
Agriscanner

*A deployable weather station network and linked microclimate forecasting
webapp*

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Executive summary

Dedication and acknowledgments

Author's declaration

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1 Introduction

In this report, I describe an online webapp called Agriscanner, which collects and displays microclimate data from an *Internet of things* (IoT) weather station network that I designed and built. The webapp can present live, historical and forecasted weather data to the user. The live and historical data is retrieved from a separate PostgreSQL database that collects and stores readings from my weather station sensor nodes every minute. These historical readings were used to build a machine learning model that can predict future microclimate specific weather based on the general forecast.

The weather station network was built using off-the-shelf components and housed in hand made enclosures. The deployed system consisted of four components: two field sensor nodes capable of reading weather data and transmitting it using a modern radio protocol called LoRa; a repeater that boosts received LoRa signals; and an internet connected gateway that uploads the weather data to an online database. The hardware in this project was tested in a private garden with deployment to Small Brook Farm in Exeter planned in future. Due to the timeframe this was not possible within the submission deadline.

1.1 Motivation and aims

Weather forecasts are typically based on data from distant weather stations and large scale models which fail to capture variations that exist within a single farm or even field. These local variations, known as microclimates, can differ significantly even across relatively short distances due to differences in factors such as elevation, tree cover, or soil type.

For example, in a set of interviews with the owners of Small Brook Farm (Appendix B) the owners note that the use of traditional forecasts on their orchard is not particularly useful for them. As weather forecasts tend to cover wide areas and are not always indicative of very local conditions. The owners even mentioned that the weather conditions across a single field of apple trees was different, with higher winds on one side compared to other.

This uncertainty has real world consequences for farmers, at Small Brook Farm for instance wind speed is a key determinant of when the farmers can spray their crops with pesticides. Equally, general forecasts are not well equipped to predict a spring frost that damages crops or the precise incubation period of pests and diseases.

Agriscanner aims to address this need for accessible local weather forecasting by giving farmers a weather station platform that can both relay current weather information from different sections of their field and predict future weather for their specific location.

1.2 Contributions

The key contributions of this paper are:

- The development of a low cost, long-range remote weather station system with superior range and reduced cost compared to current solutions on the market. The long range allows for readings from the field to be communicated to the cloud without a need for internet access in the field.
- A publicly available web application for visualising live data from multiple field locations, that demonstrates a high degree of usability across both mobile and desktop platforms, as

confirmed by quantitative System Usability Scale (SUS) evaluation.

- A method for enabling microclimate forecasting using a machine learning process that compares local sensor data with broader regional weather forecasts. This allows farmers to get a hyper-local forecast of future weather conditions that is specific to their field and optimise agricultural tasks such as spraying.

1.3 Project schematic and layout

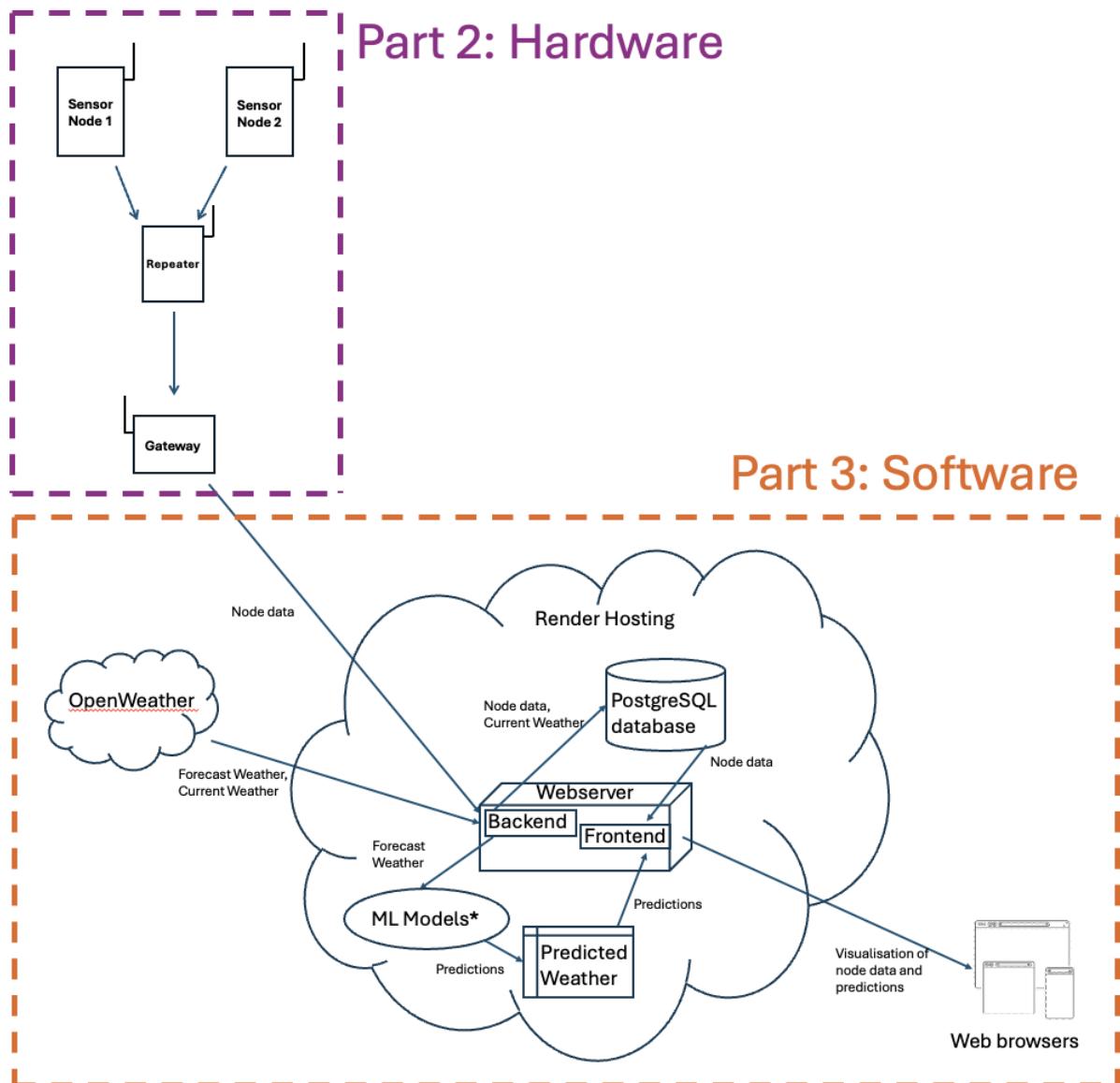


Figure 1: Schematic of entire project showing data paths

Figure 1 shows the design of the my entire project, which has been split into hardware and software categories that correspond to parts 2 and 3 of this dissertation. A zoomed in version of each category is shown on the overview of its respective part (see hardware overview in Chapter 5 , and software overview in Chapter 10).

Part 1 provides the technical background to understand the project, including an overview of

the core technologies used and a review of related work in the field.

Part 4 then offers a critical evaluation of the system, discussing its performance, usability, and limitations, as well as highlighting opportunities for future development improvements and research.

Part I

Background

2 LoRa

Before analysing IoT systems more generally, I will explain the most critical hardware enabling technology for this project which is the radio communication technique known as LoRa.

2.1 What is LoRa?

LoRa stands for **L**ong **R**ange and it is a radio modulation technique invented in 2014 that allows for the transmission of data over very long distances. It is one of several competing low power wide area networks (LPWAN) but the hardware to use it is much more widespread than these other networks. LoRa has a range over 4000 times greater than WiFi [1], a range that it can achieve with remarkably little power (Table 1). This makes LoRa the preferred technology choice for the remote, off-grid application in this project.

For a brief overview of the principles behind LoRa I have written the supplementary section "How LoRa works" in Appendix G. However, to summarise, the most important principle that separates LoRa from traditional radio modulation is the fact that it can demodulate incoming signals more efficiently.

2.2 Benefits and limitations

The benefits from the ability of the LoRa receiver to demodulate signals more efficiently is two-fold. First it reduces the power needs on transmitter and receiver: the transmitter sends less powerful signals because the receiver can more easily distinguish signals; in turn the receiver can also demodulate with a lower power budget because of the easier correlation process with LoRa chirps.

The second related benefit is the ability for the receiver to demodulate signals which are below the noise floor (the sum of all interfering signals). Essentially, even when background noise is 'louder' than the LoRa signal, the receiver is still able to distinguish and process the data in the signal. This helps LoRa transmitters to broadcast signals with a far greater effective range despite it's low power.

Technology	Wireless Communication	Range	Tx Power
Bluetooth	Short range	10 m	2.5 mW
WiFi	Short range	50 m	80 mW
3G/4G	Mobile network	5,000m	5000 mW
LoRa	LPWAN	2,000–15,000m	20 mW

Table 1: Comparison of wireless technologies (Source: [2])

3 *Internet of Things*

3.1 What is IoT?

The Internet of Things (IoT) refers to the concept of integrating networking capability in a range of devices, allowing for cooperation to reach common goals [3]. A similar but more colloquial term would be "smart" devices.

IoT has become increasingly common in recent years as a number of technological breakthroughs has made deploying these networks more practical. These advances, which I am referred to as "enabling technologies", provide the foundation for modern IoT systems. LoRa is a key example described in Chapter 2, a further list of enabling technologies is available as a supplement in Appendix H.

3.2 The layers of IoT

All IoT relies on the existence of three fundamental network layers [4], working from the bottom to the top there is:

1. Perception - This layer contains sensors that collect information about conditions in the world around them. This layer may perform some transformations on the data it receives (e.g. sorting, formatting) or just transmit raw data. An example of this is a smart car charger collecting data on the charge level of an electric car.
2. Network - This layer acts as the bridge between the perception layer and the application layer. It is the medium and protocols associated with the transmission of data and the hardware necessary to interpret this. Following the above example this could be the use of WiFi or a mesh protocol such as Zigby to transmit the car's current charge level to a gateway - such as a WiFi router.
3. Application - This encompasses any software that manipulates, displays or otherwise uses data from the perception layer. This could be hosted on the cloud or locally. In the example above this could be an app that shows the current charge status of the car.

The hardware overview in Chapter 5 presents the components of my IoT solution in the context of these layers.

3.3 Studies using LoRa IoT weather stations in agriculture

The use of IoT in agriculture has become widespread in recent years as it offers the opportunity for farmers to improve yields and cut costs by bringing digital solutions that would not have previously been viable without access to power and internet connectivity. The use of IoT in agriculture is often wrapped up in the moniker of "Smart Farming", which encompasses a range of digital, robotic, and internet-enabled approaches to improving efficiency. A 2019 review by Farooq et al. [5] reveals the scope of IoT applications in agriculture. These include precision farming (IoT weather monitoring), automated irrigation, pest and disease prediction with

machine learning, and even the deployment of agricultural drones for spraying, mapping and imaging.

There have been a few studies around the use of LoRa in smart farming applications. In [6] LoRa was used in an edge computing exercise - a procedure to compress data from multiple LoRa sensor nodes is created and analysed. However, a criticism of this study is that they only implement a single sensor and all results are drawn from a computer generated sample. Additionally the range used for this single sensor to the gateway is only 200m, which is not a realistic distance for most agricultural purposes which the study is explicitly targeting for.

The study in [7] implements a LoRa based weather station prototype in India. The authors create a fairly simple node with two sensor types. After this the data from the nodes viewed using an OLED screen on the receiver.

However, a significant criticism of this work is that it fails to specify the range at which the LoRa communication was tested, which is a critical parameter given that the technology was chosen specifically for its long-range capabilities. Additionally, while the paper suggests the model is suitable for large-scale deployment in a farm field , the experimental setup only consists of a single transmitter node and gives no details on whether had any weather proofing put on it.

This project aims to contribute to this literature by producing a more complete weather station prototype that is weatherproofed for outdoor deployment using multiple nodes and validated over more realistic distances.

3.4 Commercial IoT agricultural solutions with LoRa

While IoT weather station solutions are available commercially there are issues with using these.

Virtually all affordable weather stations rely on WiFi to stay connected which is not viable for most farms as there is a large separation between the fields they need to be deployed in and buildings with WiFi access. As discussed in section 2.2, WiFi has just a fraction of the range of LoRa so these types of stations are not comparable to my own. This is explored in greater depth in the evaluation (see Chapter 15).

