THE BACKYARD FOREST

A Microclimate Study

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CS 415-01 DATA COMMUNICATION AND COMPUTER NETWORKS

Anna Ransom
Brent Reynolds
Matt Rice

Introduction

This project is the culmination of our research in the CS 415 course, Data Communications and Computer Networks. The project entails creating a wireless sensor network (WSN) which is a network of connected sensors that communicate with each other to gather and transmit information from one location and transmit them to another. They are important as they provide a simple way for a system to collect and store information in the cloud by allowing one sensor node to be in a location collecting and sending data to another sensor node that can connect to the cloud and store the collected data there. Systems can be more complex if more sensor nodes are added to the system allowing for data to be captured in many areas at the same time and be stored and processed in the cloud.

The goal for this project is to set up a wireless sensor network with two sensor nodes to collect temperature, pressure, and humidity readings from Anna's backyard and compare them to results fetched from an API to view the difference in weather between two close microclimates. We also tested the range of the LoRa chips in both obstructed and unobstructed environments to find out how far they can transmit in different environments.

Literature Review

LoRa WAN is commonly used for wide-area environmental IoT projects because of its ability to perform over long distances. LoRa modules such as the RYLR896 provide ultralong range spread spectrum communication while providing immunity to interference by incorporating Forward Error Correction codes. In addition to this, LoRa modules such as the above mentioned are frequently used due to their low power consumption. According to Van-Diep Bui, Van-Anh Bui, and Quoc-Yuan To from the Department of Electrical and Mechanical Engineering at HaiPhong University in Vietnam, “LoRa is emerging as a promising solution for large-scale IoT deployments with low power consumption, including smart agriculture applications” and they further emphasize that “data can be transmitted over distances of several kilometers without the need for power amplifiers, thus saving energy consumption during data transmission/reception” which makes it a compelling option for environmental sensing applications such as *The Backyard Forest* (62).

In many environmental applications, sensors must be placed in remote areas that may not have direct access to a power source other than a battery. In this case, it is important to use as little power as possible in order to extend the period of time that the sensor can operate before downtime to change batteries. Minimizing downtime for maintenance is an important point to consider in environmental applications because conditions can fluctuate rapidly such as temperature, humidity, and atmospheric pressure. In one smart city deployment, researchers from the Department of Electronics and Communication Engineering at Sahrdaya College of Technology and Engineering in Kerala, India used LoRa modules in conjunction with ESP32 microcontrollers to monitor air quality and optimize street lighting energy consumption in urban areas (1431). Additionally, they used the ThingSpeak platform in order to visualize data gathered from the sensors in real time. In instances such as this, conditions such as air quality can fluctuate rapidly showing that the amount of downtime for a sensor is an important consideration. This is especially important in applications that transmit critical data from sensors such as air quality or smoke detection. The combination of LoRa, ESP32, and cloud-based software such as ThingSpeak provide a powerful platform for smart environmental applications, enabling users to deploy power efficient sensor networks.

Compared to other short-range communication methods such as Wi-Fi, Zigbee, or Bluetooth, LoRa can reliably support a much longer distance of communication which makes it the preferred method for smart environmental applications. In addition, other wireless standards such as Wi-Fi, Zigbee, or Bluetooth consume much more power making LoRa a more cost-effective solution. According to researchers from HaiPhong University, "Wi-Fi, Zigbee, and Bluetooth have limited operating ranges of 10 to 100 meters" and systems that use these communication technologies have "high energy consumption" which causes a "decrease in the battery life of the sensor nodes" making them higher resource consumption methods (62). Because of these limitations, LoRa has become the preferred solution in many smart environmental applications as they have many advantages over short-range alternatives.

Methodology

This section will detail how the basic network was set up and what tools were used. Additionally, it will describe how we conducted range testing and our results from range testing. Finally, it will explain our design of our environmental monitoring sensor network and the challenges we ran into along the way and how we remedied them.

