Design of a Multi-Hop Wireless Network to Continuous Indoor Air Quality Monitoring

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Abstract — In indoor environments (homes, industrial buildings, etc), fires or exposure to toxic or flammable gases are non-rare incidents. Timely detection of incident-indicative air parameters is of crucial importance to incident prevention or to the minimization of the consequences to human health. The existing solutions lack in coverage and continuous real-time data accessibility. This paper presents the design and implementation of the system for near real-time continuous air quality monitoring based on Wireless Sensor Networks (WSNs). It is primarily dedicated for the indoor environments although, with some modifications, it can be used outdoors as well. The proposed system focuses on remote monitoring of the typical incident-indicative parameters such as: temperature, humidity, CO, Liquefied Petroleum Gas (LPG), and smoke. In order to increase the sensing coverage and connectivity, and to decrease the energy consumption of the smart sensors, the proposed system utilizes ZigBee based multi-hop communication paradigm along with specific sleep/active sensing and communication duty cycle. The results show that, besides being flexible and low cost, the proposed system shows satisfying performance in terms of overall functionality and reliability. Power consumption of the nodes can also be considered as satisfying, although, in this direction, additional measures could be taken for further improvements.

Index Terms—Air pollution, CO, IoT, LPG, temperature, humidity, wireless sensor networks, ZigBee

I. INTRODUCTION

Air pollution is one of the main causes of respiratory and cardiac diseases. Different pollution sources are present in different environments; e.g., major pollutants in urban (outdoor) areas come from the industry and road traffic. Due to its direct influence on human health, in most EU countries, urban air pollution monitoring is now regulated. On the other hand, air quality is rarely monitored indoors despite that, according to the US Environmental Protection Agency (EPA), indoor air may be two to five times more polluted than the outdoor air. Moreover, today, due to the technological improvements (e.g., e-services), people spend more time indoors. Indoor, air pollution is mostly invoked by microbial contaminants, gaseous pollutants (e.g., carbon monoxide, carbon dioxide, etc), or by dust and aerosols.

Generally, traditional air quality monitoring procedures have been conducted by taking samples at regular time intervals, at the specific set of locations. They use accurate and reliable sensors, but these sensors are heavyweight, large in size, and expensive. As such, sensor nodes of a conventional air quality system are usually sparsely dispersed in a given area, with their installation points constrained by the position of the monitoring centers. This implicates low spatial resolution and becomes a great drawback of these systems, especially when implemented in urban areas, where the air quality follows highly dynamic spatiotemporal distribution.

Alternative solutions to the conventional air quality measurement methods utilize Wireless Sensor Networks (WSNs). A WSN is a network of small, power autonomous devices enabled to sense the information from the environment, locally process it, and transmit it wirelessly to the user and/or datacenter. The WSNs can be placed anywhere where the conventional wired network cannot be deployed, e.g., volatile places like high-temperature areas, or chemical, and toxin prone areas [1].

In indoor living and working environments, fires or exposure to toxic or flammable gases are non-rare incidents. For example, in an apartment, the flammable gas that may leak from the heating system or from the oven may cause a fire. Also, the incomplete burning of some elements can invoke the release of the carbon monoxide (CO). As a colorless, odorless, tasteless, but poisonous gas, CO cannot be noticed easily but it can cause death if high values are reached in a closed environment. Also, the presence of high temperature, low humidity, or smoke, can indicate the fire condition. Hence, timely detection of gases and other air parameters is of crucial importance to the indoor air pollution and fire prevention. Existing, conventional indoor air quality monitoring systems are typically designed to measure CO and smoke, and to trigger an alarm when one of these parameters reaches a specific value. However, long term exposure to the specific gases, even if their values are still under the given unhealthy thresholds, may impose damage to human health. Therefore, traditional systems are not appropriate and should be replaced with the new-generation systems for remote continuous real-time monitoring.
One such system is presented in this paper. It is focused on the main indoor incident-indicative parameters (in the sense of air pollution or fire pre-conditions) such as: temperature, humidity, CO, Liquefied Petroleum Gas (LPG), and smoke. Under the controlled excitations, the system was tested in terms of functionality, reliability, and power consumption. It is a part of a project on air quality monitoring at the University for Business and Technology Laboratory for Internet of Things. With the additional web interface and mobile application capability, the target project aims to provide data access to the occupants and rescue officers for timely actions.