4 Microclimates

This section gives academic background on microclimates with a focus on their relevance to agriculture, and then looks at related attempts to predict microclimate weather.

4.1 What is a microclimate?

A microclimate is generally understood as a set of distinct climatic conditions within a small, localised area [8]. The maximum size of a microclimate is debated, but the World Meteorological Organisation (WMO) regards it as occupying an area of anywhere from less than one metre across to several hundred metres [9]. In practice, microclimates can occur in spaces such as gardens, valleys, caves, or fields. Even human-made structures can generate their own microclimates; for example, tall buildings can create *street valleys* that reduce wind flow and lead to the formation of localised pockets of warmer air, which also trap higher concentrations of pollution from vehicle emissions [10]. Vegetation plays a critical role in influencing microclimates. The addition of trees to an urban environment can reduce air temperature by as much as 2.8 °C [11].

4.2 Microclimates in agriculture

Microclimatic variations have profound implications for agriculture, as the climate that crops are exposed to has an enormous impact on overall agricultural yields. Indeed, farmers have modified the microclimate of crop fields for millennia, a clear example of this being the use of fencing to reduce soil erosion and damage to edible plants [12]. Therefore, the relationship between microclimates and agriculture has been the subject of extensive research, particularly as climate change introduces new threats to food security.

A Danish study by Haider et al. investigated how agricultural pests and diseases are influenced by microclimatic conditions. Temperature sensors were installed in six different pathogen habitats (such as hedges and cattle fields). The data revealed that the daytime temperature in these microenvironments was significantly higher than those predicted by Danish weather forecasts. Using these measurements, the researchers then estimated the incubation periods of various pests and diseases, demonstrating that elevated temperatures in microclimates could shorten incubation times and thus accelerate the risk of outbreaks [13].

Another important aspect of microclimates for farmers is how it can affect frost risk - sudden and unpredictable drops below freezing in crop fields that damages plants and are particularly common in spring. A principal factor for this is a lack of "cold-air drainage". In areas with depressed topography, cold, dense air can accumulate to form pockets of cold air where temperatures can be several degrees lower than the surrounding landscape [14]. These local conditions may not be captured by weather forecasts highlighting the need for more precise monitoring and development of effective early warning systems.

4.3 Microclimate prediction using machine learning

There have been a number of recent studies where machine learning has been used to help predict micro climate conditions in agricultural settings. General weather models operate at magnitudes between 1 and 10 km and microclimate predictions require models that operate at scales of roughly 100m or less. Using current numerical weather prediction models for micro-scale predictions is computationally expensive [15], and these models have lower accuracy rates than predictions using ML due to the inherent complexity and non-linear nature of microclimates.

A number of the studies described here focus on comparing the accuracy achieved by different types of Machine Learning, and highlighted a distinction between Machine Learning (ML) and Deep Learning (DL). They are both systems that learn from data and make decisions based on datasets provided when the systems are trained. Machine Learning techniques include decision trees, regression and neural networks. Deep Learning systems are a type of Machine Learning that uses neural networks with many layers and is used to model more complex patterns with larger datasets. The table below provides a summary of the studies included in this section

Table 2: Selected summary of machine learning studies

Study	Location	Type of learning	Learning framework	Source of forecast data	Source of training target data
Agriscanner (This work)	Outside rural - South Gloucestershire, UK	ML	LightGBM	OpenWeather	Sensor readings
Kumar et al. (2021)[16]	Various	DL	LSTM	Not specified	Sensor readings
Zanchi et al. (2023)[17]	Outside rural; Italy, Lombardy	DL	Feed-forward neural network	ERA5 ARPA	Sensor readings
Blum et al. (2024)[15]	Outside urban; London, UK	ML & DL	Multilayer Perceptron Random Forest XGBoost	UKV weather data	Citizen weather stations
Abdelmadjid (2025)[18]	Greenhouse - Unknown	ML & DL	CNN-LSTM LSTM (DL) SVM-RBF Prophet LightGBM XGBoost	Public kaggle dataset	Public kaggle dataset

A 2021 study by Kumar et al [16] developed a machine learning framework called DeepMC as a part of a Microsoft Research initiative. Their model is able to predict a variety of climatic variables such as soil moisture, wind speed and temperature using inputs from weather station forecasts and IoT sensors. They were able to get up to 90% accuracy with a 12-120 hour forecast range.

Zanchi et al [17] used physical modelling of local terrain combined with deep learning to forecast the microclimate in the foothills of Lombardy. The objective was to predict the local conditions at the meter-scale as opposed to the 10km+ scale of regional and global weather forecasts. The initial model combined data about the morphology of the local terrain and weather forecast data to provide the input data for two feed-forward neural networks. These neural networks were trained to predict the local weather variables using data from 25 sensors deployed in the region being studied. The study demonstrated that local predictions were more accurate when using forecast data from local weather stations (ARPA) as opposed to global climate datasets (ERA5), but accuracy was still good either.

This study is of particular interest for this dissertation as it used IoT sensors to generate the training targets for the neural networks and in this regard is the most similar to my design. The paper also includes a discussion of problems with reliability of the sensors - only 4 out of 25 units ran with failure over the period of the study - and the need to clean the data to ensure these failures were excluded from the training data.

Blunn et al [15] ran a study focussed on predicting temperatures in urban environments during heatwaves, using data from eight heatwaves in London, UK. They used data from the UKV - a high-resolution weather forecasting model - and from citizen weather stations (CWS), made available via the Weather Observations Website - a cloud platform where individuals can upload data from their personal weather stations. The study tested a variety of ML models including one DL model. The authors used a similar model training design to that used in this dissertation. The models were trained on UKV variables and CWS variables to bias correct the UKV readings and create a forecast prediction model that could predict the CWS readings accurately (mean average error: 0.12°C) compared with the general weather readings from UKV (mean average error: 0.64°C).

A very recent paper from Abdelmadjid 2025 et al used online datasets from Kaggle to develop an ML tool to predict changes in temperature and humidity within greenhouses in response to changes to external weather conditions. They used this data to test 3 ML models and 3 DL models and selected the LightGBM ML model and the LSTM DL model as the best performing models for prediction. The overall system design consisted of 4 LSTM models feeding into the LightGBM model. This design resulted in 98.45% accuracy for temperature predictions and 99.61% accuracy for humidity predictions. This study informed my decision to use the LightGBM model for my system as they found it to be reliable and effective in capturing underlying data patterns.

Part II

Hardware development

5 Overview of hardware

The design for the final IoT system involved three distinct module types: Sensor node, repeater and gateway. The system involves two separate sensor nodes that are placed in range of the repeater. The repeater is then placed in range of an internet-enabled gateway endpoint to allow the uploading of climate data to the cloud.

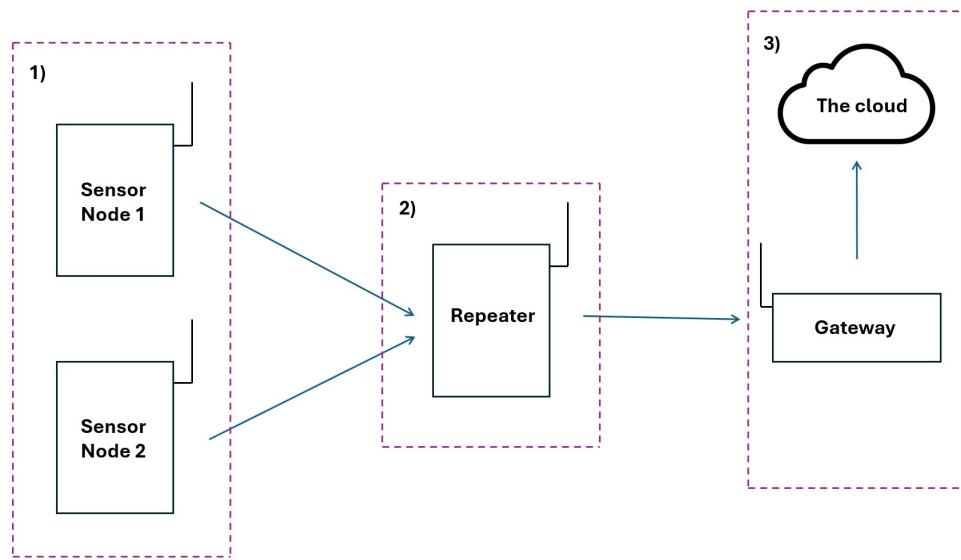


Figure 2: Network diagram of the system

1. **Sensor Node:** The two nodes in this part of the network are in the perception layer. The nodes collect readings on temperature, humidity, wind speed and soil moisture levels. The results are collated into a comma separated string which is then emitted as a single packet from the LoRa transmitter.
2. **Repeater:** This module is part of the network layer of the system as it facilitates communication between the perception layer and the application layer. The repeater reads and decodes received LoRa signals from the sensor nodes. It then adds signal strength information to the string and re-emits the LoRa signal. The repeater has no sensors but is otherwise identical to the nodes.
3. **Gateway:** The final part of the hardware system is the gateway - which is also part of the network layer. The gateway consists of a challenger to receive LoRa signals connected to a raspberry pi which can read the the decoded LoRa messages from the challenger's serial output. The raspberry pi also has a WiFi radio onboard so it is responsible for the uploading of data to the cloud.

6 Design

6.1 Nodes

6.1.1 Components

The first step in the design process was selecting hardware components that could operate autonomously without mains power. This required devices that were highly power-efficient, while also being capable of transmitting small data packets via LoRa. An equally important consideration was weatherproofing the final enclosure to protect the sensitive electronics from water ingress and environmental damage.

Challenger RP2040 LoRa

The iLabs Challenger RP2040 LoRa (Figure 3) is an embedded computer that uses the Raspberry Pi RP2040 chip that was released in 2021. The RP2040 itself is a low-cost and power-efficient processor with ample power to perform the data encoding and transmission in my use case. Additionally, the chip is extremely popular with over 10 million units being produced in the first two years of release [19]. This popularity means there is ample documentation for developing with this processor.

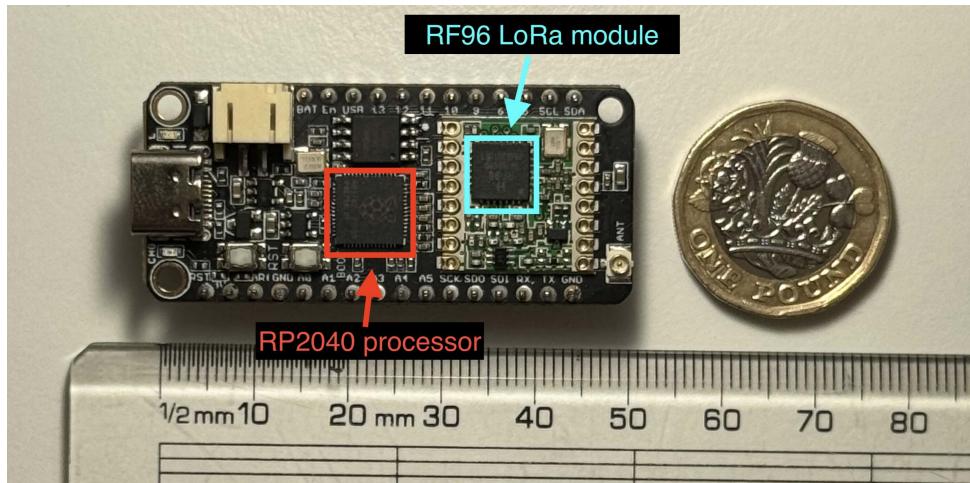


Figure 3: iLabs Challenger RP2040

The Challenger board itself is well suited for this project for several reasons. It uses the compact Adafruit feather form factor, giving a board dimension of just 5cm by 2cm, making it easy to mount in a small enclosure. The onboard Hope RF96 LoRa modem is built directly into the board and the U.FL antenna connector allows for the swapping of antenna's to different varieties. This board's LoRa module is also set to transmit at a frequency of 868mhz which is a standard UK frequency for LoRa and gives a good balance between range and bandwidth.

