected, the system can operate outdoor as well.

C. Challenges

The application scenario posses a number of challenges.

- *Wireless Network Coexistence:* Heterogeneity and coexistence are characteristics of every unlicensed band. As more and more wireless devices use the 2.4 GHz radio spectrum, the coexistence of 2.4 GHz wireless devices which operate at the same place has become a challenging topic. The system should be able to cope with issues such as spectrum availability detection, interference mitigation and spectrum sharing.
- *Dynamic Changes:* The monitoring system is deployed and should work unattended for long periods of time. Hence, it needs mechanisms to adapt successfully to a rapidly changing environment. For instance, the link between nodes might not be available due to obstacles from the environment. The system should be able to transmit the necessary packets to the destination on time.
- *Drop-and-Play Units:* The units should be able to join or leave the network at any time.

IV. System Architecture

In this section, the different modules of the introduced system are described. The proof-of-concept is achieved via prototyping, where a real-time CO_2 monitoring application is supported. Indoor air quality sensors are used and batteries power the units. The proposed system is flexible and adaptable to the needs of the monitoring environment. Although the core communication architecture remains the same, most of the system components, such as the type of the sensor or the power supply can easily be adjusted to meet any other application requirements.

A. System Framework

The system concept and the design principles were built into an application specific framework, aiming to deal with specific scientific and technological challenges. The proposed framework has the following three important units:

- *Wireless Monitoring Nodes:* Carbon dioxide sensors are combined with radio modules to form wireless monitoring nodes. The data from the sensor are passed to the radio, formed into packets and transmitted toward the control room. Each sensor node monitors the area around it continuously.
- *Relay Nodes:* A wireless ad hoc network system is composed from easy-to-use devices. The relay nodes forward any received packet toward the control room, following the designed routing protocol [4]. The protocol supports transmission of real-time sensed data from various sources. The number of the devices vary over time and nodes – either monitoring or relay – can join or leave the network any time.
- *Control Room:* The data aggregation and network maintenance takes place at the control room. All the collected data are processed and expressed in a summary form. Also, useful network information are collected and used for better network maintenance.

The system framework is shown in Fig. 2.

B. Hardware Infrastructure

The system is decomposed into the following three parts:

1) *Sensor Unit:* It senses the CO_2 concentration in the area around it. It passes all the data to the radio module.

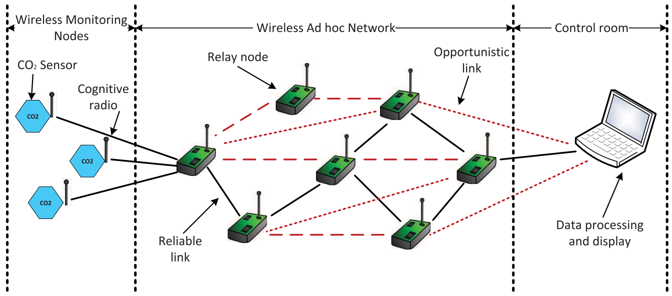


Fig. 2. System framework of indoor CO_2 monitoring system.

2) *Radio Module:* The main module of the system. It has a microcontroller for programming and two antennas for transmission. It forwards all the packets toward the control room.
   a) When the radio module is programmed only to receive and forward packets, it acts as a relay node in the system.
   b) When it is connected with the sensor unit, it is a monitoring node.
3) *Control Room:* It is the destination of all the data in the network. It is a simple radio module attached to a computer. The data processing and storage takes place at the control room.

The details of the hardware components are described in the following sections.

1) Sensor Unit: For CO_2 detection, indoor air quality sensor modules from Applied Sensor [16] are used. iAQ-2000 sensor can measure CO_2 levels. It is a sensitive, low-cost solution for detecting poor air quality in an indoor environment. The module uses micro-machined MOS gas sensor components to detect a broad range of VOCs, such as CO, CH_4 and LPG. The sensor does not report explicitly which of the substances was detected however, it correlates these levels directly with CO_2 levels in a specific range. To monitor the different gases, further sensors that are sensitive only on those gases are needed. This would increase the accuracy of the system however, it would also increase the cost and energy consumption per unit.

A change of resistance in the presence of these gases generates a signal that is translated into parts per million (ppm) CO_2 equivalent units, following the sensor specifications [16]. Also, a threshold can be defined to alert that the climate has changed when the limits are exceeded or to decrease ventilation on minimum VOC levels. Figure 3 shows an iAQ-2000 sensor unit and the specifications in Table I.