Network Setup

With respect to hardware, our project utilizes two ESP32 microcontrollers (loaded with code from Arduino IDE), our laptops with USB-C cables to power the ESP32 chips, two LoRa transmitter chips, and a BME280 chip to track the temperature, humidity, and pressure of Anna's backyard. We also fetched information from Open-Meteo API[1] to quantify the differences in the microclimate of Anna's backyard, vs. the temperature, humidity, and atmospheric pressure at Louisville's Bowman Field Airport. We used Arduino IDE in order to write code to be executed by the ESP32s. To store our data in the cloud, we used ThingSpeak IOT[2] which allowed us to store and categorize our data into several different charts and export them as a CSV file.

To set up the WSN using LoRa, we first attached the ESP32s and LoRa chips to two separate breadboards. Then they were properly wired to make sure that the LoRa has 3.3v power, gnd, and two ports to communicate with the ESP32. We then designated one of them as a transmitter and the other as a receiver and code was uploaded to each of them accordingly to test if they can efficiently send messages. Then we soldered our BME280 chip to its chip base so that it could be connected to the breadboard. Finally, we wired the BME280 so that it can send its data readings to the ESP32 and updated the code to let the

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[1] Open-Meteo API is an API that allows for fetching weather data for given map coordinates.
[2] ThinkSpeak IOT is a free, browser-based cloud storage platform that can store data in tables and return them as CSVs.

transmitter collect and send data from the BME280 to the receiver. Finally, we updated the receiver code to receive the weather data from the transmitter and fetch the weather data from Open-Meteo API and send all of this to ThingSpeak.

Range Testing

Range testing was conducted in two different environments: unobstructed and obstructed. The unobstructed environment testing took place in the Bellarmine University parking lot where there is a large amount of flat space. Both wireless sensors were outside with the receiver walking away from the transmitter until 200m, which was the furthest location we could find. The obstructed environment took place with the transmitter inside of the computer science lab (Pasteur 111) and the receiver moving away into the parking lot. We stopped at 100m when we stopped receiving transmissions.

Figure 1: Range Testing Locations

In Figure 1, the transmitter's location in the unobstructed environment is shown as a red circle and the ending point of the receiver is the red arrow with the path along the way in the middle. The same is true for the obstructed environment, except it is represented in yellow.

The parameters measured along the way were the packet loss, latency (RTT (ms)), and received signal strength (RSSI (dBm)). Our packet loss, the ratio of lost transmissions to the total number of transmissions, was around 50% throughout the duration of the obstructed environment, but was closer to 30% at shorter distances. For the duration of the unobstructed environment, the package loss was around 25%. Our RTT (ms) and RSSI (dBm) formulas were not calculated correctly so our results were a constant 1000 ms and -

157, respectively. We found that the LoRa modules could communicate very well, even at far distances, with a relatively low overall packet loss when unobstructed. We also found that when obstructed, the LoRa can receive messages with about a 50% packet loss up to around 100m. With these findings, we can know the maximum distances we can have between the wireless sensors when we collect data.

Application: Environmental Monitoring

Our WSN system for environmental monitoring was designed with one ESP32 outside (the transmitter) which was powered by a laptop using a USB-C cable. The transmitter shared a breadboard with a LoRa module and a BME280 chip capable of measuring the temperature, humidity, and pressure of an environment. The transmitter was running code uploaded from Arduino IDE which fetched weather data from a BME280 chip connected to it and using the LoRa module, sends the data to the LoRa module of the receiver BME280 chip. The receiver is set up in a similar way to the transmitter as it is powered by a laptop with a USB-C cable and is connected to another LoRa module. The receiver runs Arduino code that receives the data from the transmitter, makes an API call from the ESP32 to Open-Meteo API to fetch the weather data from Bowman Field Airport, and sends this data to ThingSpeak IOT so that each of the data values can be stored in the cloud in separate tables. Figure 2 details the design of our WSN and the purpose of each component.