Another useful aspect of the board is the abundance of GPIO pins (20 in total) allowing for a large number of sensors to be fitted to the board.

Antennae

The selection of antennae is one of the largest determinants of range and reliability in the context of wireless communication systems [20]. Initially I used a simple PCB antenna as shown in Figure 4, however as explained in the next chapter, the range of this was insufficient for my use.



Figure 4: Low range PCB antenna

To improve overall range I switched to a more capable omnidirectional whip antenna that was made specifically for the Challenger RP2040. The antenna is tuned to perform best at the 868mhz frequency range - which is the range I was using.

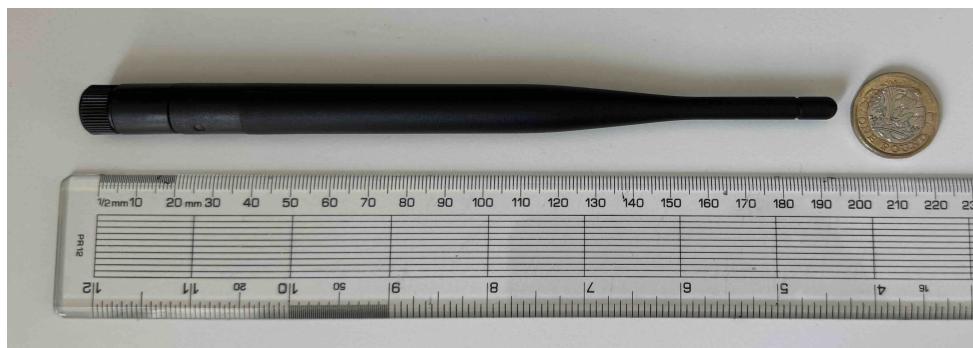


Figure 5: iLabs whip style LoRa antenna (868mhz)

Sensor selection

Temperature and humidity sensor

I used a DHT11 temperature/humidity sensor (Figure 6) for each node to provide basic readings. It was chosen for it's low cost, availability and compatibility with both the RP2040 Challenger and CircuitPython (via libraries). The sensor can be connected to the microcontroller using a single GPIO pin as well as the usual power and ground pin.

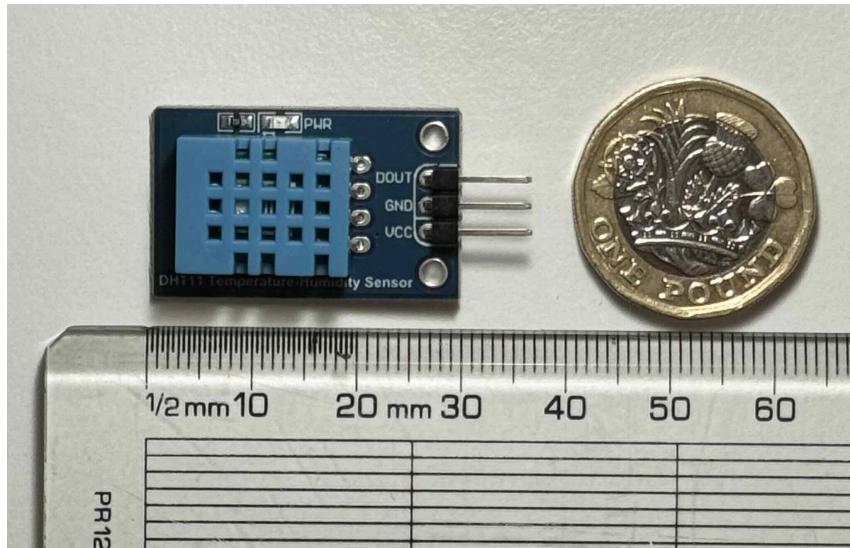


Figure 6: Waveshare DHT11 temperature/humidity sensor

Soil moisture sensor

A capacitative soil moisture sensor (Figure 7) was chosen over the alternative resistive style. The benefit of capacitative sensors is they are not as prone to corrosion of the diodes. In a resistance sensor the diodes must be bare plated metal in order for resistance between each diode to be measured. However the disadvantage of this is that bare metal corrodes in the presence of water, and corrosion affects the accuracy of the sensor. For this reason I went with a capacitive sensor as the diodes are covered by a protective layer making them much less susceptible to corrosion.

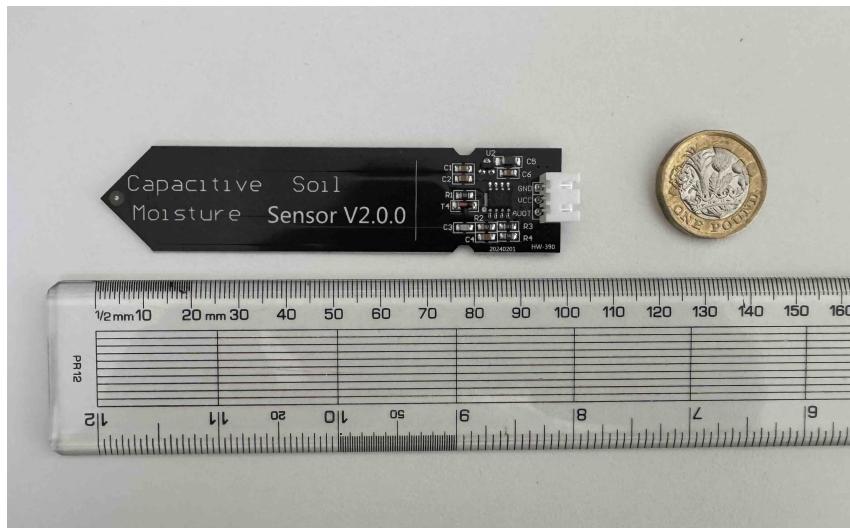


Figure 7: The Pi Hut capacitive soil moisture sensor

Wind speed sensor (Anemometer)

The anemometer chosen (Figure 8) was the DFROBOT wind speed sensor. It balances value with construction quality as unlike many other cup style sensors this is made of metal and rated for outdoor use. At the time of purchase I was unaware that the RS485 serial communication protocol that the sensor used was not compatible with the Challengers UART protocol. Fortunately, I was able to purchase an RS485 to UART serial converter that allowed the devices to communicate.



Figure 8: DFROBOT wind speed sensor

A second issue was that the anemometer needed a 7v-24V input voltage to take readings while the maximum voltage the Challenger can provide was 5V. To remedy this I bought a 9V step up converter to boost the Challengers voltage to the required level.

Powering the node

To allow for continuous operation away from power sources, I set up a 6W Monocrystalline Silicon Solar Panel (Figure 9) to each of the nodes. As the output from the solar panels was at too high a voltage to directly power the nodes, and as power was required overnight, I also installed a solar power management module (Figure 9) onto the Challengers. This module uses the solar panel to charge a battery that is installed on it. When solar power dips overnight the battery will discharge to power throughout the day.

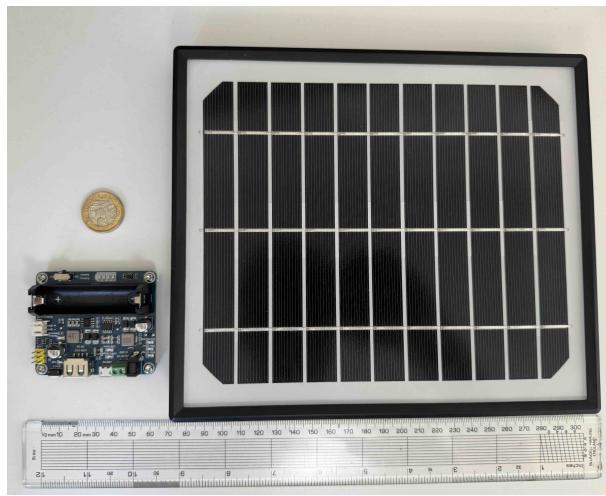


Figure 9: Waveshare solar power management module (left), solar panel (right)

6.1.2 Repeater node

To improve range I used one of the Challenger boards as a repeater. This meant it did not require sensors and instead simply had an antenna, solar panel and battery connected up to it.

The repeater would receive signals from the two nodes before relaying them to the final gateway. This has the effect of essentially doubling range.

6.2 Gateway

The gateway consisted of a fourth Challenger RP2040 connected to a Raspberry Pi 5 with 8GB of memory (Figure 10). This Raspberry Pi was significantly more powerful than was actually needed for the purpose of a gateway and a cheaper alternative would have been sufficient however I was able to use a university provided one for the project. The Challenger receives messages from the repeater and then transfers these to the Raspberry Pi. After receiving the Challengers output the Raspberry Pi sends a POST response to my backend API which then inserts the data into a separate SQL database.

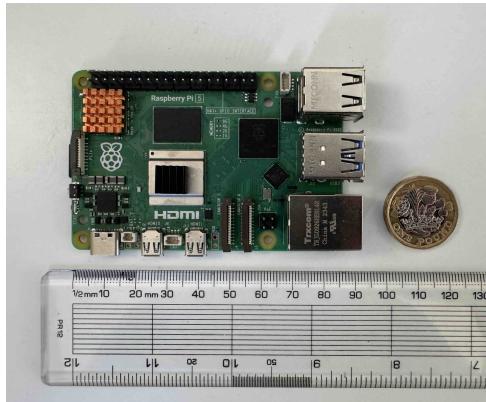


Figure 10: Raspberry Pi 5 (8GB)

7 Development and testing

7.1 Range tests

One of the most important tests to carry out prior to deployment in the field was testing the range of the devices.

In this experiment I took four Challenger RP2040s to The Downs, a large public park in Bristol. Here I tested four different antenna configurations to compare how well the signal travelled across an increasing distance. Signal strength can be measured using the received signal strength index (RSSI), a measure of the difference in signal from the transmitter to the receiver and measured in decibels.

For the test, two Challengers were programmed as transmitters, sending an example data packet similar to the data that was eventually used once deployed. One of the transmitters used a simple PCB antenna (Figure 4) while the other used a higher range whip style antenna (Figure 5). Then I programmed two Challengers as receivers, again one had a low range antenna and the other a long range one.

This meant that four different antenna configurations could be tested concurrently, as the receivers could pick up the signal from each transmitter. Before performing the test I estimated that the maximum range of each configuration would look like the below:

1. Whip antenna to whip antenna (Likely best result)

2. PCB antenna to whip antenna
3. Whip antenna to PCB antenna
4. PCB antenna to PCB antenna (Likely poorest result)

The reason I predicted the PCB transmitter to whip receiver to outperform the whip to PCB configuration is that improving receiver sensitivity (i.e. the ability of the receiver to 'hear') is more efficient than increasing the transmitters effective radiated power (how loud it shouts) [21].

Nine different distances from transmitter to receiver were tested, in 200m increments starting from 0m as a baseline to a distance of 1600m (Figure 11). An important aspect in getting a successful LoRa connection is whether there is line of sight between the transmitter and receiver. Figure 12 shows the elevation profile of the test area, with the initial large dip being an inaccuracy from google earth's topology data as the 0m point is near a cliff edge. The lowest elevation point is at the starting point at around 83m above sea level, while the highest point was at the 1km mark at around 94m making an elevation range of 11m. My hypothesis was that signal would likely drop off or stop entirely beyond this point as points beyond 1000m would be below the hill line. This would effectively mean that the receivers would be in a signal shadow point where the transmission waves would not be able to reach them. The only possibility for signal to reach this area would be from reflections either from nearby buildings or topology. However the effects of reflections are virtually impossible to account for in the real world and therefore no accurate predictions could be made.