It is important to mention that the CO_2 levels can be affected from changes in the temperature and humidity of the room. In this work, a centralized ventilation system keeps the temperature and humidity in between acceptable values. In a different setup, the use of a T/RH sensor is necessary.

The sensor unit monitors CO_2 concentration in ppm, in the environment continuously. All the data from the sensor unit are passed to the radio module for initial processing, packet forming and transmission.

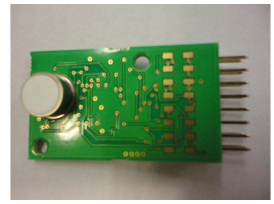


Fig. 3. iAQ-2000 sensor.

TABLE I
SPECIFICATION

Type	MOS
Substances detected	CO, CH_4, LPG
Power supply	$5V$
Power consumption	$30mA$

2) Radio Module: Radio module performs all the data exchange between different nodes. The networking technology is based upon a cognitive networking architecture which utilizes both the spectrum and networking radios opportunistically [17] to establish reliable communication in large wireless networks. Each radio module has two antennas and performs cognitive networking over three channels at 2.4 GHz [18].

The functions necessary to achieve this can be divided into two distinct levels, namely the communication and application levels. Communication between different radio modules is done at the communication level. When a node transmits or receives packets, the communication level is responsible for the successful transmission reception. The data formatting and processing is done at the application level. The application level is responsible for the basic data processing such as outlier detection.

At the communication level, the radios have been implemented using a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method. First, the transmitter waits to assemble the packet. When the packet is ready, it checks if any of the three channels is idle and available for immediate transmission. From the available channels, the best one, according to channel estimation metrics, is selected for transmitting the data. If another transmission is heard, the transmitter has to wait for a period of time for the other node to stop transmitting before listening again for an available channel.

At the application level, there is a unicast transmission that transmits any data received from the Universal Asynchronous Receiver/Transmitter (UART) to the radio. In unicast mode, radios only establish point to point transmission where the transmitter sends the data to the destination.

A radio module that receives and forwards packets is the relay node of our system. A typical relay node is shown in Fig. 4. The specification of the node, as they were carefully selected for this application, can be seen in Table II. A RapidMesh OPM15 board [19] is used as the radio module. The radio is based on the IEEE 802.15.4 standard to realize Opportunistic Mesh (OPM) dynamic networking with multi-frequency. The frequency range is $2.405 - 2.483$ GHz.

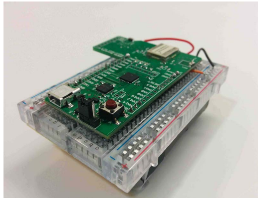
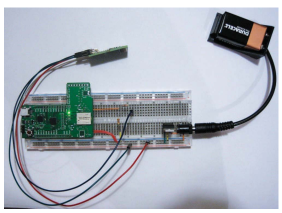


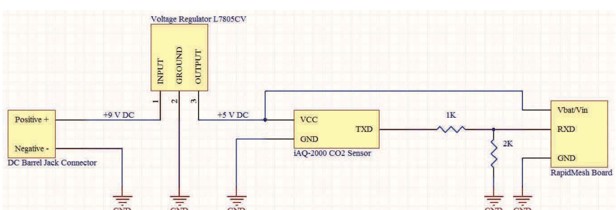
Fig. 4. OPM15 relay node.

TABLE II
SPECIFICATION

Radio range	$20m$
Frequency band	$2.4GHz$
Channels	3
Bandwidth (per channel)	$5MHz$
Transmitting power	$-25dBm$
Power supply	$3.3V$
Power cons. (Sleep)	$1uA$
Power cons. (Work)	$25mA$



(a)



(b)

Fig. 5. The indoor version of the prototype with (a) the assembly kit of the monitoring board, where a sensor unit is connected to a radio module through (b) a simple electric circuit.

OPM 15 has a microchip PIC18F26K22 programmable microcontroller. The relay nodes are powered with three AA batteries, each being 1.5V.

