SPIRI: Low Power IoT Solution for Monitoring Indoor Air Quality

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Abstract: Annually, millions of people worldwide die prematurely as a consequence of air pollution. Many of these deaths occur in large cities, where exhaust from cars, factories, and power plants fills the air with hazardous particles. However, the issue is not only in outdoor areas of the cities because most people spend more than 90% of their time in their houses, offices or cars. Indoor air pollution (IAP) affects human health, safety, productivity, and comfort. There are some reports about attacking the indoor air quality (IAQ) problem by utilizing IoT technology, but most solutions are driving the urban environmental problem. This paper presents the SPIRI platform which proposes to measure IAP using an IoT network of connected sensors that gather and send important information like temperature, relative humidity, volatile organic compounds (VOC), particulate matter (PM), among others. Using this data, indoor environments can be mapped, track changes over time, identify pollutions sources, and analyze potential interventions to reduce the IAP. Initial results of the current development of our IoT platform to perform the realtime monitoring of the IAP are presented. Hardware and software are also presented because our solution needs to be aware of the current IoT challenges such as scalability, security and interoperability. Both 6LoWPAN and IEEE 802.15.4 standards were implemented to establish the communication between the devices.

1 INTRODUCTION

Air pollution is a critical issue nowadays, millions people worldwide die each year as a consequence of air pollution. Many of these deaths occur in large cities, where exhaust from cars, factories, and power plants fills the air with hazardous particles (EPA, 2017b). Indoor concentrations of pollutants or indoor air pollution (IAP) can be higher than outdoor concentrations up to five times, due to incorrect functionality coming from Heating, ventilation, and air conditioning (HVAC) system. People spend a considerable amount of time indoors at home, office or transportation means. For instance, 4.3 million people a year die prematurely due to IAP (WHO, 2017). Indoor Air Quality (IAQ) can be affected by several agents or parameters like temperature, humidity, volatile organic compounds (VOC), particulate matter (PM), aerosols, etc. There are many reports that demonstrate insufficient IAQ levels can generate health problems to building occupants (Zhou et al., 2017) (De Gennaro et al., 2013). The World Health Organization (WHO) has published some guidelines to protect people living in indoor environments. The report presents the common substances that can be found and the maximum concentrations to prevent health risks (Penney D, 2010). The term "Sick Building Syndrome" (SBS) has been reported many years ago and it is used to describe health and comfort problems related to time spent inside buildings (Joshi, 2008). These complaints can be found in specific areas or among the whole building. Popular symptoms of SBS may include itchy, irritated, dry or watery eyes, nasal congestion, throat soreness, itchy skin, headache, lethargy, or difficulty concentrating. Some causes of SBS can be high building temperature, poor ventilation, high humidity, sealed windows, paints, coatings, etc. (Guo et al., 2013) (EPA, 2017a). To avoid such serious consequences of the SBS, an IAQ monitoring system is utmost required. An IoT network can be a wireless sensor network (WSN) with several dedicated sensor nodes, which can sense and monitor the physical parameters and transmit the collected data to a central location using wireless communication technologies. Then, we can take advantage of the IoT technology to save lives and to detect, analyze and improve indoor environments where the pollution is a real problem.

In this paper, we present the SPIRI platform, our IoT solution for monitoring indoor environments. We focus on the main parameters that determine the pollution inside buildings like offices, hospitals, homes, schools, etc. We have developed our custom hard-

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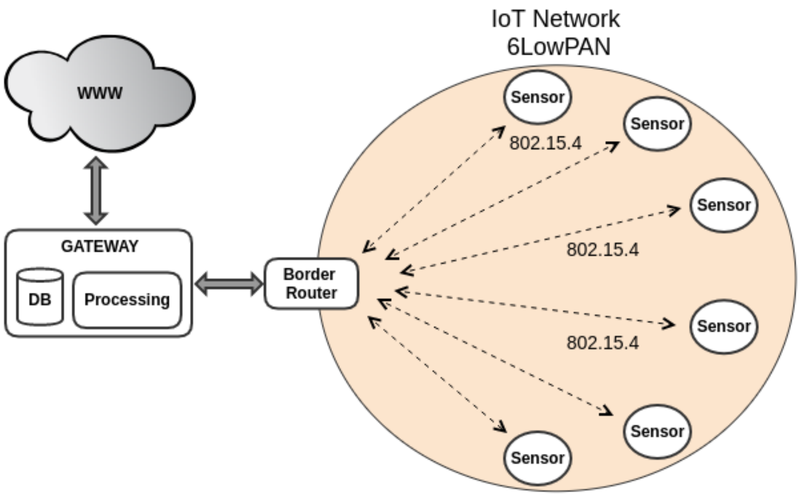

Figure 1: IoT System Architecture.

ware and firmware focusing to drive current IoT challenges such as scalability and security. The remainder of this paper is organized as follows: Section II presents the related work about IoT solutions for air quality monitoring. Section III highlights the architecture overview of our IoT platform. Initial results and analysis are presented in Section IV. Section V concludes the paper with final considerations and future work.