Figure 11: Google earth image of data collection points

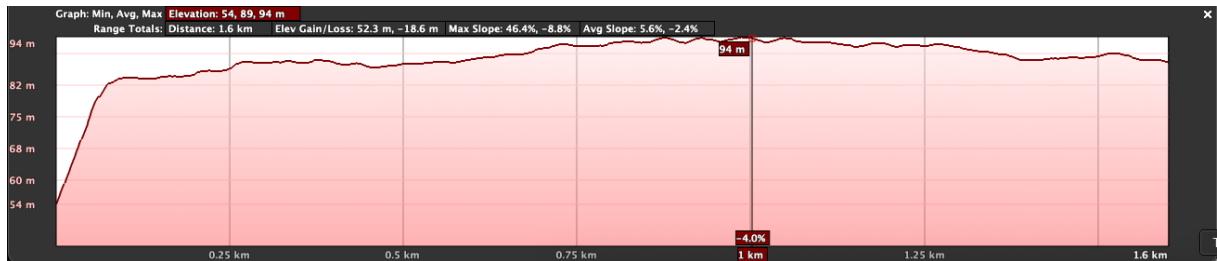


Figure 12: Elevation profile of test area (ignore large dip at start)

At the time of the actual test however a festival was being run between the 1200m and 1400m mark. The festival had a number of large tents and temporary buildings constructed which very likely negatively affected the signal. Final data for the range test is shown below

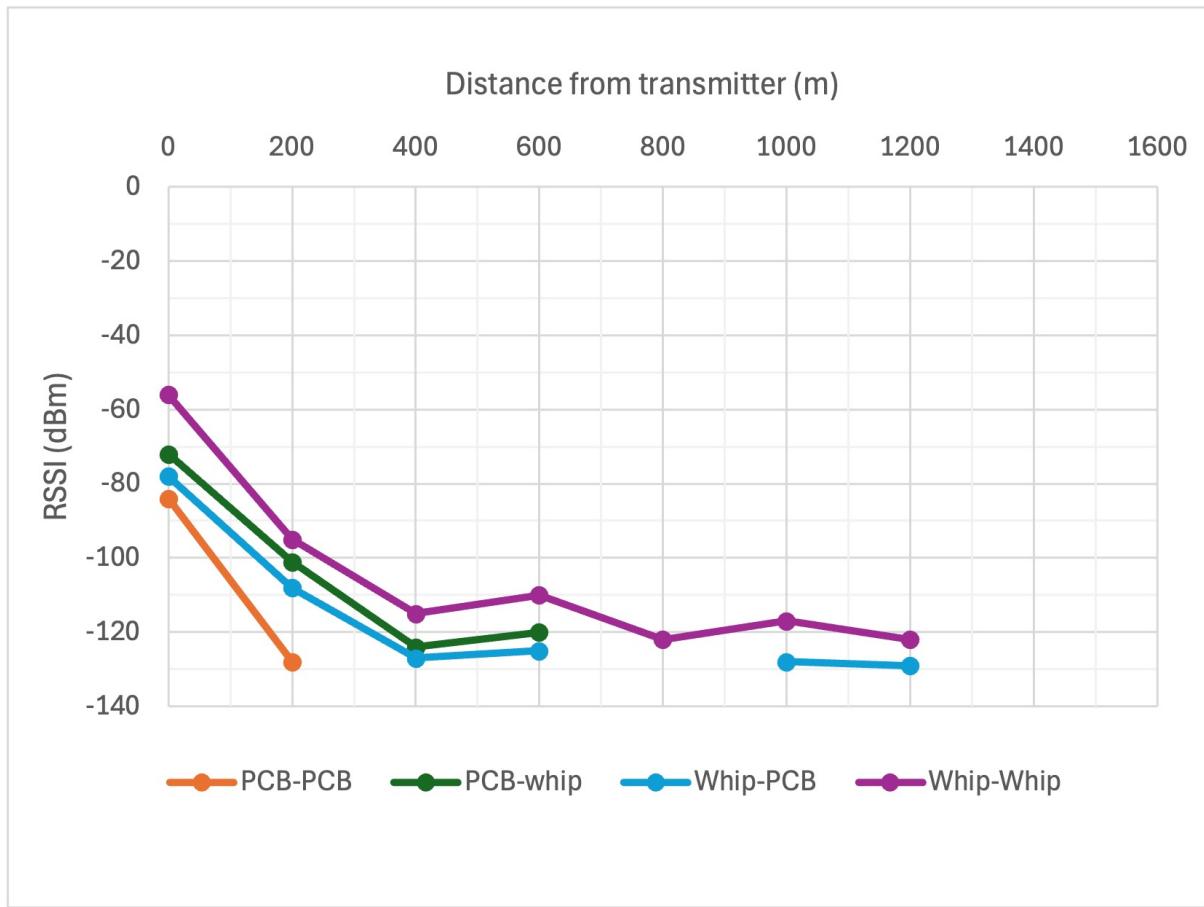


Figure 13: Graph to show signal loss from different receiver and transmitter configurations (higher is better)

Unsurprisingly, the results show that the whip to whip antennas had the best performance. It was the only configuration that consistently received signal all the way to 1200m. In contrast with my prediction, the whip to PCB configuration was the second best and even received a signal at 1200m; although this was less consistent and had a lower signal strength compared to the whip-whip. I am unsure why this was superior to the PCB-whip but clearly the increased effective radiative power had a greater bearing on the RSSI than the sensitivity at the receiver end. The PCB-whip managed only half the range at 600m and the PCB to PCB managed just 200m, demonstrating its inadequacy for application in my project.

7.2 Battery tests

There is no mains electricity available in the apple field so the nodes must be able to operate without an external power source. Even with the use of a solar panel the node must be able to work through the night and during periods of dense cloud coverage where the solar panel will not have sufficient power to keep the node running. This is where the use of a battery is particularly useful as the solar panel can charge the battery with excess energy during periods of excess solar radiation, such as during midday hours, and then store this energy for periods of low or no solar radiation.

However, while daylight will be of little concern during the summer months when this dissertation is being written, there will be far fewer days of usable sunlight over the winter period. As the UK has very high latitude, there is large seasonal variation in the length of a day. For the town of Crediton (the nearest town to Small Brook Farm), in the summer there are 16.5 hours of daylight while in winter it receives only 7.6 hours; making one night 16.4 hours long. Therefore the node must have a battery sufficiently large to power it for a minimum of 16.4 hours with some additional charge to account for high cloud cover during the early evening and morning period.

To see if the battery solution was sufficient for this environment a test was run on a fully charged 18650 battery that was then connected to the solar power manager to allow the voltage to be regulated up to the Challenger's 5V input voltage.

A digital multimeter was installed between the solar power manager and the Challenger's usb c input to view the voltage and current in real time as well as running a timer for the test and a calculation of the number of watt-hours consumed by the node. The node was then run with a full suite of sensors attached. During the test the node used 80ma at 5V for a wattage of 0.4W.

The node ran until the battery would no longer discharge, with the final battery life of the node being 19 hours and 17 minutes. The meter showed that the node consumed 7.96Wh of power. Considering the battery capacity is 9 Wh it may seem that the battery ran out too quickly. However, the solar power manager documentation tells us that the battery boost efficiency - being the conversion of battery voltage from native 3.7V to 5V output - is only 86%. With that in mind the predicted effective capacity is 7.74Wh, which is very similar to the actual result.

The achieved result of 19 hours should be sufficient for running the node continuously for much of the year as this compares to the longest night period of 16.4 hours. However, during periods of heavy cloud cover in winter there is a chance the node would not be able to charge the battery sufficiently in the day to allow the node to run over night.

7.3 Solar panel testing

The solar panel is rated for 6W maximum power. This however would only realistically be achieved under optimal conditions with a clear sky and full sun around midday. This power rating was verified using a multimeter on such a day where a voltage of 7.02V and an amperage of 0.87A was measured, giving a final power of 6.1W.

As explained in the battery section above, the node consumed about 7.96wH over a 19 hour and 17 minute period. We can therefore determine that the node requires roughly 10wH of energy per day to be able to run continuously. It would be tempting to then say that the node would need less than 2 hours of ideal sunlight to operate for an entire day (being $6W * 2h = 12Wh$). However we must also account for the energy loss when converting from raw solar output to the regulated 5V input that Challenger accepts.

The solar panel manager rates its conversion efficiency for solar at 78% meaning for each watt of solar energy received 22% of this will be wasted as heat when converted to the correct voltage.

If we adjust for this loss we would need effectively 12.8Wh of energy just to power the node for a day, which equates to 2 hours and 8 minutes of ideal conditions.

An additional 9Wh is needed to charge the battery which if we adjust again for solar efficiency factor we get 11.5Wh. This is an additional 1h:55m of ideal sun, leaving a total sunlight requirement each day of 4h:03m.

7.4 Hardware assembly and weatherproofing

Since most of the hardware in this project contains exposed electronics, the final assembled devices needed to be made wind and water resistant to prevent failure. However the sensors and solar panel also needed to be exposed to perform their function effectively - e.g. a solar panel must have a clear view of the sun throughout the day. The final design therefore needed to balance multiple conflicting purposes:

- The core electronics (Challenger, solar manager, battery etc) must be kept dry, cool and away from wind which may damage electronics.
- The wind sensor must be exposed to the elements and securely fastened to withstand intense wind, it must also be kept high off the ground for more accurate readings.
- The solar panel must be exposed to the elements and be south facing at an angle of 30-40 degrees to optimise solar efficiency.
- The soil moisture sensor must be inserted into the ground and as it has exposed electronics must be made waterproof.
- The antenna of the Challenger must be placed as high as possible (at least 1.5m from the ground).
- The temperature/humidity sensor must be exposed to the elements to ensure accurate readings but cannot be exposed to rain due to the exposed electronics on it.

Due to the conflicting nature of some of these needs. The final device would need to allow for positioning of different components at different heights.

The final design therefore was to place most of the sensitive electronics inside a waterproof box with cut-outs for the to allow for external component wires. This was then mounted onto a 2m pole to allow for a good antenna signal and more accurate wind speed readings.

7.4.1 Sensitive electronics

An IP65 waterproof junction box (Figure 14) was selected to house the non-sensor portion of the electronics. An IP rating measures the Ingress Protection of a devices housing against water and dust defined by the International Electrotechnical Commission. The first number of an IP code is a measure of dust resistance while the second number is a measure of water resistance. An IP code of 65 therefore means the box used here has perfect dust resistance and can withstand water jets being sprayed at it from multiple directions [22]. This level of protection should be more than adequate to withstand the heavy rainfall it will experience.

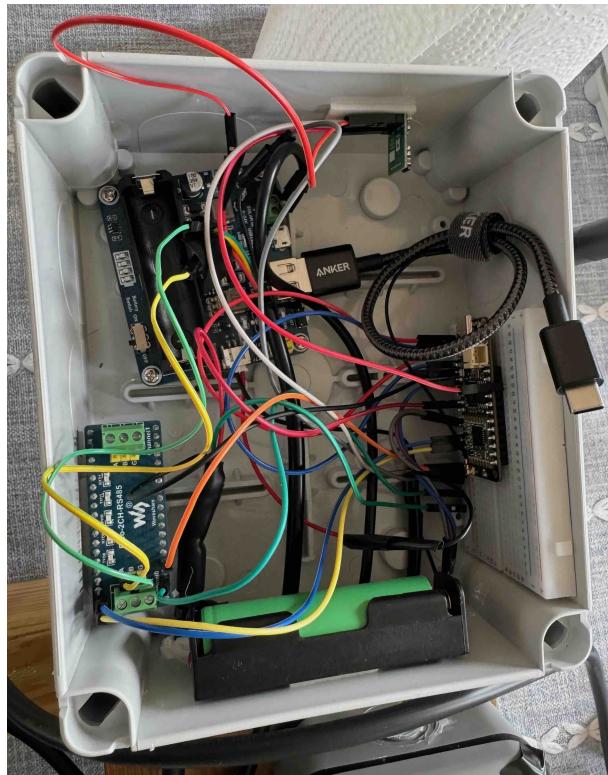


Figure 14: Open junction box showing internal wiring

The Challenger microcontroller was inserted onto a half size breadboard and then stuck to one side of the box. The antenna cable was routed to the top right corner where a small hole was drilled to allow for the antenna to be mounted externally. All the other components were then wired into the breadboard and stuck down with double sided sticky pads to prevent damage during transport or heavy winds. The bottom of the box then had holes drilled for the anemometer, soil moisture sensor, solar panel and temperature/humidity sensor respectively. To prevent water ingress into these holes, sealant was deposited over the holes.

The entire box was then attached to a plank of wood measuring roughly 25cm by 60cm. This board holds all the sensors with the exception of the soil moisture sensor which must be able to hang freely.

