Pilot Study of Deploying IoT Micro Air Quality Sensors in an Urban Environment: Lessons Learned*

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Abstract

In the United States, overall air quality has steadily improved since the passage of the Clean Air Act of 1970. However, not all communities have realized these gains and reported air quality can differ significantly between communities. One approach to improve awareness is to add additional regulatory sensors to provide more fine-grained sensing. However, regulatory sensors are expensive and may not be an affordable option. To provide fine-grained sensing and localized air quality, low-cost sensors that detect particulate matter have become an affordable option. Combined with an Internet of Things (IoT) platform, these sensors can provide real-time data to communities. This paper presents findings from a pilot deployment of an IoT air quality sensor network in Slavic Village within Cleveland, Ohio. Through this research, we share our findings and lessons learned from deploying these sensors in partnership with a community partner. From a pilot deployment, we are able to determine a significant difference between two locations that are less than 4 miles apart, supporting the need for fine-grained air quality monitoring. We discuss challenges in deploying in urban environments where both power and connectivity are constraints and how future work will reduce both of these constraints.

1 Introduction

Air quality is an important factor for human health. The World Health Organization (WHO) estimates that each year, 7 million people die prematurely due to ambient and indoor air pollution [10]. Whether or not an individual has any previous health conditions, the quality of the air they breathe can have a dramatic effect on their health. Particulate Matter 2.5 (PM 2.5) poses the greatest risk to humans, as these particles have a 2.5 micrometer diameter, allowing them to not only penetrate into human lungs, but into the bloodstream as well [2]. PM 2.5 contributes to premature death, heart attack, decreased lung function, and other health effects [1]. Long term exposure can lead to asthma and lung cancer, among other health conditions. Confirmed by epidemiological studies, humans can contract respiratory diseases more easily with PM 2.5 exposure[11].

The EPA provides the *AirNow* portal for communities to check current PM 2.5 levels [5]. However, in the area of this study which includes a major metropolitan area, one PM 2.5 sensor is shown to cover an area of more than 400 square miles. Other studies have shown that air quality can differ between different streets and based on the orientation of bus shelters [7, 3]. Deploying more regulatory sensors may not be an affordable option. However, with the advent of low-cost particulate matter sensors combined with an Internet of Things (IoT) platform, fine-grained air quality monitoring can become a reality. While these low-cost sensors may not be as accurate as a regulatory sensors [9], they can used to provide general trends to the community as well as identify pollution sources.

In this paper, we describe a pilot study of deploying low-cost sensors on an IoT platform. We utilize generally available single-board computers (Raspberry Pis) and common low-cost particulate matter sensors (Plantower PMS5003). We deployed these sensors in partnership with a community partner that provides low-cost internet access to low-income communities. Through this pilot deployment, we found a significant difference in air quality in a distance of less than 4 miles and differences between reported data from regulatory sensors and the sensors we deployed. The rest of this paper is organized as follows: Section 2 discusses the related work in this area, Section 3 describes the methodology for this study including sensor design and deployment, Section 4 includes findings from the evaluation of our study, and Section 5 summarizes the study and discusses future work.

2 Related Work

Building and deploying an IoT platform is the first step for being able to monitor air quality in urban environments. Frequent monitoring of urban environments in EU countries is now regulated, and one study found that using high-quality sensors may not provide data with an appropriate spatial and temporal resolution, and that instead a wireless sensor network with a large number of low-cost sensors is best for monitoring urban environments [6]. Besides keeping sensor costs down, factors such as low maintenance of both the sensors and infrastructure are important when aimed to be used in amateur or community projects [4]. It is important to consider all factors from both a software and hardware perspective.

When deploying a large network of sensors in an urban environment, it is critical to think of their placement when compared to environmental events (highways, steel mills, parks) so the data can accurately represent the urban environment. Regulation and previous research states that these sensors should be 1.6 meters, or 5.25 feet, above the ground to determine pollution exposures for adults [6]. Lamp-posts seem to provide an ideal infrastructure, as most contain the power and height requirements specific to air quality sensors[4]. By deploying a large network of IoT devices, it reduces human effort to collect, transfer, and log a large amount of data [8].

With the major causes of air pollution being industrialization, urbanization, and motorization, it is important to monitor outdoor air quality [8]. To accurately capture outdoor air quality, it requires housing that protects it from the elements, while still making sure enough air is getting passed to the sensor and that the sensor is still able to communicate its data to the network. For example, in a deployment of sensors in metal cages, the sensors are protected from the elements and possible human interference, but the metal enclosure can interfere with wireless connectivity [6].