2 RELATED WORK

In IoT systems, there are lots of applications being developed by the academic and industry communities. The heterogeneity of the components of an IoT solution implies the development of new test methods and architectures to ensure the performance of the system and to meet user requirements. A system of several distributed monitoring stations that communicate wirelessly with a back-end server using machine-to-machine communication was presented in (Kadri et al., 2013). This solution collects urban information from gaseous and meteorological sensors and send through a wireless sensor network. Data is available in a web portal and in a mobile application. A real time wireless air pollution monitoring system is an effective solution for pollution monitoring using wireless sensor networks (WSN) (Prasad et al., 2011). The solution uses commercially available discrete gas sensors for sensing the concentration of gases like CO_2, NO_2, CO and O_2. Zigbee technology was used to implement the wireless sensor networks with multihop data aggregation algorithm. A Smart global Air Quality Monitoring system is presented by (Mohieddine et al., 2017). The system employs different technologies, such as gas sensing, WSN and Smart mobile. It is a typical case of an IoT application where data is collected and delivered to a local gateway and data is displayed via a remote web server. (Lozano et al., 2012) presents a sensor network for indoor air quality monitoring. The network consists of a base station connected to the internet and several nodes sensors to measure temperature, humidity, light and air quality. The standard IEEE 802.15.4 (Zig-Bee protocol) using the XBee module was utilized to perform the communication between the nodes and the host. State-of-the-art solutions are focused on urban pollution where pollutants are different from the indoor pollutants. There are some reports covering the IAP by using IoT networks, but most of these solutions use Arduino-based hardware and common IoT issues such as scalability, security and low power characteristics are not being addressed (Raju et al., 2013) (Pham et al., 2013).

3 PROPOSED ARCHITECTURE

The proposed IoT IAQ monitoring system was designed and developed to obtain a fine-grain record of indoor environment conditions. The parameters monitored were chosen, so that the following conditions could be studied: hygrothermal comfort, IAP and system operation optimization. The current sensor node version is capable of simultaneously monitor temperature, relative humidity, absolute pressure, luminosity, PM, CO_2 and VOC. The architecture of the system is shown in Figure 1. The system is composed of a relatively simple infrastructure composed of sensor nodes, a border router and a gateway that pools all the data acquired by each sensor node. The data is either passed along the mesh network or sent directly to the border router which communicates with the gateway. The gateway then inserts new data points to the data base which can be stored locally or remotely (cloud system). The communication between all individuals of the network is based on the IEEE 802.15.4 specification (IEEE, 2017). For a facilitated and accelerated deployment, a development board was used to implement the RF-Transceivers. The LAUNCHXL-CC2650 SimpleLink™ is a low-cost RF-Module with integrated programmer and debugger.

3.1 Hardware

3.1.1 Gateway

The gateway is an important module of the system because it performs the interface to Internet, store all data in a local database and can execute some pre-processing tasks. For the new IoT paradigm, board size, power requirements and cost are also critic. Raspberry Pi Zero W was selected because it provides reasonable functionalities to execute the gateway tasks (Raspberry, 2017), it is also very compact and easy to configure and maintain. Raspbian linux was installed and used as a operating system of the platform. All these features are not available with other embedded solutions. Finally, it offers a great scalability factor, for the whole system can be booted from a Micro SD card, which can be separately reproduced.

3.1.2 Border Router

The border router is the interface between the IoT network and the gateway. It serves to maintain the communication between the nodes in case the gateway is not available. In our platform, the CC2650 System on Chip (SoC) performs the border router functionality. Communication is established by utilizing RPL protocol and a proprietary RF 802.15.4 protocol. Communication to the gateway is accomplished through an UART interface.

3.1.3 Sensor Nodes

The sensor nodes are designed to incorporate as many sensors as possible without compromising the validity of each parameter. A special attention to Low Power operation was taken to avoid critical temperature operation points and to evaluate the possibility of a battery powered device in future works. Each sensor node must have an RF communication interface to send out the acquired data. Thus, the sensor node was designed as a shield PCB to the development platform described in section 3. A small memory block of the MCU is reserved to back up a few measurements in case of a lost network signal. Figure 2 shows a block diagram of the sensor node. The main difficulties faced in this design was to aggregate as many sensors as possible without compromising the operation of each one individually. The final hardware is shown in the figure 3. The sensors deployed in the shield PCB are presented in Table 1.