7.4.2 Soil moisture sensor

The sensor that required the most thought as to waterproofing and mounting was the capacitative moisture sensor. The first challenge was the need for the soil moisture sensor to be able to reach ground level while the microcontroller collecting its readings was secured 2m above it. The solution to this was to swap the small included wires with a 2.5m weatherproof cable containing three cores (one for power, one for ground and one for data). Each cable core was then soldered onto the sensor as in figure 15, allowing for the sensor to be inserted into the ground.



Figure 15: Soldered soil moisture sensor

Waterproofing the sensor was necessary as while the bottom three quarters of the board are designed to be inserted into soil, the part above this is made up of exposed electronics that must not come into contact with water (Refer to figure 7). This means it was essential to waterproof this part of the board.

To achieve this I followed an online tutorial on a hobbyist website [23]. and painted the electronics using nail varnish. While this sounds unconventional, nail varnish is a non-conductive compound that can be easily painted over electronics using the brush included and so is quite a popular low-cost method for waterproofing electronics. After this is applied the portion of the board with the electronics is covered in heatshrink to form a tight seal over the board, with a layer of nail polish on the edges to reduces the chance of water ingress under the heat shrink's plastic.

7.4.3 Other external components

The DHT11 sensor was mounted inside a smaller IP55-rated junction box, which provides the same resistance against rain as the larger box. To allow for more accurate readings, small holes were drilled on the bottom panel of this so the air temperature inside the box would better match the external temperature/humidity. To further improve the sensor's accuracy, the box was painted white to reflect sunlight, and a solar shield made from a cut and reshaped aluminium can was mounted to the south facing side. This shield (see red box in Figure 15) helps to prevent the sensor being exposed to direct sunlight, reducing temperature distortion while still allowing airflow from the sides.

The solar panel was mounted below the main enclosure using the included adjustable gimbal mount. It was fixed at an angle of approximately 40° from horizontal, which balances solar efficiency throughout the year [24]. This angle is steeper than the optimal summer setting but allows for improved performance during winter months when the sun is lower in the sky. The gimble allows for rotation in all planes which is useful in case the box itself cannot be mounted in a perfect southerly direction.

The anemometer was secured to a separate length of wood, positioned approximately 0.5 metres away from the main unit. This separation reduces turbulence caused by the box and pole, leading to more accurate wind speed readings. The sensor was screwed directly into the wood and positioned at a height of 2m.

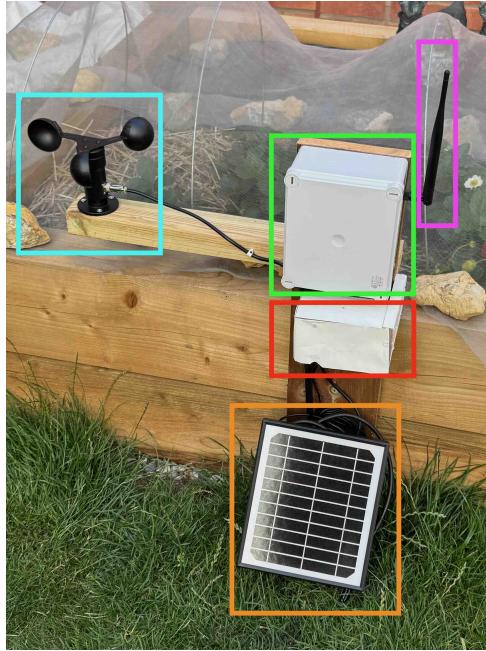


Figure 16: Final node design

Figure 16 shows the final assembled node. From top to bottom, the purple box shows the antenna, the blue box shows the anemometer on its separate arm, the green box contains the electronics, the red box is the solar shield that surrounds the temperature/humidity sensor and the orange box shows the solar panel. Not pictured is the 2m wooden post that extends the height of the node.

7.4.4 Gateway



Figure 17: Completed gateway

The gateway node (Figure 17) required less careful engineering as there was no requirement for it to be waterproofed or mounted externally. As this would eventually be placed inside a persons private home, the aim was therefore to make a minimally imposing and so a design similar to an internet router was chosen.

The two devices inside the box would be the raspberry pi used to upload data and the Challenger which received incoming LoRa packets from the repeater. A plastic box was used with cut outs for the pi's outputs and power cable, with an additional cut out on the lid for the Challenger's antenna. The pi and Challenger were then secured to the box's base with velcro tape, as both

devices would potentially need to be removed for any trouble shooting.

8 Deployment

Before setting up the nodes at the farm it was important to run the equipment in an area where repairs and updates could be more easily performed. The nodes were therefore placed at different locations in my garden and ran continuously from the 15th of August.

8.1 Challenges and solutions from test deployment

An initial challenge identified during the test deployment was that the battery capacity on the sensor nodes was insufficient for continuous 24/7 operation. This became evident on the fourth day of the deployment when, following an overcast evening, one node ceased transmitting at approximately 6:00 AM due to power depletion.

To resolve this, the battery capacity on each sensor node was doubled by adding a second battery. The repeater node did not require this upgrade due to its lower power consumption. Post-upgrade, monitoring of the battery voltage confirmed that the existing solar panels were sufficient to fully recharge both batteries by early afternoon each day. This modification proved largely effective, although there were two more losses of power during the night even after the upgrade. Performance of batteries is explored more in Section 15.1.1.

A related problem was that when the node died it did not start repeating again after this despite solar power returning and the battery getting recharged. I discovered that when the microcontroller detected brownout - being a sudden dip in voltage - the device would enter a safeboot mode. In this safeboot mode the default code.py file would not automatically be run and instead the device would create and use a safemode.py file that without modification would essentially run infinitely unless the reset button on the device was pressed or the device was powered off and on again.

Clearly this behaviour was not appropriate for field deployment where brownouts would potentially occur whenever the battery was discharged completely. Even with the additional battery capacity provided by a second battery there would still be a high chance of this occurring on particularly dark days during winter, where continuous uptime could not be guaranteed.

To remedy this, I modified the safemode.py file using a template I found in the CircuitPython documentation [25]. This version of the safemode.py file was made specifically for the case I was using i.e. remote solar powered projects where manual reset of the board could not be achieved easily. Instead of entering an infinite loop this safemode is designed to enter a low power mode for a short period and then try to cycle power back on.

Disappointingly, the addition of this new safemode was not reliable and occasionally the device would enter a state where a hard manual reset was necessary. This problem is discussed further in Section 15.1.4.

A separate issue was the behaviour of the temperature-humidity sensor when exposed to direct sunlight. While the junction box used to encase the sensor was painted white to reduce any heat transfer from solar radiation, the readings taken on very sunny days showed a large delta of around 5 celsius between the sensor readings and local air temperature readings that could not be explained with the existence of a microclimate.

To reduce this effect an additional solar shield was made to surround the sensor. Consisting of a wooden frame and aluminium shield to block light falling directly on the junction box. This

reduced the delta to a negligible amount.

Part III

Software development

9 Programming the hardware

The Challenger boards can be programmed in a few different languages. The most common of these are C (including C++) and python. I decided to program the boards in python due to the large availability of sensor libraries written in this language. Programming in C, while potentially more efficient, would likely have meant I would need to write my own libraries and functions to get many of the sensors to function properly and therefore was not selected.

The RP2040 processor of the Challenger uses relatively low power, so the versions of python for the chip tend to be stripped down to accommodate this. The two main python versions available are CircuitPython and MicroPython. They both have extensive libraries and work with all the sensors I have selected. With no major difference in their functionality, I settled on CircuitPython as this was the version recommended by iLabs (the makers of the Challenger board) and included a library that supports Challenger as well as example code.

The development process for the sensor nodes, repeaters, and gateway was similar, so the rest of this section will briefly summarise how the sensor nodes were programmed for, as they presented the greatest challenge. The full code for sensor node 1 is available in Appendix I.

I began with the example code that comes as standard on each of the Challengers [26], this was a simple "ping/pong" test program but the LoRa radio initialisation code was very helpful here. I then adapted this program for the sensors outlined in Section 6.1.1, adding the necessary Python libraries for each component. Acquiring readings was relatively straightforward for all sensors except the anemometer.

The anemometer used a communication protocol not natively supported by CircuitPython, which meant I had to build the function `get_wind_speed()` based on the developer's documentation [27] to acquire readings. Getting this function to work with the wind speed sensor was quite time consuming and this software issue was in addition to needing two additional modules to power and connect the device (Section 6.1.1). This made the anemometer one of the most difficult hardware and software challenges of the project.

Once this issue was resolved, the readings were converted to CSV format, and the sensor nodes began transmitting successfully.

9.1 LoRa settings configuration

The most fundamental part of the program for each of the nodes in the LoRa network was that they could communicate with each other. This required the careful matching of LoRa configuration settings between them (see top of Appendix I for full settings). A description of the most impactful LoRa parameters are shown below:

1. **Spreading factor:** Determines how much the signal is spread out over the air, higher rates increase range at the cost of a lower data rate and increased transmission time (which affects

battery life of transmitter).

2. **Frequency:** Must match across devices - this project uses 868 MHz, the UK LoRa ISM band.
3. **Bandwidth:** Determines how wide the signal is, I am using 125 kHz.
4. **Transmit power:** Affects the power and therefore range. This must be set within legal limits (e.g., 14 dBm in the UK).

9.1.1 Compliance with regulatory limits on radio power

The UK has strict regulations on the usage of radio transmitters under the Ofcom ISM band rules. For the 868MHz band, the maximum effective radiated power that can be used is 25mW. This corresponds to a transmit power of roughly 14dB.

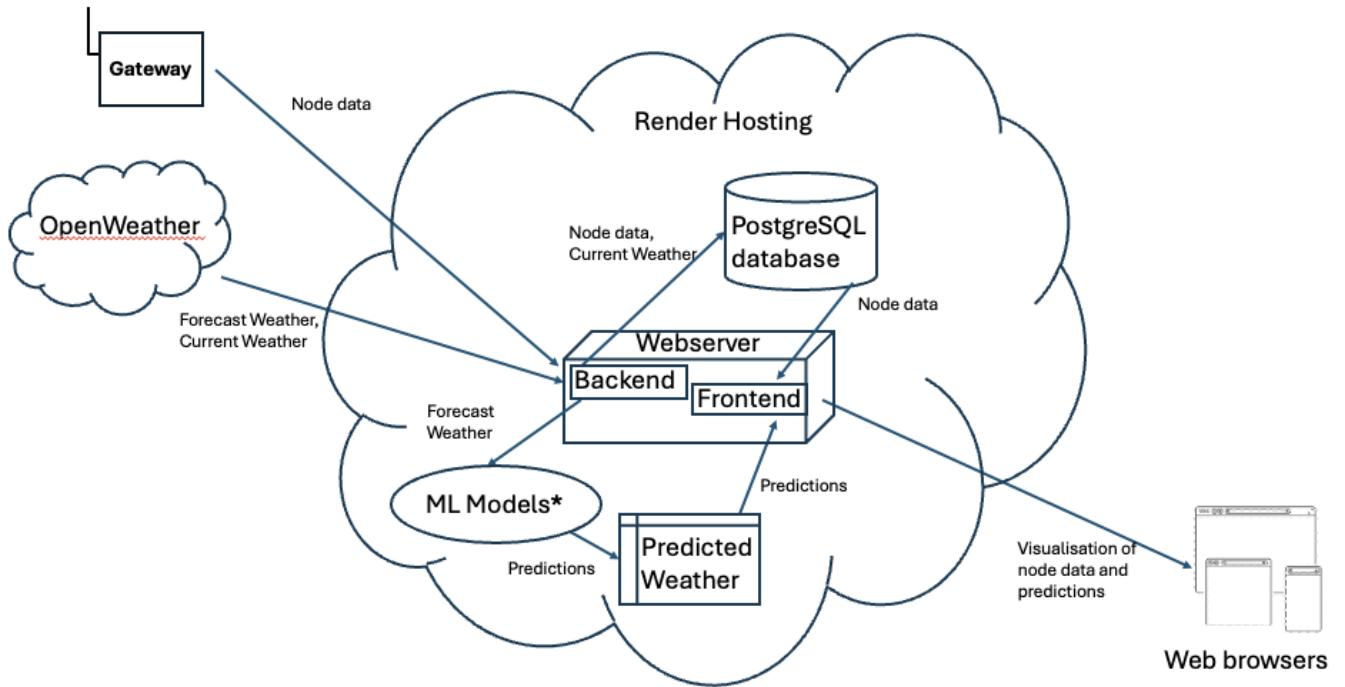
Additionally, the UK has rules on duty cycle rates. This is essentially how long radio signals are permitted to be on air. For example at a spreading factor of 7 a 20 byte message takes approximately 1/15th of a second to send. The duty cycle limit in the UK is 1%, meaning you may only transmit for 1% of the time on a given day. 1% of a day is 864 seconds. This means to stay in line with UK regulations only $864 * 15 = 12960$ messages can be sent on a given day - or roughly 1 message every 6 seconds. My nodes send a new LoRa packet every minute so are well within this limit.