The paper is structured as follows. Next Section gives an overview to some examples of the existing researches and systems. Section III describes the proposed system, its hardware, software, and communication aspects. The experimental setup and settings, along with the respective results are given in Section IV. Section V concludes the paper.

II. RELATED WORK

Due to their specific advantages such as high spatial coverage and resolution, small nodes’ physical dimensions, power autonomy, wireless ad hoc deployment, and small overall network cost, significant research efforts have been made towards the development and the deployment of low-cost WSN-based systems for environmental monitoring. Some of the proposed solutions are shortly presented in the next paragraph.

A point-to-point ZigBee system for indoor air quality monitoring is presented in [2]. The sensing node is based on Libelium Wasp mote while the gateway is based on Raspberry Pi 2 platform. The system enables for the evaluation of CO, CO$_2$, ozone, chlorine, temperature, and humidity in a school and was tested only on functionality. Another multi-sensing ZigBee-based platform is presented in [3]. The star-topology network was tested regarding the sensing and communication capabilities. A similar infrastructure for measuring and calculation of the Air Quality Index (AQI) was used in [4]. In [5] the authors describe the architecture of a smart sensor node for indoor air quality monitoring. Sensors that were used in this work are similar to those described in this paper, namely MQ-7 and MQ-4. A somewhat different approach to measuring the air quality and ventilation rate based on the levels of Dioxide Carbon (CO$_2$) is presented in [6]. The system relies on a fixed Arduino-based smart sensor platform and a mobile Sensordrone which uses Bluetooth technology to transfer data to a Smartphone. Both fixed and mobile platform upload data to the IoT Cloud via WiFi links. A five-sensor system is presented in [7]. Again, the processing is based on Arduino board while communication is realized via ZigBee technology.

In contrast to the most of the previous implementations, except for a few works (such as e.g. the one presented in [8]), the proposed system utilizes the multi-hop communication paradigm in order to increase the sensing coverage and connectivity, and to decrease the node’s energy consumption. It also focuses on flexibility, low cost, and adaptable design.

III. SYSTEM DESCRIPTION

A. System Overview

The power-autonomous sensor nodes are placed at the specific indoor locations, and equipped with the sensing, processing, and wireless communication capabilities. As such, they can sense the air parameters, process them locally, and transmit data wirelessly to the monitoring center for further data visualization and analyses. In scope of this work, the measured parameters are: CO, LPG, smoke, temperature, and humidity. Data dissemination is performed in multi-hop manner.

In order to minimize the power consumption as much as possible, the wireless communication is achieved via low power short range 2.4 GHz IEEE 802.15.4 enabled communication modules. An XBee/ZigBee-compliant node can be configured as an end-device, a router, or as a coordinator. Hence, regardless of the short range nature of this technology (tens of meters indoors), the required network coverage can be achieved through multi-hop communication, by using routers as the intermediate nodes. This communication manner decreases the power consumption of each node because the nodes adapt their output transmission power to the communication distances. The technology generally enables for the various networking topologies, such as star, tree, and mesh. The mostly used topologies are star and tree. Accordingly, in order for the higher spatial resolution and coverage to be achieved, the final, target topology of the proposed system is envisioned to contain multiple end nodes and multiple routers utilizing multi-hop structure organized in tree topology. However, as for the testing purposes, the prototype system is composed of an end-device, a router, and a coordinator (Fig. 1).

![Fig. 1. The overall system’s architecture.](image)

The smart sensor performs sensing and data processing, before it transmits data wirelessly to the router. Besides some additional circuits for the component adaptation, its main components are: sensors, the microcontroller board, and a ZigBee transceiver. The router only relays data towards the destination; hence it only contains a
transceiver configured as a router. The coordinator sets up the network and the topology. Since it is directly connected to the PC through the USB interface (Fig. 1), it does not need the processing and storage functionality, i.e., it does not contain the microcontroller and/or storage modules. Instead, data processing, storage, and visualization are performed within the data center - PC.