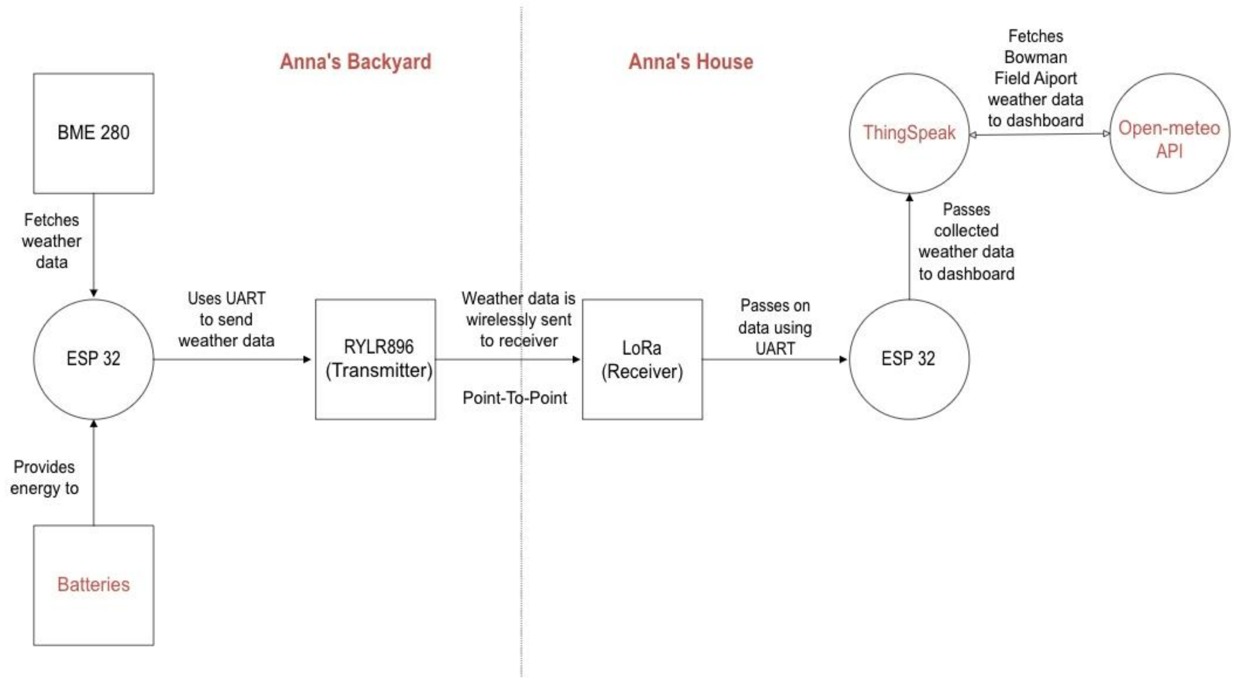


Figure 2: Design of our Environmental Monitoring WSN

It was difficult for us to narrow down how we would get our weather data as we originally planned to get it through weather.gov, but we were struggling to get the correct results from there. We eventually decided to pursue other options which led us to find Open-Meteo API. Open-Meteo API allowed us to easily fetch the weather results as we were able to make an HTTP request directly to it with the exact coordinates of Bowman Field Airport. We also struggled to find a suitable cloud platform that would fit our needs of adding data continuously to several different tables. We originally were going to use Arduino Cloud, but we found that it did not suit our project's goals very well, so we continued our search until we found ThingSpeak IOT. ThingSpeak allowed us to create our own cloud project and send our data results up to the cloud where each of the points would be stored in their own tables and could be exported in the form of a CSV file.

Results and Discussion

LoRa Range Data

Unobstructed Outdoor Range Testing

The range testing was conducted in two distinct environments: unobstructed in the Bellarmine University parking lot and obstructed primarily inside the Pasteur 111 computer science lab. The unobstructed environment was outside, in open air, and there was a clear line of sight between the transmitter and the receiver. In the unobstructed environment, the LoRa communication demonstrated relatively low packet loss, around 25%. The test was stopped at a range of 200 meters because we could not find an adequate amount of space on campus to maintain line of sight. This allowed for effective communication at distances up to 200 meters and we believe the maximum line of sight range to be even longer. This proves that the LoRa technology as implemented in this experiment is robust enough for long-range wireless sensor networks.