The integration of the sensor unit with the radio module builds the monitoring node, shown in Fig. 5. The monitoring node uses one 9V battery as the power source and hence there is a 5V voltage regulator to reduce the voltage before supplying the RapidMesh board and the iAQ-2000 sensor. Next, the output of the sensor is connected to the input of the RapidMesh board via a resistor voltage divider. The divider is to reduce the 5V output of the sensor to 3.3V for the RapidMesh board. The assembled monitoring node is shown in Fig. 5(a). The collected data are fed to the radio module, through the electronic circuit shown in Fig. 5(b). The data packets will then be transmitted toward the control room through a number of relay nodes. A preliminary version of the monitoring node was demonstrated in [20].

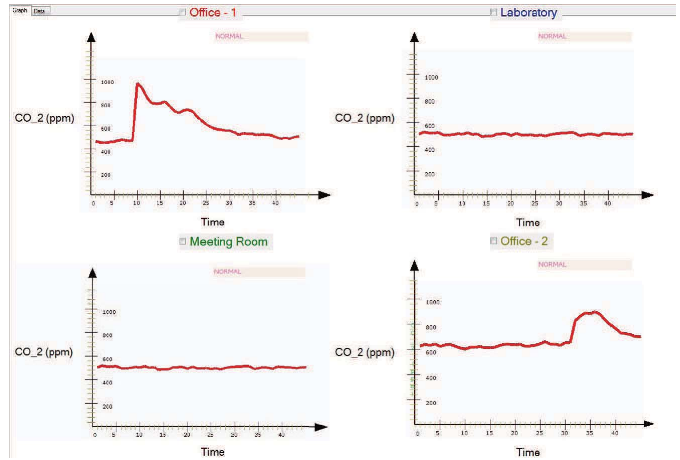


Fig. 6. Graphical User Interface (GUI) to monitor the CO_2 concentration in four different rooms. NORMAL refers to the concentration in the room.

Both monitoring and relay nodes are programmed to implement opportunistic utilization [4] hence, any node can join or leave the network at any time, without the need of special configuration. In a complex indoor infrastructure, the air quality monitoring of a room can be enhanced by adding a number of monitoring nodes in the room. Similarly, a weak signal from a room in distance from the control room can be enhanced by adding relay nodes between the monitoring area and the control room. Nodes can be moved to different locations without any special configuration procedure.

3) Control Room: All the data packet from the sensor units are forwarded toward the destination node at the control room. In the proposed system, one simple transmission (radio) module is connected to a computer. This module decodes the packets and extracts all the useful information. A Graphical User Interface (GUI) is developed and runs at the control room. The radio module passes all the data to the computer which displays the data in real-time through the GUI. The collected data is also stored in files for later retrieval and review. If the collected CO_2 concentration exceeds a user-defined threshold, the application notifies the system administrator. The application can support large scale networks with simultaneous packet decoding from multiple sensors. Figure 6 shows a screenshot of the developed GUI.

C. Information Processing

In this section, the main information processing parts are described. The collected data are not of equal importance while sometimes it might be corrupted due to unreliable readings. Hence, an initial processing takes place at the radio module, before data transmission. The module processes the data collected from the sensors and transmits only the necessary information to the destination. In this way both the bandwidth and energy are saved. The system minimizes useless data transmissions, minimizing the traffic in the network and the energy consumption per node. The data is transmitted into packets. The data is processed and stored at the control room.

1) Noise Reduction, Data Smoothing and Calibration: One of the major problems of using low-cost MOS sensors is their unreliable readings. To reduce the sensor noise, we use an accurate mobile sensor [21]. The mobile node moves between the rooms once every hour and helps in the calibration of the nodes. If the sensor reading for one minute is within $\pm 4\sigma$ from the mobile sensor reading, the mobile sensor informs the control room for the necessary calibration. If there is a greater difference, there might be a need to replace the sensor node and the system administrator needs to check the sensor on the site. The mobile node periodically updates the sensor units with the expected values according the history levels in the area.