The system design follows the modular approach, i.e., its architecture is composed of various off-the-shelf low-cost interconnected components. This approach provides greater flexibility regarding the process control, applicability, and optimization. The details on the used hardware and the hardware setup, as well as the software implementation, are given in the next subsections.

B. Hardware Details

From the hardware point of view, three different nodes (with somewhat different number of components) were applied, namely: end device, router, and coordinator.

The simpler variants of the nodes are the coordinator and the router. An XBee S2C (Xb24cz7wit-004) Digi module is configured as a coordinator and connected directly through the USB cable to the PC. The intermediate node uses the same transceiver now configured as the router. The configurations of each transceiver were performed by using the manufacturer’s XCTU configuration platform.

The most complex node is the end node. It is composed of (Fig. 2):

a) MQ2 gas sensor (to measure CO, LPG, and smoke), and DHT11 temperature and humidity sensor.

b) Arduino Uno board (with the integrated Atmel ATmega328P microcontroller).

c) XBee S2C (Xb24cz7wit-004) Digi module,

d) XBee Shield V03 module.

Fig. 2. The schematic view of the end node.

The preview of the smart sensor during the experiments is given in Fig. 3.

Fig. 3. The experimental prototype of the end-node.

The MQ-2 is a wide range gas sensor characterized with long term stability, fast response, and high sensitivity. The latter can be adjusted by its potentiometer. This sensor is mostly used in gas leakage detection, suitable for indoor (industrial and home) monitoring solutions. It can detect H2, LPG, CH4, CO, Alcohol, smoke, and Propane. Its resistance \( R_s \) changes differently when the sensor is exposed to different gases. The typical logarithmic-scale characteristics of the MQ-2 sensor are given in Fig. 4.

Fig. 4. Log. values of gases’ concentration in parts per million (PPM), depending on the resistance \( R_s \) [9].

It is obvious that the curves can be approximated as linear functions. Thus, for each of the gas measures a linear function of the following form can be constructed:

\[
y - y_{0i} = k_i(x - x_{0i})
\]

(1)

where, \((x_{0i}, y_{0i})\) are the coordinates of a selected point in a given graph \(i\), and \(k_i\) is the slope of the linear function for the specific gas \(i\). The slope can be derived from two points of the graph.

The low cost off-the-shelf sensors are generally sensitive to variations caused by the environment. In order to incorporate the actual environmental influences, the sensor should be calibrated. There are two approaches to sensor calibration: a) by using high-quality (expensive) sensors as the calibration reference point, and b) by establishing the ground truth value with the estimated reference [10]. In this work, the second approach was
used. To establish the reference point, the average value of the 50 resistance measurements was calculated and stored in $R_0$ variable. The voltage readings from the load resistor $R_L = 5000\Omega$, in the voltage divider circuit, give the resistance $R_S$. By knowing the ratio $y_{0i} = R_S/R_0$, the logarithmic value of the according $x_{0i}$ can be extracted. Finally, the PPM value is calculated as:

$$PPM = 10^{y_{0i}}$$  \hspace{1cm} (2)

As it can be noticed from the Fig. 2, the power supply of the MQ-2 sensor is controlled from an Arduino output digital pin. This was done because this sensor is the most power hungry component of the system, hence it is important to put it in sleep mode at the same time when other components go to sleep mode.

The DHT11 is a reliable digital sensor with a good long-term stability. It can measure the temperature in range of 0°C-60 °C and humidity in range of 20%-90%. Also, the libraries for attaching this sensor to the Arduino board are well defined and the readings can be directly used.

Arduino Uno is the most used and documented board of the whole Arduino family with lots of existing libraries. It is based on 8-bit ATmega328P microcontroller (with 32KB of flash memory for storing code, 2 KB of SRAM, and 1 KB of EEPROM), and has 14 digital input/output pins (with some of them having specialized functions, e.g. RX and TX), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, etc. Its technical characteristics and easy integration make it flexible and hence suitable for the modular-based application development and analysis, even though the power consumption might be somewhat high for the long term continuous monitoring [11].

The power consumption of a ZigBee- compliant module is expected to be of few tens of mA in active mode and around ten µA in sleep mode [12]. The XBee S2C embedded module can be adapted to various applications. The host interface enables for the easy module setup and adjustments.