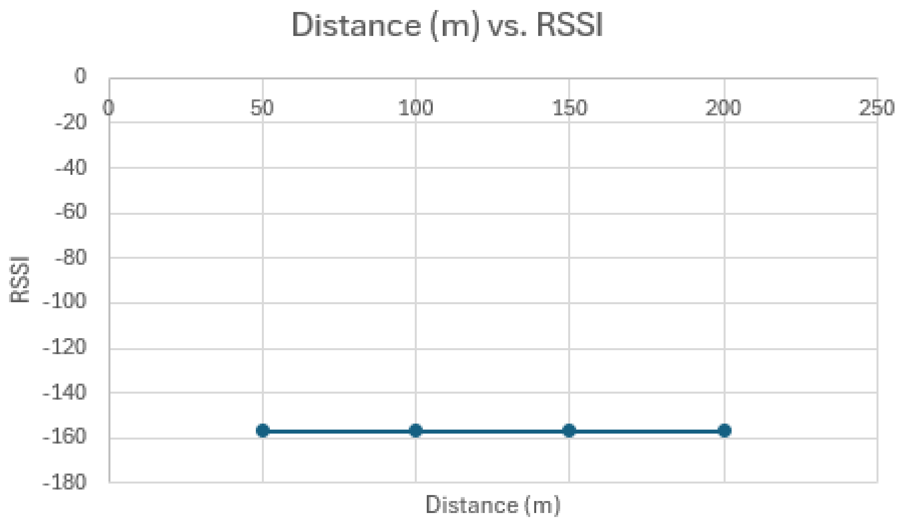
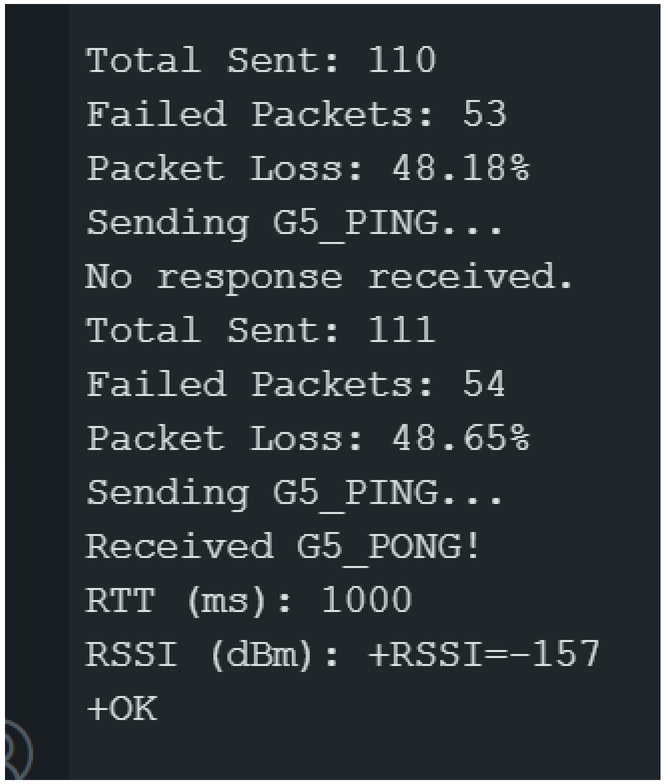


Figure 3: Unobstructed distance versus Received Signal Strength Indicator (RSSI)

Obstructed Indoor Range Testing

However, in the obstructed environment, communication was significantly affected by physical barriers, resulting in a 50% packet loss. The receiver stayed inside the Pasteur building, which is primarily constructed from brick and concrete blocks. The transmitter was never within sight of the receiver and was tested both inside and outside. Packet loss was up to 50% at distances of only 100 meters. Transmission completely failed at 164 meters.



```
Total Sent: 110
Failed Packets: 53
Packet Loss: 48.18%
Sending G5_PING...
No response received.
Total Sent: 111
Failed Packets: 54
Packet Loss: 48.65%
Sending G5_PING...
Received G5_PONG!
RTT (ms): 1000
RSSI (dBm): +RSSI=-157
+OK
```