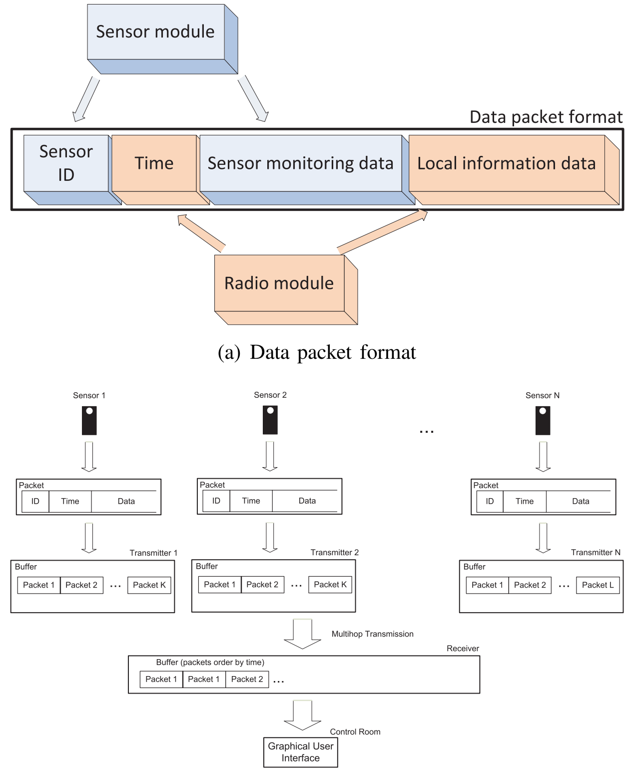
To identify outliers and remove them from the measurements, a smoothing algorithm is followed. If a random spike occurs within a window of time, the node ignores the data and does not transmit it. The selection of the window size follows the monitoring gas specifications. In case of indoor CO_2 the proposed system has a window of 6 sec., three sec. before the possible outlier and three sec. after. The radio module stores the last ten measurements of the sensor. When a high measurement, that exceeds the threshold is reported, the radio module waits for three more measurements while it also retrieves the last three measurements. After this time, the sensor transmits the correct data.

2) Packet Formation Process: Data packet formation and processing takes place at every monitoring board. Packets are created every second at the same rate as the sensor sends out data. A packet consists of the following four fields:

- *Sensor Identifier:* This identifier comes from the sensor module and it is related with its product serial number. It is unique for every sensor module in the network. The identifier stores the number of the transmitter that sends the packet and allows the receiver to identify the origin of the packet. For every sensor ID there is a corresponding location stored at the control room. The location can be updated if the sensor is moved to a new location.
- *Time:* The time comes from the radio module. This field stores the exact time when the packet was created. When the receiver receives the packets, it can order their transmission based on the timestamps. For a CO_2 monitoring application, the time is of high importance since it shows the variation of the CO_2 levels over time.
- *Sensor Monitoring Data:* The data passed from the sensor to the radio module. The data field stores all the crucial information related with the CO_2 concentration.
- *Local Information Data:* This information comes from the radio module. This field includes information such as the remaining power level of a unit and average Received Signal Strength Indication (RSSI) for location information maintenance.

Figure 7(a) shows the packet format and from which module each piece of information comes. The data processing, transmission and reception is shown in Fig. 7(b).

3) Data Processing and Storage: When a packet reaches the control room, the developed program performs a final process to the packet. The packet is decomposed to different parts (sensor ID, time, data etc.) and each part is plotted in real time. Moreover, each part is stored into files to keep record of the data over time. The data is available to the system administrator offline for further processing.



(a) Data packet format

(b) Packet process and transmission/reception

Fig. 7. The data packet format in (a) and the data process procedure in (b).

The stored data is used from the mobile node for calibration purposes as well. There are expected normal levels of CO_2 in the different rooms of a building. Hence, this information is given to the mobile node to help with the calibration of newly deployed sensors in the building.

D. Indoor Monitoring System

In the proposed monitoring system application, cognitive networking is used along with opportunistic routing in a wireless multihop network, for CO_2 monitoring. Inside a complex indoor environment, multiple contributions between radio nodes are constructed by reflections, transmissions and diffractions on the building structures [22]. An overview of the system can be seen in Fig. 8.

The final indoor monitoring board has two types of nodes: the wireless sensor nodes (monitoring boards) and the relay nodes. The wireless sensor nodes, as well as the relay nodes, are deployed in a complex indoor environment. The wireless sensor nodes know their relative location. The relay nodes will find their location during the initialization phase of the proposed protocol. Each wireless sensor node is able to monitor the area around it, form packets and forward these packets to one of the neighbor relay nodes which will then opportunistically forward the packet to the destination.