Table 1: SPIRI sensors.

Sensor	Description
BME280	Temperature, Humidity , Pressure
CCS811	VOC and $eqCO_2$
PMS7003I	Particulate Material Sensor
CDM7160	CO_2 sensor module
TSL4531	Luminosity sensor
SPH0645LM4H	Sound Pressure sensor
Energy	Energy meter sensor
PIR	Pyroelectric InfraRed Sensor

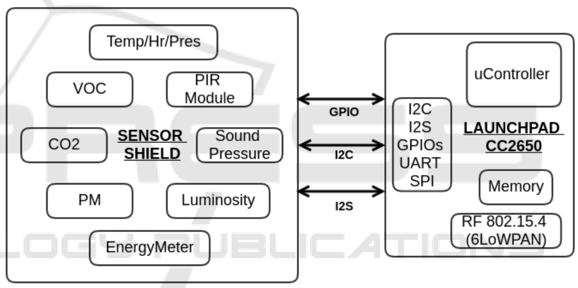

Figure 2: Sensor Node Block Diagram.

3.2 Firmware

3.2.1 Contiki OS

To provide stability and the basic functionality to operate the system, the sensor nodes were programmed with the latest version of the Contiki Operating System (Contiki, 2017). The advantage of using Contiki is the availability of timers, networking and many other tools developed by the Contiki community. It allows a quick and effective implementation of the application needed. However, Contiki OS only provides basic functionalities and hardware abstraction. To develop a complete solution, an OSYS framework was developed locally.

3.2.2 OSYS Framework

OSYS Framework is a hardware and operational system abstraction that has only four functions to imple-

Figure 3: Final hardware.

ment when using in a new system: a start time, a stop timer, a check if timer is expired, and a timestamp. With only those functions OSYS builds a framework of functionalities to help the development on any platform, such as drivers timing, SNTP protocol, and more. OSYS is the solution used by the developers for fast programming and easy implementation of necessary functionalities. Besides, interoperability is an IoT challenge that can be driven by the OSYS framework because it gives us a new abstraction layer between the OS and the hardware.

3.2.3 Protocols

As we described before, Contiki OS provides networking capabilities. Then, 6LowPAN protocol implementation was chosen as a communication protocol. To implement the communication over 6LoWPAN with security and low footprint, Ripple (RPL) was used as the routing protocol to map and connect neighbor devices. As we use a low power and low cost hardware platform, a new communication protocol called CoEP was used. CoEP (*Constrained Extensible Protocol*), is a protocol developed within OSYS to be released as open-source. CoEP is capable in a single unified layer to provide full data security with public and symmetric key exchange and management; authentication; single packet authentication; integrity and confidentiality. Furthermore, it can provide fragmentation; acknowledgment; message concatenation; and modularity to implement custom users messages, handshakes (called connectors) and protocols within it with a lower footprint than conventional protocols such as CoAP. Figure 4 shows the CoEP packet, where:

- **V:** Version of the protocol, currently 0x0.
- **C:** Type of cryptography used in the payload: 0x0 for none; 0x1 for public key (to be chosen and implemented by the user, however its advised to use the current implementation of elliptic curves of type 256r1); 0x2 for point-to-point symmetric key cryptography; 0x3 for network symmetric key, where all nodes can read the message.
- **F:** Fragment number. For being designed for 6LoWPAN networks, the maximum payload is of 128 bytes, or 3 fragments maximum.
- **A:** Whether the packet needs an acknowledgement reply.
- **L:** Last fragment identification.
- **Items marked with *:** Parts of the message that are encrypted.

3.2.4 Security Modes

CoEP protocol gives option to use asymmetric and symmetric key exchange. The system was implemented with micro-ECC, an cortex mthumb optimized code that can handle varioyus eliptic curves cryptography schemes. This application use secp256r1 elliptic curves, using the Elliptic-curve DiffieHellman (ECDH) key agreement protocol implemented within CoEP as a connector. A custom key derivation function (KDF) is used to generate the symmetric key from the secret. Because the handshake establishes the symmetric key and each CoEP packet has its own authentication token, there is no change in header length. However, because the symmetric cryptography is AES-128 CBC, packets payload will always be multiples of 16bytes. CoEP limits its payload to 48 bytes per packet in this application.