Figure 4: Screenshot of obstructed results at 100 meters

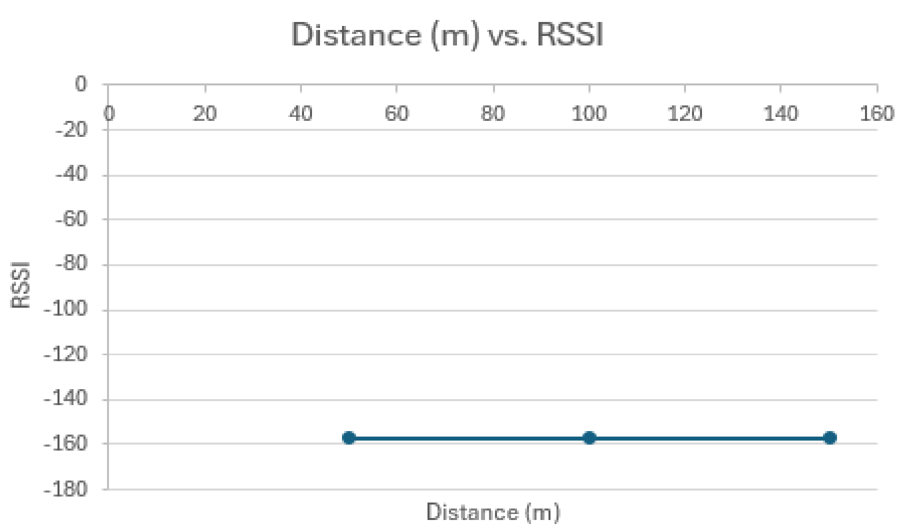


Figure 5: Obstructed distance versus Received Signal Strength Indicator (RSSI)

Given these challenges, we decided to change our strategy. We had initially planned to place the transmitter in Anna's backyard and keep the receiver inside Pasteur 111. To maintain an acceptable packet loss rate, we ended up installing the transmitter and the receiver in the backyard.

Environmental Monitoring Data

Temperature Data Collection

The temperature readings from Anna's backyard, as measured by the BME280 sensor, were consistently higher than those from Bowman Field, as reported by the Open-Meteo API. Specifically, the temperature in Anna's backyard ranged from 23.5°C to 34.55°C, while the temperature from Bowman Field ranged from 20.8°C to 23.1°C. These observations suggest that the BME280 sensor captured more dynamic and immediate temperature changes. The higher temperatures recorded in Anna's backyard reflect a more localized environmental condition, which could be influenced by factors such as lack of shade, less area vegetation, or nearby structures. In contrast, the Open-Meteo API provided a much smoother, more stable output with a significantly narrower range. This likely represents a moving average or smoothed data from a broader physical area. The differences in the temperature range and trend suggest that Anna's backyard may be considered a microclimate that is hotter than the surrounding area as demonstrated by readings from Bowman Field.