V. Experiments and Results

We conducted experiments in a complex indoor environment to illustrate the overall functionality of the prototype system,

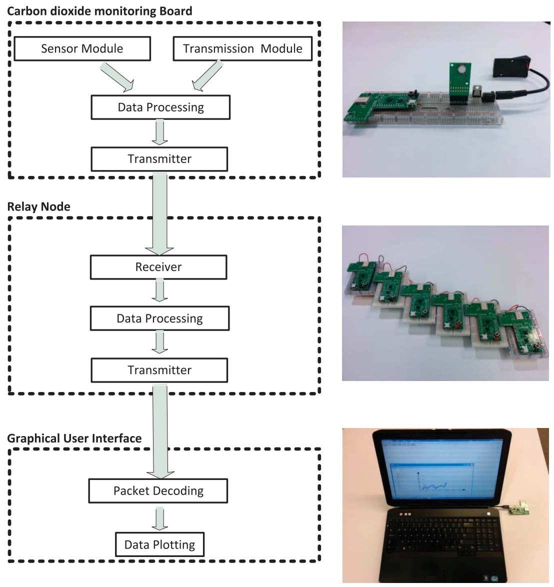


Fig. 8. Overview of the monitoring system.

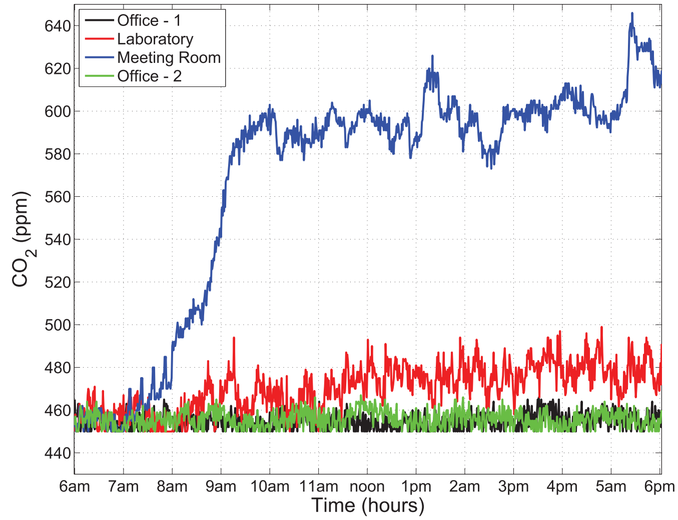


Fig. 9. Time series representation of air quality measurements over 12 hours.

the factors that impact indoor air quality and the need and the efficiency of data smoothing and calibration.

A. Experimental Setup

A part of the 7th floor of Bahen Centre for Information Technology at the University of Toronto was used for the experiments. We used two medium-size offices ($3m \times 5m$), one medium-size lab ($3m \times 6m$) and a meeting room ($12m \times 6m$), shown in Fig. 1.

The offices have one or two researchers and there are chairs for two more visitors. There are two desktop computers in each office. The lab is for the graduate students. It has four desks for up to four graduate students and there are also four desktop computers. The meeting room is the biggest room examined. It is designed for 15 to 20 people and there are four desktop computers. In all the four examined rooms, the windows are always closed, while the doors work with mechanism that keep them closed. The ventilation system is centralized and it operates according to the needs of the whole floor and not of each room separately.

Given the size of the room, the sensor specification and the radio transmission range, four monitoring nodes, four relay nodes and one radio module connected to a computer and act as the control room, were used. The sensors in the offices and the lab were placed in equal distance from the door and workstations. In the meeting room, the sensor was placed over the main meeting table, hanging on the roof of the room.

The experiments lasted for a month, between March 1 and March 31, 2015. After the initial setup the mobile node visited each monitoring room every day for data calibration. The data sampling is every 1 second. All the data are stored into files.

When the sensor system is turned on for the first time, it needs 15 minutes to reach stable time due to the initial action needed for the sensors.

B. Results Analysis

Carbon dioxide concentration over 12 hours is shown in Fig. 9. This measurement is during the peak hours at the examined rooms. Both people and computers contribute to the CO_2 levels. As the number of the people increases, the CO_2 concentration increases as well.

In the early morning, between 6 *am* and 8 *am* all the rooms report similar CO_2 levels. Since the rooms are empty, there is no great variation between the different room size and number of computers. As people start coming into the examine area, there are some noticeable differences.