3 Methodology

3.1 Sensor Design

The sensor modules designed for this study utilize generally available single-board computers (Raspberry Pi Model 3B+) and a Plantower PMS5003 particulate matter sensor, which uses light scattering to measure the quantity and diameter of particles. For this study, we gather PM 1.0, PM 2.5, and PM 10.0. The sensor software was written in Python where sensor readings are collected every 60 seconds and reported to a web service. Other models were developed using microcontrollers where the software was written in the C programming language. However, for this study, only the Raspberry Pi Model 3B+ units were used. A web service on a Linux, Apache, MySQL, PHP (LAMP) stack receives the sensor ID and PM readings and stores the data in a MySQL database. The sensors that were deployed in the field utilize Ethernet to connect to the internet. However in testing differences in enclosures in our lab, we utilized a Raspberry Pi Zero W, where we used WiFi connectivity. An image of the sensor module outside the enclosure is shown in Figure 1.

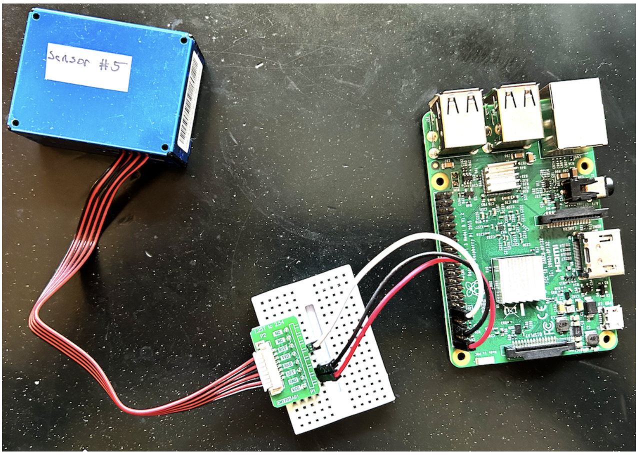

Figure 1: Sensor Module with PM 2.5 Sensor Connected to Raspberry Pi 3B+

The primary motivation in using generally available boards is to support a future goal in creating curriculum for middle and high school students where they can learn to build their own sensor module, create the software, and install it at their school. Within this curriculum, we aim for students to learn computer science and engineering topics that allows them to apply these concepts to an area that affects their community.

3.2 Local Partnership

Two common constraints in deploying IoT-enabled sensors in the field is supplying sufficient power and connectivity to the internet. Various approaches exist such as utilizing battery powered sensors, charging batteries via solar, or having fixed units that have a consistent source of power. With connectivity, popular options have included WiFi and cellular connectivity. To address these two constraints, we partnered with *PCs for People*, a non-profit organization that provides refurbished computers and WiFi hotspots to communities in need. Through this partnership, we were able to put our sensor modules in their towers, providing both power and connectivity. The location of *PCs* *for People's* towers was ideal for our pilot study due to their proximity to one of our neighborhoods of interest which is an area with close proximity to steel mills.

3.3 Web Dashboard

Beyond deploying the sensors and capturing the data, we wanted to provide an easy and intuitive way to view and interact with the data. To do this end, we created a web dashboard that shows the readings from each sensor in a line chart in real-time. The web dashboard also utilizes a background service to pull data from a nearby EPA regulatory sensor to compare the PM 2.5 data that was sensed with the regulatory sensor. To create the line chart, we use PlotlyJS, which allows us to pan and zoom into areas of interest and examine different trends. A screenshot of the dashboard is shown in Figure 2.