9.2 Remote diagnostics and error handling

Since all the sensors would not be accessible easily errors needed to be reported remotely to diagnose faults and problems. Unfortunately, while the sensor nodes and repeater are LoRa enabled, there is no simple way to send software updates to them other than manually. Therefore I developed my code (see Appendix I) with `try/exception` blocks in python so that if a sensor became disconnected or failed, the exception is caught and the program continues running. Then before the packet is sent out my `find_err()` function scans the payload for errors (which would show as None from the error catching above) and if an error is found then the string `ERR` is sent with the packet.

Diagnostics on the gateway node was luckily much simpler as this was powered on 24/7 and network connected. I therefore could remotely access it with the gateway was added to a Tailscale virtual private network (VPN) [28]. This created a secure connection, allowing diagnostics from any location without complex firewall configuration.

10 Overview of software design



* Training the machine learning models is not pictured on this graph.

Figure 18: Network diagram of webapp

11 Hosting

Both the backend and frontend were hosted on Render [29]. I chose Render as a good low cost option for hosting the web service as it offers a free trial period, constant uptime and backups. A feature I particularly liked was the ability for the server to instantly deploy whenever I pushed a commit through to github, if the deployment on render failed then it would revert back to the previous instance meaning the website was never down.

I have two servers with render, one handles the database and the other runs the backend and frontend. The database server has 256 MB of RAM; 0.1 share of a CPU and 1 GB of storage. A single instance of a Postgres database is available on this service - which is free for the first 30 days and then costs \$5 a month. Meanwhile the backend and frontend instance are run with 512MB of ram and a 0.5 share of a CPU with no storage as all permanent data is held on the database. This second service costs \$7 for a cost of about £10. These resources should be sufficient for this project as only small amounts of data are involved. Eventually, I aim to migrate the website to a university hosted server to remove this ongoing cost.

12 Backend

12.1 postgresSQL database

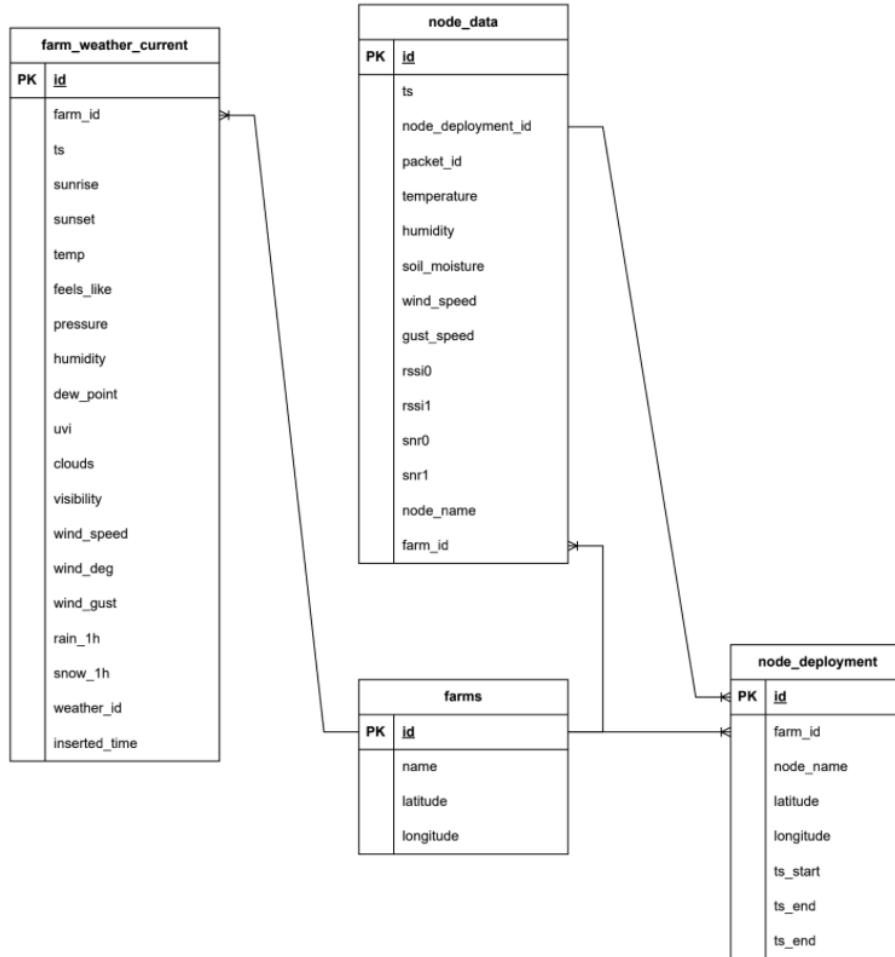


Figure 19: Table schema for PostgreSQL database

The database has four tables:

- farms: this holds a list of where the nodes are (or have been) deployed. The longitude and latitude of the farm is then used in API calls to OpenWeather (more on this below) which is used to fetch current and forecasted weather data.
- node_deployment - This holds the precise longitude and latitude of each node as well as information on when the deployment started and ended. If the nodes are moved then this table is updated with new information.
- node_data - Holds the full set of readings from each node.
- farm_weather_current - Holds current weather information from API calls to OpenWeather taken every 10 minutes and is strictly used to train the machine model explained in the machine learning section.

12.2 Building an API

With the database configured, I then developed a backend API using TypeScript [30], Node.js [31], and Express [32]. This service is responsible for interpreting incoming HTTP requests and performing corresponding database operations - it is essentially the bridge between the gateway hardware and the database. In addition to handling sensor data, the service also integrates with an external weather API in order to retrieve both current conditions and forecast data, which are then stored alongside the locally collected sensor readings as explained in Section 12.1.

The API inserts data into the database when it receives a POST request. The body of the POST request contains a JSON body which is parsed, processed and added to the database by the API. Data can be retrieved for display by the frontend using a GET request.

The entire api is written using TypeScript. TypeScript is JavaScript with added syntax that forces strong typing and features to enable error catching earlier on. When TypeScript is compiled it produces a JavaScript file which contains the actual code that is then executed. The main benefit of TypeScript is that it leads to much more robust code with vastly fewer typing errors that vanilla JavaScript can often let slip by. As I needed my API to have constant up time and reliably insert and select from my database this made TypeScript ideal for this application.

On top of TypeScript I used Node.js and the Express framework. Node.js allows JavaScript to run on the server instead of inside a client browser, which lets the project share a single language (i.e. JavaScript) across frontend and backend development. It is well suited to creating APIs that handle many simultaneous HTTP requests while calling on external APIs. This is because Node runs asynchronously: when slow database queries are being executed Node will continue listening and processing further requests. This non-blocking behaviour means Node can handle large numbers of concurrent requests at the same time. Additionally the node package manager (called with npm) has a large set of useful libraries and allows my project to be rapidly set up on new computers without having to retrieve required packages from different sources.

Express is a framework specific to Node.js that gives useful tools for creating the API endpoints. I used express to write my request-handling functions for each URL endpoint. These functions process incoming HTTP requests to the endpoint and then execute the SQL query associated with that endpoint. Instead of constantly opening new connections with the database I used the pg.Pool library to pool requests together on the same connection. This helped to improve the speed of SQL lookups and inserts helping requests to be executed faster, which in turn improved the perceived performance of the webapp.

In total my api has five endpoints:

- POST '/api/database/insert-node-data' - This endpoint is used by the gateway to fill the database with sensor data. When a valid HTTP request posts to this endpoint the JSON in the body of the request is parsed and inserted into the node_data table. This endpoint has been included in J as an example.
- POST '/api/database/insert-weather-data' - This endpoint is used to insert general weather data from the OpenWeather API into the relevant table. The backend calls this every 10 minutes to collect the latest general weather data.
- GET '/api/database/select-latest' - This endpoint sends the latest sensor data from the node_data table to the computer that sent the GET request. It is used by the front end to display current weather data.
- GET '/api/database/select-node-range' - This endpoint sends back the range of sensor data that is specified in the request body. It is used by the front end to build chart data.

- GET '/api/database/forecast' - This endpoint is used by the frontend to retrieve the latest forecast model data from the backend.

12.3 Security

Security was important in the design of the backend API as the end points are exposed to the internet and thus any internet connected device is able to call these. Therefore I had to take steps to prevent erroneous calls (such as from bots) to my API endpoints which could insert data incorrectly or scrape the contents.

12.3.1 Environment variables

The first step I took was to use environment variables inside Render to hide sensitive information such as API keys and passwords. These variables are hidden from any source documents and are injected separately at deploy time. This prevents the information from leaking into the public domain.

12.3.2 Bearer tokens

Then I needed to prevent any unauthorised machine attempting to perform API calls on my backend. The approach I took to this was to follow guidelines set out in RFC 6750 related to the use of 'Bearer tokens' (essentially a password check) [33]. For this I checked that all incoming HTTP requests to my API had an 'Authorization' line in their headers. I then checked whether the string token after this matched the SECRET_WORD variable in my environment variables. Any request to the database without the correct header and token is automatically rejected.

12.3.3 Protecting against SQL injection

Finally in case those security measures are not sufficient and a malicious actor gets access to my API end points I then added protections against SQL injections. SQL injections are a technique where an attacker can try to manipulate a database by sending a crafted input that alters the intended purpose of the endpoint.

For example if my API end point was designed to allow selections from a database it might naively allow queries such as this:

```
SELECT ${httpBody.column} FROM ${httpBody.table_name};
```

Expecting the `httpBody` to contain a JSON with `column = "*"` and `table_name = "node_data"`, for instance.

However, if someone were to name their column as `"*"` and their `table_name` as `"node_data; DROP TABLE node_data;"` the effective command would change to:

```
SELECT * FROM node_data; DROP TABLE node_data;
```

This command would then select the data as intended before completely destroying the table and all of its data. To prevent this from happening I whitelisted valid inputs like so (psuedo-code for clarity);

```
const white_listed_columns = new Set('*');

const white_listed_tables = new Set('node_data');

if (!white_listed_tables.has(httpBody.table_name)
    or !white_listed_columns.has(httpBody.column)) {
```

```
    return 404 error;  
}
```

12.4 Weather API integration

The weather API I settled on using to help build data for the forecasting function of the webapp was the One Call API 3.0 by OpenWeather [34]. This API offers current weather data at a 10 minute resolution as well as 48 hour ahead hourly and 8 day ahead daily weather forecasts. The API permits up to 1000 calls per day before separate payment is required. As I would only be requesting one current weather data reading and one forecast data reading on 10 minute intervals I would only put through 288 requests per day which is well within the free limits.

To set up automatic API retrieval from my backend to the weather API I used the node-cron library [35] to set up a 10 minute job on my host server. This then called related functions to get both current and forecasted data for use with my machine learning model.

13 Frontend webapp

13.1 Design choices

Before creating the frontend, I reviewed a handful of websites that display weather and other data—including the Met Office, BBC Weather, and Apple Weather—and informally discussed the preferred designs with peers.

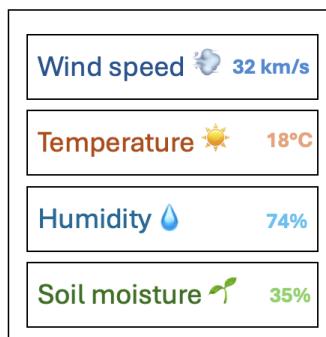


Figure 20: Initial paper prototype for webapp with live information shown in clickable boxes

Ultimately, I settled on a tile-based design similar to the paper prototype in Figure 20, as this offered a simple and intuitive way to view all current information at a glance. The concept was for users to click on any tile to load a detailed chart for that specific data type. The following sections describe the technologies selected to achieve this.