The greatest increase during day time is shown in the meeting room. As the number of the people in the meeting room increases, CO_2 concentration reported around 580 *ppm* to 640 *ppm*. The proposed system managed to report an increase in the level which is probably related to the people's existence and activity in the room [23]. On the other hand, the two offices report similar levels of CO_2 throughout the day. In the laboratory, the levels reported are higher than the levels at the offices. Since the conditions are normal (no fire detection etc.), it can be inferred that the number of the people in the laboratory is higher than the number of the people in the offices.

During monitoring, there is a number of outliers which cause detection errors. Outliers need to be detected and removed to have an accurate system. Figure 10 shows the sensor data before and after the proposed data smoothing algorithm. The data before smoothing is from the sensor memory and the data after smoothing is those that was transmitted. The algorithm examines a window of total 6 sec. before and after the reported value that over exceeds the mean value. The GUI at the control room is designed in order to ignore the outliers, following the proposed algorithm.

Figure 11 shows the CO_2 concentration as reported of the proposed system during March 2015. As it can be inferred, the days the monitoring rooms have a high number of people is clearly noticeable. Especially the meeting room, when it is used, the concentration is clearly higher than the normal levels.

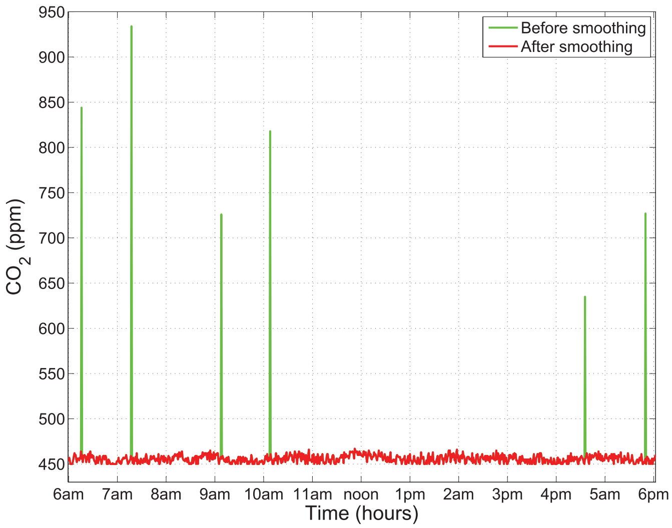


Fig. 10. Time series representation of air quality measurements at Office - 2 over 12 hours before and after smoothing.

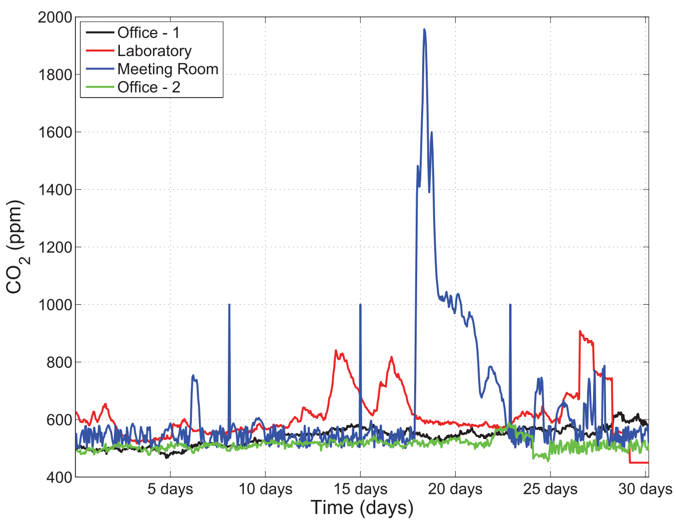


Fig. 11. Time series representation of air quality measurements over March 2015.

Similarly for the laboratory, based on students activities, some days throughout the month the levels are high. The concentration of CO_2 in the offices seems stable and around normal during the monitoring month.

Figure 12 shows the data, as reported from the meeting room, before and after the smoothing at the control room. The algorithm examines the reported data in an hour period and decides the value. In a month period, the smoothing algorithm is necessary to remove noise from the data that was not removed locally inside each monitoring node.