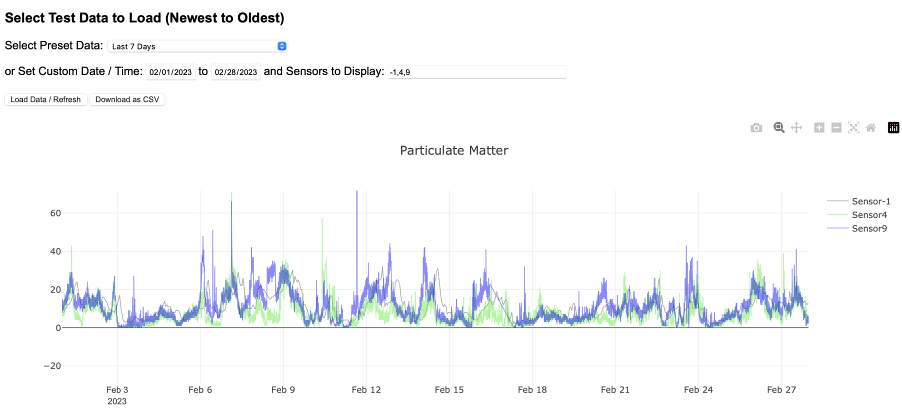

Figure 2: Screenshot of Web Dashboard Showing Sensor Data in Real-Time

4 Evaluation

4.1 Pilot Deployment

Our initial deployment involved having one sensor deployed in the office location of *PCs for People* from June 18th 2022 to August 13th 2022 and then at one of their cellular towers that provides internet access to low-income households from August 14th to September 12th 2022. There were two interesting observations from this deployment. One is that on the 4th of July at approximately the same time as a city fireworks show located west of the office location, the detected PM 2.5 level spiked to 125, as can be seen in Figure 3. The other interesting observation was that after moving the sensor to one of the cellular towers that was less than 4 miles south of the office location, the average PM 2.5 level doubled from 5.314 to 11.892. These averages include the entire readings from the deployment at both corresponding locations from June 18th to September 12th. Additionally, with the sensors placed near the major highways in Cleveland, the higher averages corresponded to rush hour times in the morning and evening. This pilot deployment supports the need for deploying more fine-grained air quality monitoring in this region as it showed a considerable difference in a distance of less than 4 miles.

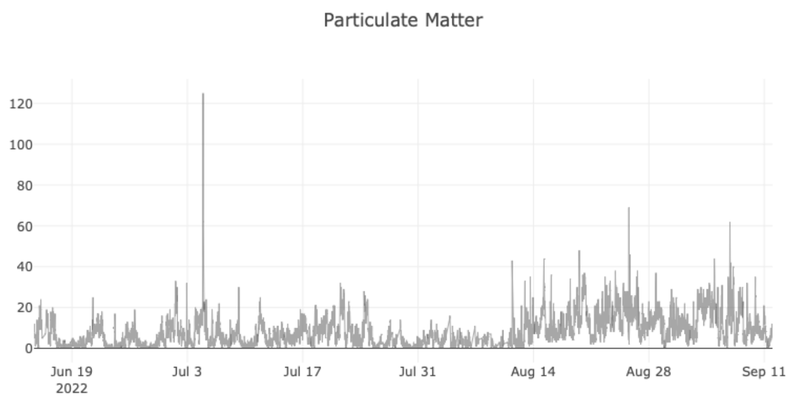

Figure 3: Initial Deployment of Air Quality Monitor in Two Separate Locations Less Than 4 Miles Apart

4.2 4 Month Deployment

An additional sensor was deployed in the region of the cellular tower 0.5 miles to the southeast. This location showed higher variability in the sensed particulate matter compared to the existing sensor where the new sensor had a standard deviation of 8.31 compared to the existing sensor of 6.14 and the regulatory sensor of 6.42. This difference is noticeable in observing the sensor data from the web dashboard where the sensors report higher peaks of PM 2.5 levels as shown in Figure 4.

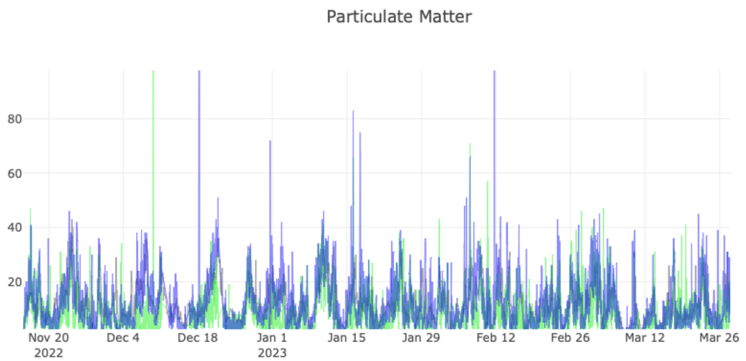

Figure 4: Deployment of Two Air Quality Monitors Over 4 Months

4.3 Enclosure

For situations where the *PCs for People* infrastructure isn't available (e.g., for future anticipated "edge nodes"), our sensing nodes will require their own enclosure to protect them from varying environmental conditions. The challenge with these enclosures is that they have competing requirements of preventing moisture (i.e., ran, snow, etc.) from entering, but allowing sufficient air flow to achieve high fidelity readings from the PM 2.5 sensors. As such, we developed a prototype enclosure from polyethylene terephthalate glycol (PETG), which is a polymer with high impact resistance and an adequate temperature range for our anticipated use [1].