13.2 Choice of language in webapp

The frontend of my project is written in HTML, CSS and JavaScript, which is an archetypal web development stack.

13.3 PicoCSS

PicoCSS is the library I used for the default styling of my webapp. I liked its minimal and low distraction look which I thought was ideal for presenting data. It also had good mobile to desktop scaling which meant my webapp (at least the non-chart parts) worked on mobile and desktop with little work needed.

13.4 Apache Echarts

Apache Echarts is a JavaScript library that I have used to build the charts for my webapp. Data for charts is fetched from the backend and then loaded into a 'series' object. Apache Echarts then renders the data series onto a graph with a variety of options that I have chosen to improve data clarity.

13.5 Walkthrough of Webapp features

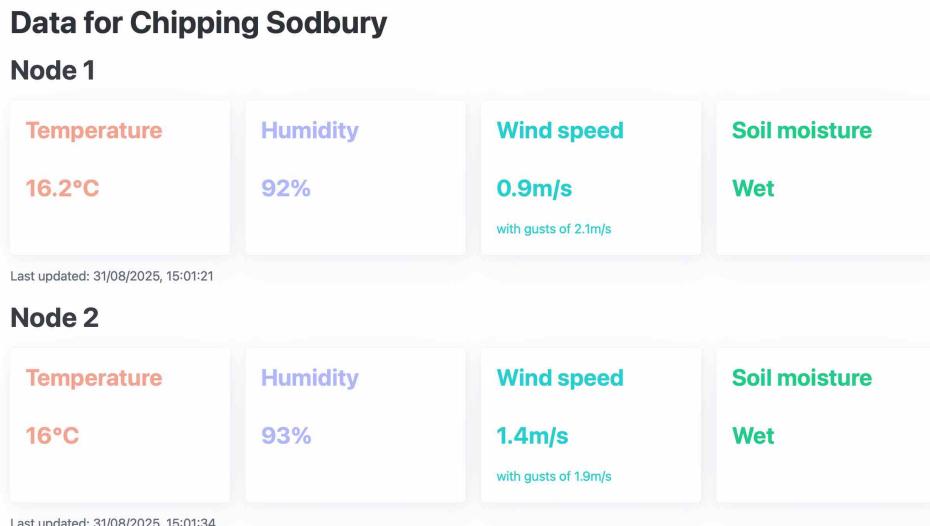


Figure 21: Main page of website showing current sensor readings

Figure 21 shows the main page of the webapp, which displays the most recent readings for each node. A "Last updated" timestamp appears under each set of readings, indicating how recently the data was received. Clicking on any of these tiles opens a detailed chart for that specific metric.

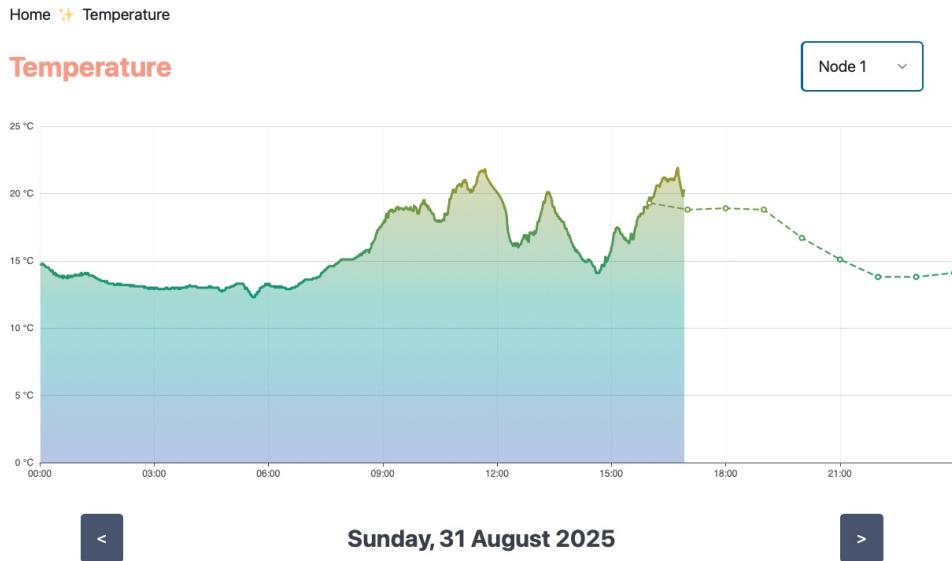


Figure 22: Temperature page with chart showing data for node 1

The temperature page in Figure 22 features a colour gradient across the temperature range, with warmer values appearing more reddish and cooler values more bluish. This is generated by the `visualMap()` function in Echarts and provides the user with a quick visual cue of the current conditions.



Figure 23: Humidity page with chart showing data for node 2

The Humidity page in Figure 23 similarly has a gradient applied. Another noteworthy page element is the drop down menu in the top right, which allows the user to switch the view between "Node 1", "Node 2", and "Compare". Selecting an option updates the chart to show the corresponding dataset, with "Compare" displaying a combined view of both nodes.

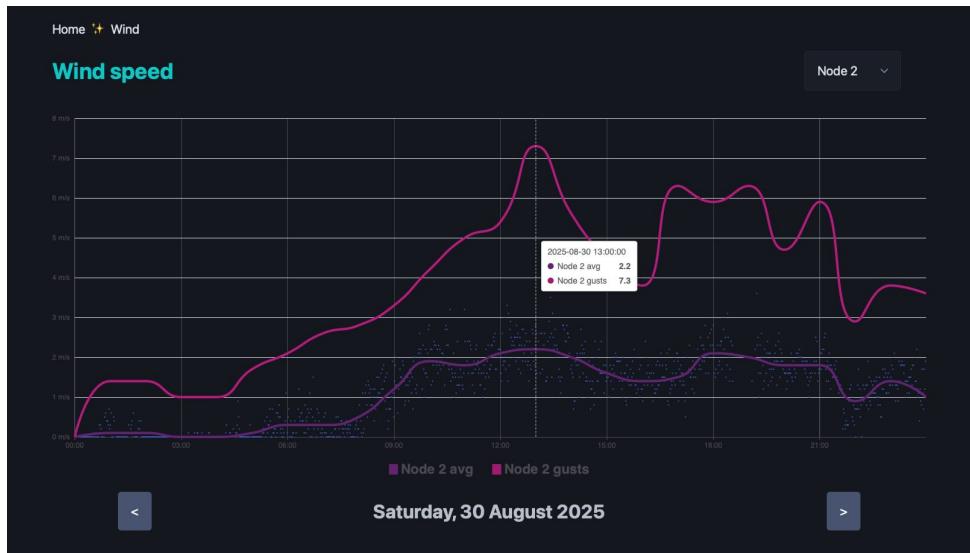


Figure 24: Wind page with chart showing data for node 2

Figure 24 shows the webapp in dark mode. This is a feature of the PicoCSS library, with the site's colour automatically adjusting to the user's preferred appearance settings on their device.

Another key feature shown here is the tooltip. It appears when a desktop user hovers over the chart or if a mobile user taps and drags. This displays the precise numerical values on the chart at the point the user is hovering over.

Compared to the other chart types, the wind speed chart displays three data series: a scatter plot of all raw wind readings (which is difficult to see in the figure), a line for the hourly average wind speed, and another for the highest gust speed recorded each hour. Also below the chart there is a legend that allows the user to toggle the visibility of the average and gust speed lines.

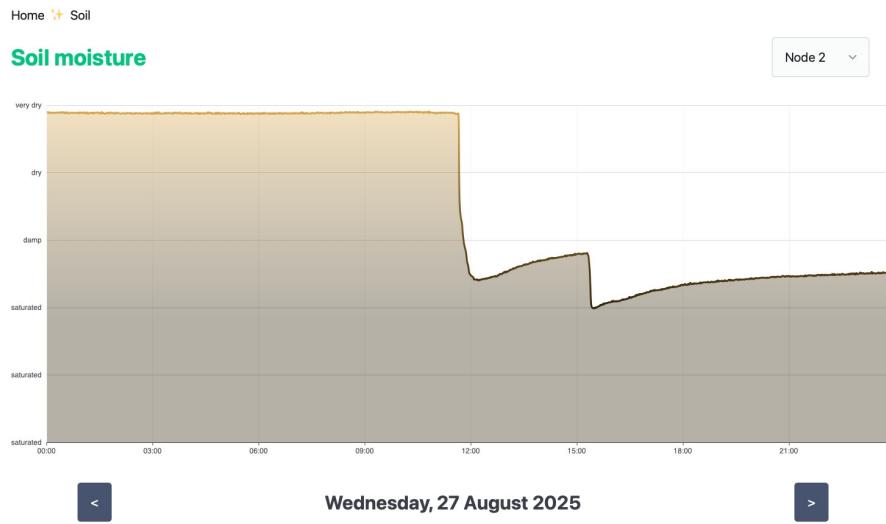


Figure 25: Soil moisture page with chart showing data for node 1

The soil moisture page in Figure 25 shows the first day of heavy rain fore the nodes. Other elements not already discussed include the navigation bar in the top left that allows users to click back to home while also showing the current page. There are also buttons to the left and right of the date that allow the user to change date.

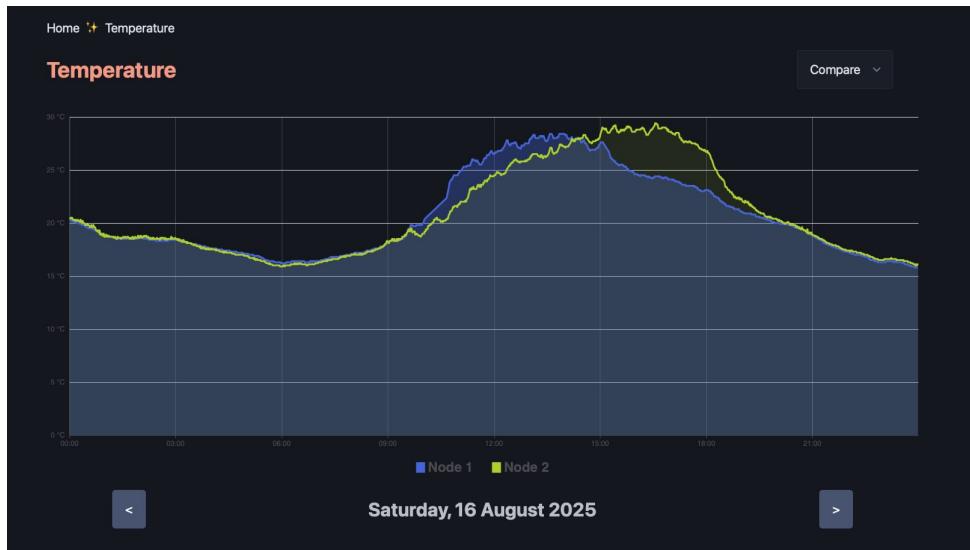


Figure 26: Temperature page showing comparison graph

Figure 26 shows the chart in comparison mode. In this view, each node's data series is assigned a distinct colour to allow for easy visual distinction between them.

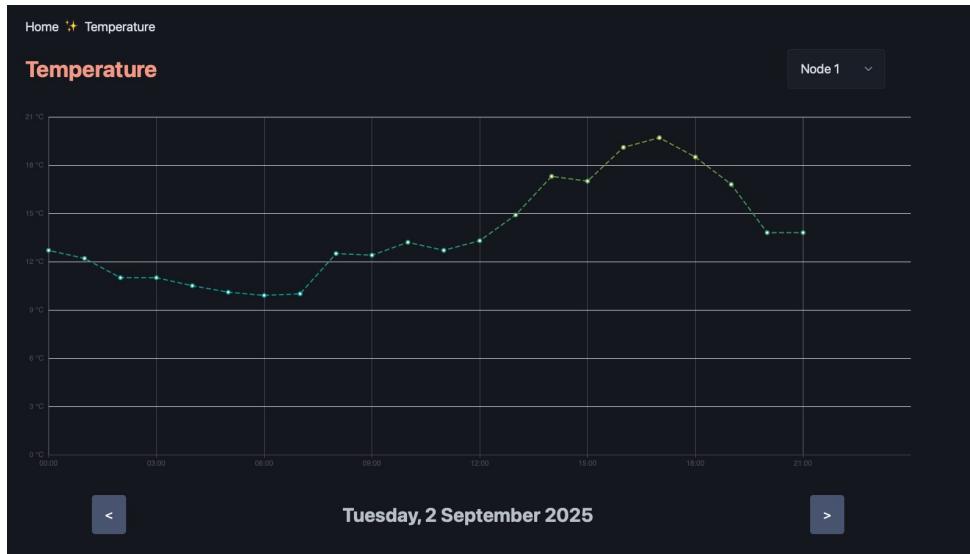


Figure 27: Temperature page for node 1 showing forecasted data

Finally Figure 27 shows the forecasting feature. This applies to future time periods, presenting sensor data forecasted up to 48 hours in advance by a machine learning model.