C. Comparison of Simulation and Experiments

The experimental results compared with simulation results [4]. Figure 13 shows a comparison – both simulation and experimental results – of a system without opportunistic routing and cognitive networking (simple monitoring system), and the proposed system in terms of packet delay. Packet delay

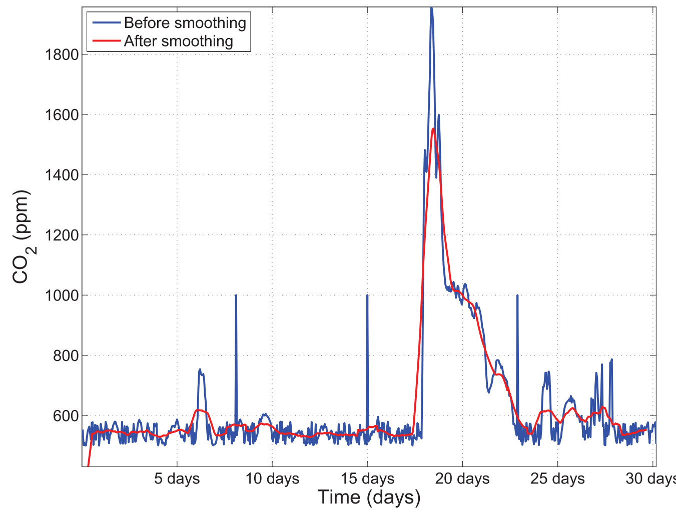


Fig. 12. Time series representation of air quality measurements at Meeting Room over March 2015 before and after smoothing.

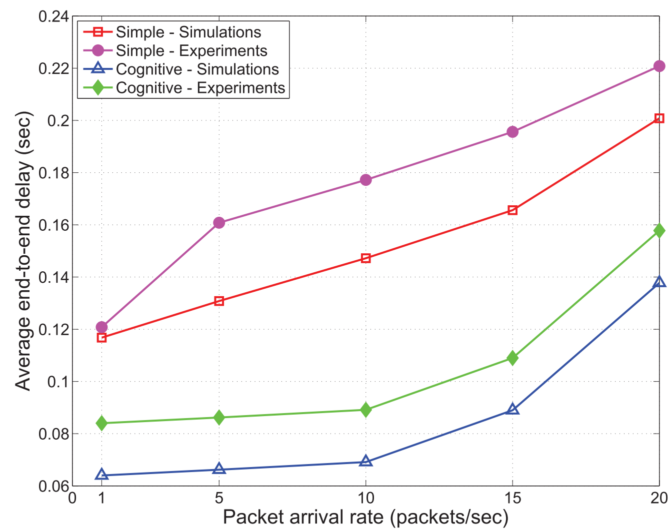


Fig. 13. Comparison of experimental and simulation results.

is crucial for every monitoring system. The experimental results are close to the simulation results. The difference is due to unpredictable parameters such as other system interference, people movement etc.

The proposed system performs better than a simple monitoring system in terms of packet delay. The use of cognitive networking is important in a complex indoor environment with many transmissions over the unlicensed band. Moreover, the use of opportunistic routing minimize the effect of the dynamic changes on the network performance. The hardware modules of the proposed system were designed to meet these two requirements.

VI. Conclusions

This work addressed the concept of a real-time WSN capable of monitoring indoor carbon dioxide concentration and dangerous situations. The main goal of our approach is to build a prototype that has minimum impact on the existing infrastructure of the building. To achieve this, we followed a cognitive networking technique with an opportunistic routing protocol. An information processing framework is proposed, to detect outliers, form data packets and calibrate the sensors.

The performance of the system was examined in a small region of a building. The system manage to report CO_2 concentration in real-time, while the information processing framework minimized outliers. The system was compared in terms of packet delay with a simple monitoring system. The comparison was both in simulation and in experiments. The proposed system performs better than a simple monitoring system.

REFERENCES

[1] *Indoor Air Quality*, Can. Centre Occupat. Health Safety, Hamilton, ON, Canada, Jul. 2013.

[2] *Buildings and Their Impact on the Environment: A Statistical Summary*, U.S. Environ. Protection Agency Green Building Workgroup, Washington, DC, USA, Oct. 2014.

[3] H. Liu, B. Zhang, H. T. Mouftah, X. Shen, and J. Ma, "Opportunistic routing for wireless ad hoc and sensor networks: Present and future directions," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 103–109, Dec. 2009.

[4] P. Spachos and D. Hantzinakos, "Scalable dynamic routing protocol for cognitive radio sensor networks," *IEEE Sensors J.*, vol. 14, no. 7, pp. 2257–2266, Jul. 2014.