To design the enclosure, we first developed a "naive" rectangular enclosure with a singular hole in the bottom for air flow. We then conducted a controlled experiment with one sensing node inside of the enclosure and one beside it, outside of the enclosure. We then observed the readings from each of the two sensors in the presence of a known source of particulate matter (an oil-based scent diffuser). In this experiment, we noted a significant difference in the two readings, which indicated that the first-generation enclosure was not allowing sufficient air flow to the PM 2.5 sensor.

To address the shortcomings of the initial sensor, we developed a computational fluid dynamics (CFD) model that allowed us to observe how air flow interacts with the enclosure. We then developed a second-generation enclosure with an external screen for blocking moisture, but offset from the main enclo-

[1] https://www.iemai3d.com/wp-content/uploads/2021/03/PETG_TDS_EN.pdf

sure by 1-2 cm to allow air flow. Through our CFD modeling, we observed that this screen allowed significantly more airflow to the sensor, and achieved near-parity with the external pressure (see Figure 5 for an example of the CFD modeling). Lastly, we conducted a second set of controlled experiments, and observed that the sensor in the second-generation enclosure recorded comparable PM 2.5 readings with the sensor located outside of the enclosure. An example of the experiment is shown in Figure 6. As a result, we concluded that this enclosure design should be adequate for deployments in locations where a *PCs for People* tower is not available.

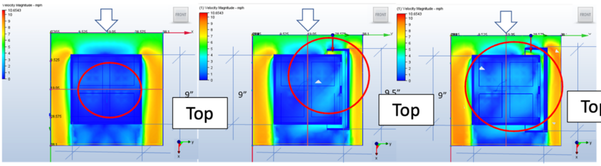

Figure 5: CFD Model of Airflow on Sensor Enclosure. Note that the newest-/final iteration shows higher airflow to the inside of the enclosure (where the sensor is located), and the airflow velocity is approximately equal to the applied velocity (5 mph).

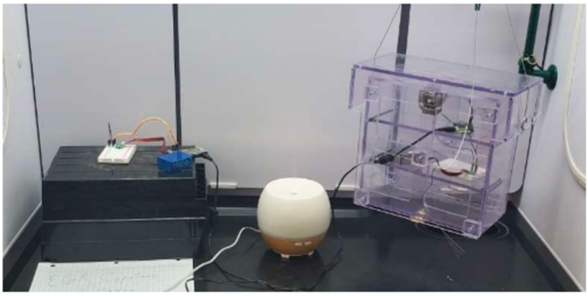

Figure 6: Controlled experiment with one sensing node located inside the prototype enclosure, and one located outside. Initial results show that the recorded PM2.5 levels were comparable between the two sensing nodes.

5 Conclusion and Future Work

This research has shown that by combining low-cost air quality sensors with an Internet of Things (IoT) platform, we can provide the community with fine-grained air quality monitoring that can provide valuable localized air quality data. From our pilot study, we found that in less than four miles there was a noticeable difference in sensed particulate matter where the average was more than double between the two locations. Additionally, in a longer-term deployment of over four months, there existed a higher variability in the sensed particulate matter than the regulatory sensor.

There are several areas of future work in this research. Limiting the deployment of sensors to cellular towers can restrict the ability to perform fine-grained sensing and detect differences among streets in close proximity to polluting sources. One approach to investigate is utilizing the modules deployed in the cellular towers as base stations that can communicate with edge sensor nodes by using LoRa. Another area is to perform more verbose error monitoring and reporting so that if a sensor is not reporting data that we can determine if it is an issue with the sensor module, the operating system itself, or a communication error. With the findings from testing the enclosure, more work is needed to design an enclosure that meets the goals of both allowing sufficient airflow while protecting the sensor module from the elements. Future work will include deploying additional sensors in the community as well as meeting with residents to better understand how air quality affects their daily lives.

Without a fine-grained deployment of air quality sensors, community members may never truly know an accurate measure of the quality of air they are breathing. Having only one PM 2.5 sensor for an area as large as Cuyahoga County is not feasible to provide this data, and it is not providing accurate or meaningful data to the community and its residents. We have found early success in our approach, and expanding the future work we have outlined will lead to more meaningful data for community members.

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