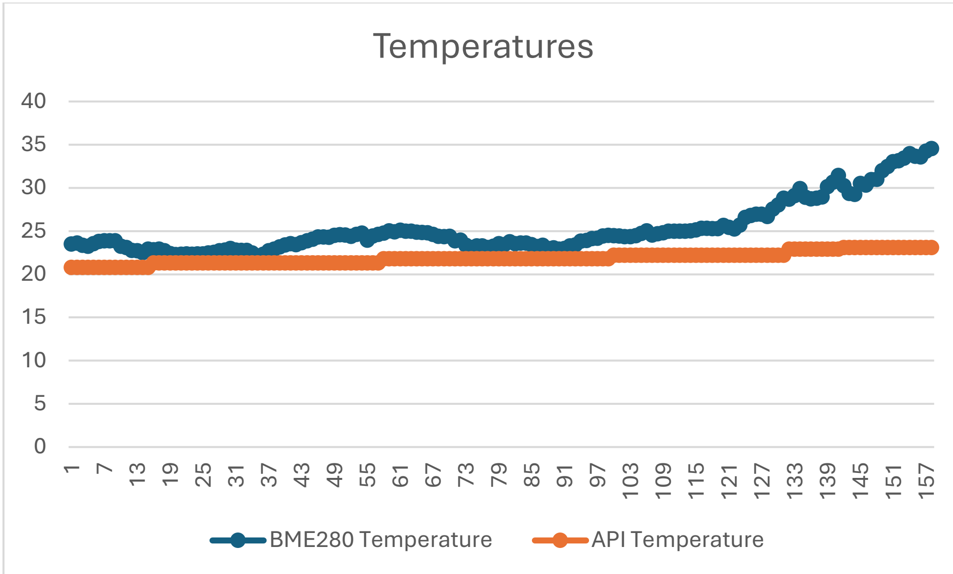


Figure 6: Temperature in Anna's backyard (blue) and Bowman Field (orange)

Humidity Data Collection

The BME280 sensor in Anna's backyard recorded values ranging from 34.46% to 37.22%. The Open-Meteo API data for Bowman Field ranged from 41% to 40%. The humidity readings in the backyard showed considerably more variation. Like the fluctuations in temperature, this suggests that the BME280 sensor was more responsive to the changes in the immediate environment. This could be due to more hyper-local factors like plant evapotranspiration and lack of nearby water sources. In contrast, the Open-Meteo data shows less variability in humidity, again, likely because of aggregating data over a larger physical area and smoothing out short-term fluctuations. These differences seem to imply that Anna's backyard loses humidity faster than Bowman Field, possibly due to differences in the ratio of vegetation to manmade structures or local temperature differences driving changes in humidity.

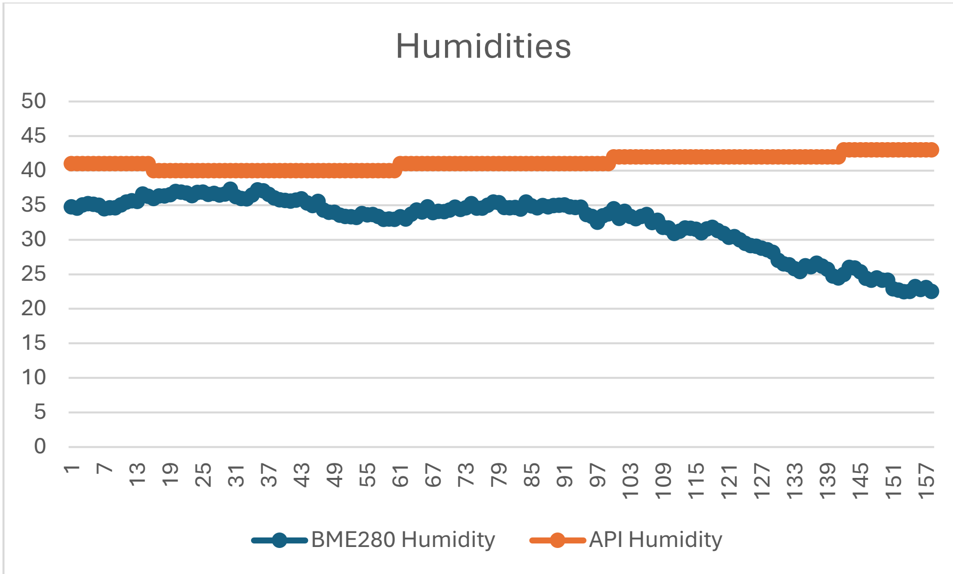


Figure 7: Humidity in Anna's backyard (blue) and Bowman Field (orange)

Pressure Data Collection

The pressure readings between Anna's backyard and Bowman Field also showed notable differences. The BME280 sensor in Anna's backyard recorded pressures between 1002.7 hPa and 1020.6 hPa. The Open-Meteo data for Bowman Field ranged from 1020.6 hPa to 1020.9 hPa. The pressure readings in Anna's backyard suggest that hyper-local environmental factors may be causing lower area pressure compared to Bowman Field.