The temperature and humidity sensor was connected to an Arduino digital port, while the gas sensor was connected to an analog port. The XBee transceiver’s Tx and Rx pins were connected to the according Arduino pins via XBee shield adapter, and communicate with the Arduino board at the speed of 9600 bauds.

C. Software Configurations and Programming

Transceivers were configured by using manufacturer’s XCTU configuration platform [13]. The XCTU enables for the PAN creation, putting a node in a specific operation mode (such as coordinator, router, or end node), setting the sleep interval etc. A fraction of the XCTU-based coordinator configuration is shown in Fig. 5.

At the coordinator’s and router’s side, only few parameters were set, such as a PAN ID, 16 bit source and destination address, and the node’s mode. In case of a larger network, 64 bit addressing is also available. On the other hand, at the end node, the power saving mode was configured additionally (SM sleep mode = Pin Sleep). Moreover, in order for the Arduino board to stay in sleep mode at the same time with the transceiver, we have also disabled the pin (D7=low) that would otherwise get activated when transceiver goes to sleep mode, which would wake up the Arduino board.

![Fig. 5. The XBee host interface - coordinator settings](image)

The microcontroller code was programmed in C, by using Arduino programming interface. At the transmitting end, the DTH.h and DHT_U.h libraries were used to read the data from the digital sensor through the Arduino digital pin, and to send them to the XBee module through Tx pin (and the XBee Shield). On the other hand, gas sensor MQ2 was connected to the Arduino input analog pin. The signal was then digitized by using 10 bit AD convertor.

The main components of the sensing and transmitting algorithm workflow are: a) Sensing module enters active mode, b) Arduino reads data from sensors and sends it through UART interface (and the XBee Shield) to the XBee module, c) XBee transceiver transmits data wirelessly, and d) both transceiver and the Arduino board enter sleep mode. As it will be shown, utilizing the sleep mode is an important method to energy saving because the transceiver operation in idle mode results considerably in high power consumption. As it will be also shown, frequent switching of the transceiver operation mode from sleep to active is also not recommended because of the higher power consumption.

Finally, the receiving end is composed of the coordinator connected to the data center – PC via USB port. The coordinator receives the data and forwards them to the data monitoring centre where the signal is visualized. The data visualizing software was written in Python.

IV. THE EXPERIMENT SETUP AND THE RESULTS

The network such as the one described in Fig. 1 was set up in an indoor environment, precisely at the University laboratory rooms. The end node was placed in one laboratory room, the router in another, and the
A sensor node was set up to measure and transmit the room temperature, humidity, and gases (smoke, CO, and LPG) continuously for a given period of test time. It is important to note that the gas sensor needs some time to warm up upon initializing, before it starts to measure the real values accurately. The sampling frequency was set to 3 minutes but, for the testing purposes, it was varied during the experiment. Every minute, the device spends approximately 1 second to wake up and sense the signals, and additional 300 ms to send data. However, during the functionality tests, where the controlled excitation was generated, the sampling frequency was set at the higher values.

The receiving node was set up as a coordinator, and was directly connected to the PC through USB port. To visualize the results, a simple code was developed in Python. A screenshot of the software interface for a short measurement interval is shown in Fig. 6. To test the system’s continuity, the system was left to work for a week. During this period no error occurred. The functionality test aims to show the changes of the measured values in accordance with the air quality changes. In order to achieve as greater accuracy as possible, we have left the gas sensor to warm up for 24 hours, although, during experimentation, we have noticed that it achieves the stability after 30 minutes. The experiment was composed of three phases: I) air parameter monitoring in the ordinary room conditions, II) air quality monitoring at the proximity of the controlled excitation - burning paper, III) the measurements taken during the gradual ventilation of the room after phase II.

The temperature-humidity sensor was not positioned close to the fire/gases during the phase II of the experiment. The sampling period was 30 seconds. The whole experiment lasted 22 minutes, precisely: Phase I was 6 minutes long, phase II one minute, and phase III was 15 minutes long. The 44 samples of the temperature and humidity are presented in Fig. 7. Due to a very high variations of smoke, CO, and LPG, that occurred during the phase II of the experiment, for practical reasons, we have first calculated the \( \log_{10} \) of the according values and then showed the logarithmic values in Fig. 8.