[5] D. S. Ghataoura, J. E. Mitchell, and G. E. Matich, "Networking and application interface technology for wireless sensor network surveillance and monitoring," *IEEE Commun. Mag.*, vol. 49, no. 10, pp. 90–97, Oct. 2011.

[6] T. Torfs *et al.*, "Low power wireless sensor network for building monitoring," *IEEE Sensors J.*, vol. 13, no. 3, pp. 909–915, Mar. 2013.

[7] E. Sazonov, H. Li, D. Curry, and P. Pillay, "Self-powered sensors for monitoring of highway bridges," *IEEE Sensors J.*, vol. 9, no. 11, pp. 1422–1429, Nov. 2009.

[8] S. D. T. Kelly, N. K. Suryadevara, and S. C. Mukhopadhyay, "Towards the implementation of IoT for environmental condition monitoring in homes," *IEEE Sensors J.*, vol. 13, no. 10, pp. 3846–3853, Oct. 2013.

[9] H. Yang, Y. Qin, G. Feng, and H. Ci, "Online monitoring of geological CO_2 storage and leakage based on wireless sensor networks," *IEEE Sensors J.*, vol. 13, no. 2, pp. 556–562, Feb. 2013.

[10] X. Mao, X. Miao, Y. He, X.-Y. Li, and Y. Liu, "CitySee: Urban CO_2 monitoring with sensors," in *Proc. IEEE INFOCOM*, Mar. 2012, pp. 1611–1619.

[11] O. A. Postolache, J. M. D. Pereira, and P. M. B. S. Girao, "Smart sensors network for air quality monitoring applications," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 9, pp. 3253–3262, Sep. 2009.

[12] J.-Y. Kim, C.-H. Chu, and S.-M. Shin, "ISSAQ: An integrated sensing systems for real-time indoor air quality monitoring," *IEEE Sensors J.*, vol. 14, no. 12, pp. 4230–4244, Dec. 2014.

[13] V. Jelicic, M. Magno, D. Brunelli, G. Paci, and L. Benini, "Context-adaptive multimodal wireless sensor network for energy-efficient gas monitoring," *IEEE Sensors J.*, vol. 13, no. 1, pp. 328–338, Jan. 2013.

[14] C. Peng, K. Qian, and C. Wang, "Design and application of a VOC-monitoring system based on a ZigBee wireless sensor network," *IEEE Sensors J.*, vol. 15, no. 4, pp. 2255–2268, Apr. 2015.

[15] C. Liu and G. Cao, "Spatial-temporal coverage optimization in wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 4, pp. 465–478, Apr. 2011.

[16] AppliedSensor—iAQ 2000. [Online]. Available: https://www.appliedsensor.com

[17] L. Song and D. Hatzinakos, "Cognitive networking of large scale wireless systems," *Int. J. Commun. Netw. Distrib. Syst.*, vol. 2, no. 4, pp. 452–475, Jun. 2009. [Online]. Available: http://dx.doi.org/10.1504/IJCNDS.2009.026558

[18] P. Spachos, P. Chatzimisios, and D. Hatzinakos, "Cognitive networking with opportunistic routing in wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 2433–2437.

[19] OMESH Networks—OPM15. [Online]. Available: http://www.omeshnet.com/

[20] P. Spachos, L. Song, and D. Hatzinakos, "Prototypes of opportunistic wireless sensor networks supporting indoor air quality monitoring," in *Proc. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2013, pp. 851–852.

[21] W. Tsujita, H. Ishida, and T. Moriizumi, "Dynamic gas sensor network for air pollution monitoring and its auto-calibration," in *Proc. IEEE Sensors*, vol. 1, Oct. 2004, pp. 56–59.

[22] P. Spachos, F. M. Bui, L. Song, Y. Lostanlen, and D. Hatzinakos, "Performance evaluation of wireless multihop communications for an indoor environment," in *Proc. IEEE 22nd Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2011, pp. 1140–1144.

[23] J. Fonollosa, I. Rodriguez-Lujan, A. V. Shevade, M. L. Homer, M. A. Ryan, and R. Huerta, "Human activity monitoring using gas sensor arrays," *Sens. Actuators B, Chem.*, vol. 199, pp. 398–402, Aug. 2014.

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