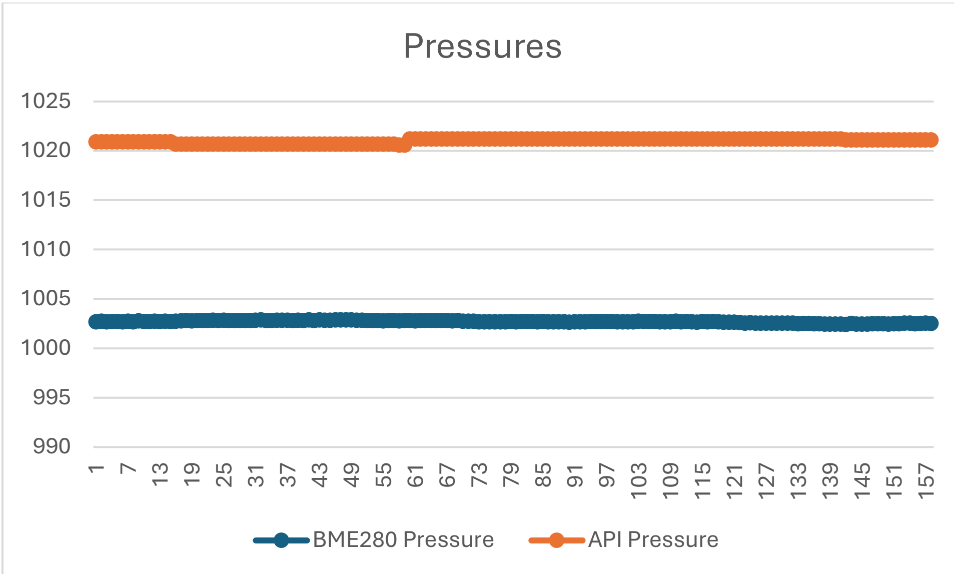


Figure 8: Pressure in Anna's backyard (blue) and Bowman Field (orange)

Statistical Significance

The p-values for the temperature, humidity, and pressure data sets were as follows: 8.37×10^{-11}, 7.64×10^{-14}, and 3.79×10^{-27}. These small p-values suggest that the differences between data from Anna' backyard and Bowman Field are real and not due to random chance.

Interpretation

The differences in temperature, humidity, and pressure between Anna's backyard and Bowman Field support the hypothesis of microclimatic variations in Anna's backyard.

One possible explanation for the observed differences is the Urban Heat Island (UHI) effect, which is common in urban areas. A UHI is an urban area with significantly higher temperatures than surrounding rural areas due to human activities and infrastructure. Key factors in UHI are man-made structures and surfaces, reduced vegetation, and increased energy consumption. Anna’s backyard is located directly next to a commercial property with a large asphalt parking lot and within a populous neighborhood with many single-family residences. Bowman Field has noticeably larger open areas and fields, but it is also a busy small airport. UHI are normally noted on a larger scale. It is an open question whether the same principles could be scaled down to backyards.

Figure 9: Slide taken from final presentation showing satellite imagery of Bowman Field and Anna’s backyard

Further testing would be needed to rule out other possible causes of the differences in temperature, humidity, and pressure like issues with sensor placement, data only collected over a short period of time, and only using a single sensor to collect backyard data. To test these issues, our next steps could include placing a BME280 sensor in multiple locations within Anna’s backyard to test its sensitivity to hyper-local environmental factors like shade or direct sun. Longer-term monitoring across different seasons could also help determine if the observed differences are persistent throughout the year. Also, deploying multiple sensors in different areas within the backyard could help account for possible issues with individual sensor's calibration.

Ultimately, the observed differences between Anna's backyard and Bowman Field are notable and could possibly suggest a microclimate in Anna's backyard, influenced by local factors such as vegetation, buildings, and possibly the UHI effect. Additional testing would be needed to support this hypothesis.

References

Bui, Van-Diep, et al. "Applying ESP32 and LoRa RA-02 Module, Controlling and Monitoring Water Saving System in Agriculture." *International Journal of Advances in Engineering and Management (IJAEM)*, vol. 6, no. 8, Aug. 2024, pp. 62–70.

Simitha, K. M., and Subodh Raj M. S. "IoT and WSN Based Air Quality Monitoring and Energy Saving System in SmartCity Project." *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, IEEE, 2019, pp. 1431–1437.