![Fig. 6. A fraction of continuous air quality measurements.](image)

![Fig. 7. Temperature and humidity variations.](image)

![Fig. 8. LPG, Smoke, and CO variations.](image)

The derived curves show variability that matches the dynamics of the experiment, except for the temperature curve that varies more frequently in phase III. However, we assume that it happened because of the turbulences from the air circulation after opening the windows and the door. In ordinary conditions, the temperature sensor showed good accuracy when compared to the readings from another thermometer. As expected, from the burning process, both smoke and CO will follow the similar changes - LPG will increase when incomplete burning process happens.

The sensing module was also tested for the energy consumption. Because the USB power regulator is considered to greatly influence the power consumption of the system, during the power consumption measurements, the boards were supplied through a special voltage regulator connected to 5V Arduino power supply pin. To measure the current drain for each of the operating modes, the Ampermeter was connected to the power supply circuit.

The measured currents for the sensing node, for all the operating modes, are given in Table I.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current drain (µC + Shield + XBee+sensors)</th>
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<tbody>
<tr>
<td>Active mode</td>
<td>( \approx 134 \text{ mA} )</td>
</tr>
<tr>
<td>Sleep-to-active mode</td>
<td>( \approx 171 \text{ mA} )</td>
</tr>
<tr>
<td>Sleep mode</td>
<td>( \approx 8 \text{ mA} )</td>
</tr>
</tbody>
</table>

As expected, when waking up the circuits from sleep to active mode, the node has consumed the greatest amount of energy. As compared to some related work in
this area, e.g., the one presented in [14], the power consumption of the nodes can be considered as low.

Another important parameter of energy consumption is duty cycle. In order to estimate the node’s lifetime, based on sleep/active intervals, the average current drain was calculated as follows:

\[
I_a = \frac{\sum_{i=1}^{3} I_i S_i}{S}
\]  

(3)

where \(I_i\) is the current in a given mode \(i\), \(S_i\) is the number of seconds the node spends in a given mode \(i\), and \(S\) is the number of seconds calculated as \(\sum_{i=1}^{3} S_i\).

An important limitation of the deployed system is the operability of the MQ2 sensor. As we have noticed from the experiments, even after warming up the sensor for 24 hour, it loses its operability, i.e., accuracy if left off for more than 5 minutes. Therefore, the sampling period is approximately 4 minutes. Given the sleep to active mode period of 1 second, and the sensing and transmission interval of 300 ms, the rest of 4 minute interval is left for sleep mode. Accordingly to the formula (1), the calculated average current was \(I \approx 11.8\ mA\).

Depending on a battery capacity, the expected lifetime of a node can vary. In order to estimate the node’s lifetime, we rely on some typical capacities of the commercially available rechargeable batteries that range from 5000mAh to 10000mAh. If incorporated within the proposed nodes, the expected lifetime of a node would be around 17 to 35 days. Although there is a lot of space for improvements in this direction, bearing in mind that the batteries may be rechargeable, the results can be considered as satisfying for the indoor environments where battery recharge is not an issue.

Finally, if compared with the nodes presented in the survey [15], the developed system can be considered as low cost. Precisely, the overall node’s cost is around 33.4$.

V. CONCLUSIONS AND FUTURE WORK

The proposed system enables for the continuous and near real-time monitoring of the indoor air pollution and gas presence. The system is modular and flexible, based on low cost off-the-shelf components and relies on multi-hop wireless communication paradigm. It was tested on reliability, sensitivity, and power consumption.

The system has shown continuity, i.e., reliability, as it was left to work continuously for a week and no error has occurred during this period. Also, the testing results have shown the satisfying system’s sensitivity, as it was exposed to the controlled excitation and the resulting curve has followed the excitation dynamics. However, regarding the power consumption, there is still space for improvements.

Our future work will be focused on minimization of the power consumption, mainly by implementation of other commercially available hardware platforms and elements, and by changing the duty cycle. In this sense, the most critical component is the gas sensor. Hence, the election of the more energy-efficient components along with the duty cycle readjustments should be considered. Also, the system should be further tested for accuracy, by comparing the results with those obtained from standard industrial sensors. Finally, the system architecture should be extended to the user-friendly web interface and mobile platforms.

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