3.2.5 Power Saving

Low power consumption could be considered a critical feature in some IoT applications. To have low power features we have chosen the CC2650 microcontroller because it has specific low voltage/current characteristics, for example: Normal operation voltage: 1.8 to 3.8 V, External regulator mode: 1.7 to 1.95V, Active-Mode RX: 5.9 mA, Active-Mode TX at 0 dBm: 6.1 mA and Active-Mode TX at +5 dBm:9.1 mA. Contiki OS takes advantage of the CC2650 power saving features. For example, when the device is sending data by using the RF interface, the CPU will enter sleep mode and will resume after the transmission process is complete. In case there are no events in the Contiki event queue, the uC will enter in low power mode that was previously configured with the LPM (Low Power Mode) driver.

4 CASE OF STUDY

The object of the experimentation is a building with a centralized HVAC System located in the Polytechnic School of the University of São Paulo. The building is called CITI-USP, it is a research center which

Figure 4: CoEP packet.

can be considered an office building. It is a multidisciplinary center where many people work in academic and industrial projects. Five sensor nodes, a border router and a gateway were deployed in the second floor of the building in specific locations where people walk every day.

Figure 5: CITI-USP Building.

4.1 Initial Results and Analysis

The first analysis to be performed are related to hygrothermal comfort. Figure 6 shows the temperature profile of the first floor of CITI-USP building on November 11th of 2017 between 10am and 12pm. A sudden decrease of the temperature during this time frame can only occur as a consequence of a active HVAC-System operating in cooling mode, which can be verified by Figure 7 that shows clearly the cycling operation of the HVAC-System with significant drops of up to 15% of relative humidity while it is on. This is a common issue in mechanical ventilated environments, which can implicate in a aggravation of respiratory conditions for sensitive people. It is also clear to observe, how the Temperature significantly drops inside the meeting room of about 4°C in approximately 45 minutes. This evidences a not well planned system that could easily be retrofit to avoid such performance and enhance people's comfort throughout the day.

The conjunction of varying Temperature and relative Humidity to increased IAP can further degrade

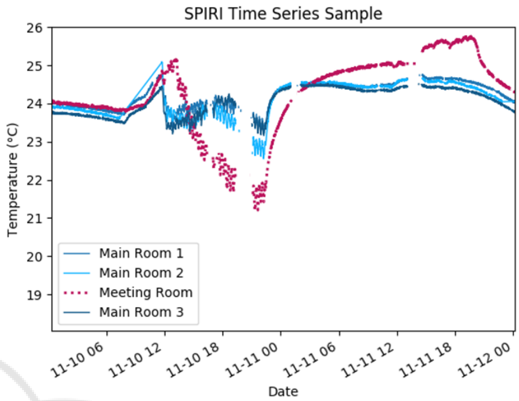

Figure 6: 2-hours temperature profile of a floor in CITI-USP.

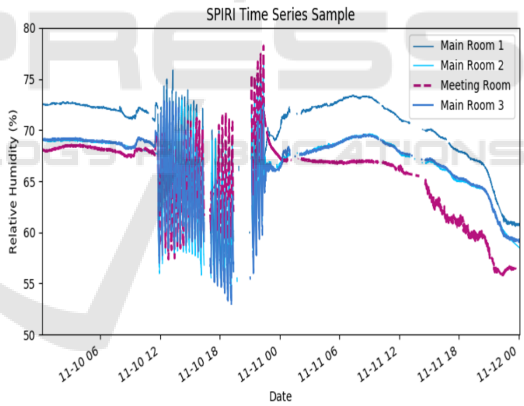

Figure 7: 2-hours relative humidity profile of a floor in CITI-USP.

the environment for its occupants. These analysis will be completed in the following weeks with a greater dataset of almost 50 days. Our prototype has eight sensors working simultaneously, so the estimated power consumption of the hardware was 400mW with some current peaks of 150mA. It can be considered a low power prototype if compared with some industrial solutions, for example CO2 sensor from Honeywell (Honeywell,).

5 CONCLUSION AND FUTURE WORK

This work presents the initial results of our IoT platform for monitoring indoor environments. We have defined the parameters to be monitored for some specific cases like houses, offices, schools, etc. Advanced sensor technologies were used to obtain accurate results of the parameters which affects the indoor air quality. We have deployed our system in a research center of Sao Paulo University where data collection was done each minute for each parameter and preliminary results give us valuable information about air quality behavior during the day.
For our future research, we plan to continue the real time monitoring and try to emulate real situations in an indoor environment like cooking, smoking and painting and analyze the results. Another challenge is to test the scalability of the system, so next phase is to deploy 10, 30, 50 and 100 nodes simultaneously. Another task is to implement a toolkit to view the live air quality data of deployed regions. Other future research is the implementation of some techniques to improve the IAQ, for example the use of photocatalytic oxidation (PCO) to remove hazardous VOC elements.

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