13.6 Making the app mobile friendly

I wanted the webapp to be accessible for both desktop and mobile users. What tends to make this difficult is the fact that scaling on desktop and mobile is normally very different. Mobile devices have a longer vertical axis while on desktop it tends to be the reverse - so I needed to ensure elements were reactive to the screen size of the viewer.

PicoCSS comes with much of this reactive formatting as standard on default HTML elements (selection boxes, divs, titles, navigation bars etc). However integrating Echarts was difficult as

PicoCSS styles cannot directly apply to this. I therefore took actions to improve the usability for mobile users, as summarised below:

1. Dynamic tooltip: The webapp can tell if the viewer is a touch screen and if so it will make the tool tip hover slightly away from the point of touch. While on desktop the user will want to hover over a datapoint and see the tool tip appear where they are hovering, on mobile the digit used to select may cover important tooltip information. By making sure the tooltip hovers slightly away from the selection this is no longer a problem.
2. Dynamic chart and font size: Echarts comes with no standard method of resizing chart data depending on the size of the device viewing the chart. So I ensured that the size of the chart (including its font) would be drawn smaller on mobile devices and recalculated if the viewing size changes (i.e. if a desktop user shrinks the window size)
3. Dynamic X axis: The interval between X axis ticks on mobile is 6 hours vs 3 hours on desktop, so that on mobile the view is less crowded.
4. Dropdown menu for chart selection: I initially used a radio design for the chart type selection (like a multiple choice question) but quickly realised this was not a mobile friendly design choice as the scaled down buttons were very hard to click. I instead opted to use a drop down box as this was much easier to select on a mobile setting while still a well known element that users should be familiar with.

One of the hardest pages to format well for mobile users was the wind sensor comparison page as this has many different series elements to display (two wind averages and two gust averages). However from Figure 28 we can see that all elements fit comfortably in frame despite the large number of series and legend data.

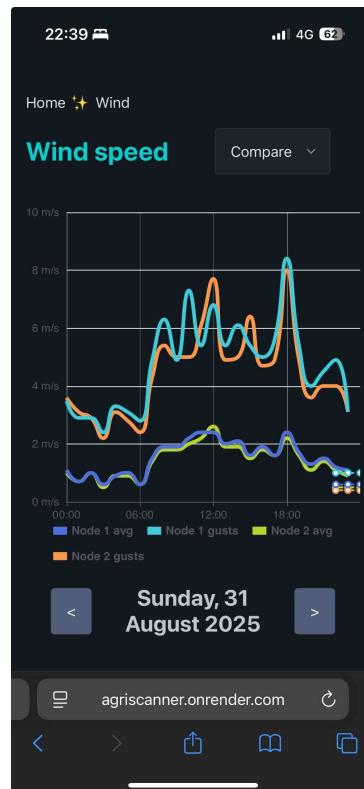


Figure 28: Mobile phone showing wind speed comparison chart

14 Forecasting with machine learning

With the webapp and database operational I moved on to attempting to forecast the microclimate with machine learning. The idea for this model would be that I could give it future general weather forecast data and then it would return adjusted microclimate datapoints based on this.

14.1 LightGBM

LightGBM is a popular machine learning algorithm developed by Microsoft. I chose LightGBM as it offers a good balance between performance and training efficiency compared to similar models such as XGBoost [36].

Both LightGBM and XGBoost are known as 'Gradient Boosted Machines'. This is a relatively new technique in machine learning that effectively combines many weaker machine learning models (called weak learners) to create a single highly accurate model. These models are excellent for tabular data (such as my node and forecast data) and regularly beat out competing learning algorithms [37]. LightGBM is also compatible with the m2cgen library that allows the final model to be converted to javascript format, allowing it to work within my webapp. All these factors made LightGBM a good algorithim for my use case.

To perform the training I installed python with the lightGBM and m2cgen libraries as described above. I then also installed pandas for data handling purposes.

14.2 Machine learning process

I aimed to create eight separate machine learning models, one for each node (node 1 and node 2) and one for each sensor type per node (temperature, humidity, wind speed and soil moisture). Training the model would require "features" which are essentially the inputs to the model that it then uses to estimate a "target" (i.e. the output).

The final models would take a 48 hour general future forecast as their input and then output a predicted microclimate specific sensor reading (e.g. predicted node 1 temperature). The models would be trained using historic current weather collected from the same api and trained against actual sensor readings to create an accurate prediction. The following diagram shows a process map this training process:

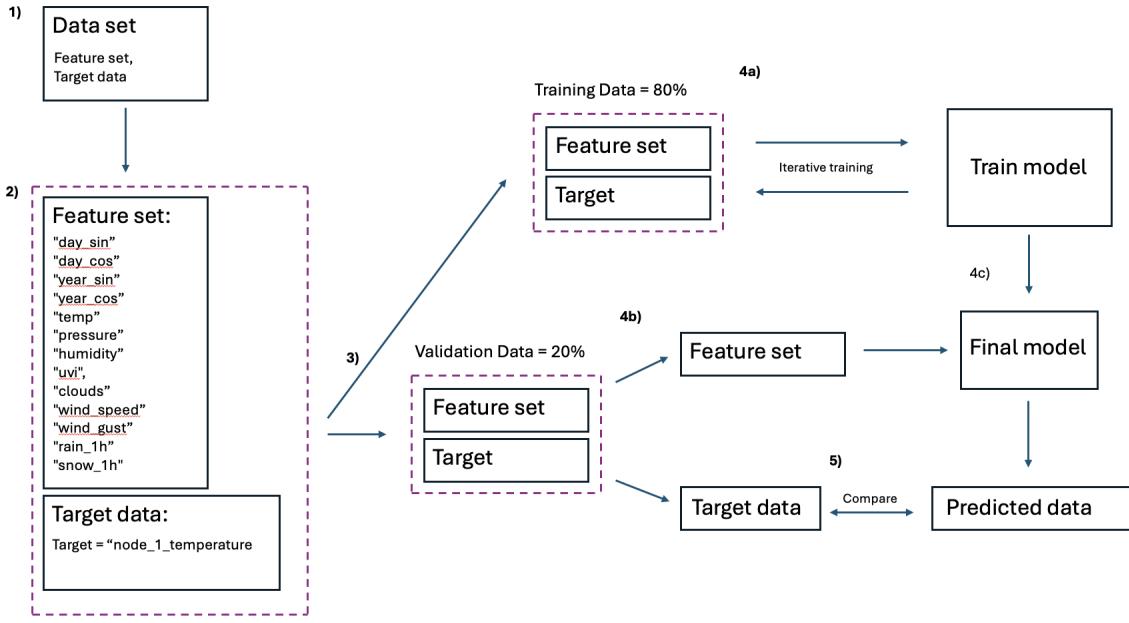


Figure 29: Infographic showing steps for training with LightGBM. This uses the temperature target for illustration.

1. Preparing the dataset: A single cleaned dataset was created with timestamps between the api weather data and node data matched. As API readings are taken every 10 minutes and node readings every 1 minute, 9/10 node readings were discarded. The final dataset was roughly 1,400 rows.
2. Define the feature set and target data: The feature set (weather API) and target (node data) were defined, and unnecessary columns discarded. The Unix timestamp used for database purposes was transformed into sine and cosine representations of day and year. This is necessary when training a time-series data set as the algorithm must be able to understand the cyclical nature of time. For example, using raw timestamps would incorrectly suggest to the algorithm that the times of 23:00 on day 1 and 00:00 on day 2 are 23 hours apart.
3. Split the dataset into training (80%) and validation (20%): This step is necessary so that
4.
 - (a) Run iterative training model: A model is trained against the feature set. It uses the target as supervision to get the best possible model.
 - (b) Remove target data from feature set: The validation data is split into feature set and target. This is so the final model can be tested without access to the actual data.
 - (c) Produce a trained model: When the model training has iterated at least 50 times with no improvements a final model is generated.
5. Use validation feature set in final model and compare predicted data with actual: This step then compares how the model performs on the validation data compared to its performance during training. In most instances the model will be less accurate on validation data as it has never seen this before.

With the eight models created they were then placed into the backend of the webapp and fed new forecast data every 10 minutes to create regularly updated predictions. The front end requests the predicted data from the backend and displays this as a chart line.

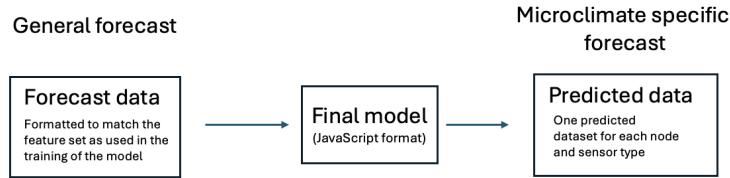


Figure 30: Infographic showing how final model is used on the webapp

Part IV

Evaluation

15 Hardware evaluation

15.1 Qualitative discussion of weather station performance

15.1.1 Battery life, solar power and outages

The nodes have had significantly more downtime than expected based on the energy budgets in Sections 7.2 and 7.3, despite doubling the battery capacity during deployment. The primary cause is site placement, with both nodes in a north-facing garden bounded by 2.5 m fencing and a two-storey house immediately to the south. As a result, they receive no direct sunlight until 09:00, and Node 1 is shaded again by 15:00 due to the shadow of a nearby garage. This leaves only ≈ 5 h of direct sunlight, which is far below the amount assumed in the design of the nodes.

Outages seem to only affect the sensor nodes; the repeater has had zero downtime since installation. This is consistent with its much lower energy budget from a lack of any peripheral sensors, which reduces average energy draw.

The limitations of the current location, plausibly explain the observed outages. Because these shading conditions are unlikely in an open field, these outages are not of primary concern for the intended deployment. However, it highlights the system's sensitivity to late sunrise and early sunsets from terrain. For example if the actual deploy site was shaded by a hill or some tall trees late in the day, which I had not properly considered in the design phase.

15.1.2 Weatherproofing

The summer of 2025 is set to be one of the hottest and driest on record with August specifically receiving roughly half its average rainfall [38]. Consequently, from the 15th of August to the 26th of August the weather stations saw only short spells of rain, making an analysis of their weather proofing hard to review up to this point.

Fortunately, from the 27th August onwards the nodes were exposed to fairly heavy sustained rainfall. Throughout this period there has been no evidence of water ingress.

Beyond ingress testing, the nodes experienced elevated ambient temperatures (exceeding 32 °C) and showed no signs of overheating. These results are encouraging, although longer-term deployment that includes colder weather and sustained heavy rain is needed to comment conclusively on their overall robustness.

15.1.3 Range

As reported in section 7.1 the challenger microcontrollers and antennas used in this configuration are able to reach at least 1200m of range in a real world situation. The conditions in that test were not ideal for LoRa as both the receiver and transmitter were positioned low to the ground at around 1-1.5m, additionally line of sight was broken at around 1000m which severely diminishes the performance of any radio communication system. There were also buildings between 1200m and 1400m that blocked LoRa signals entirely.

In the intended deployment of my full weather network, the use of an additional repeater would significantly improve range. In a flat terrain setting then the use of a repeater would clearly double the range, however if terrain is hilly a repeater can increase range by even larger multiples. The below graphic demonstrates the problem of hills when it comes to LoRa. As a LoRa signal propagates from the transmitter and collides with a hill the majority of the signals energy is reflected off the hill meaning it cannot reach the gateway.

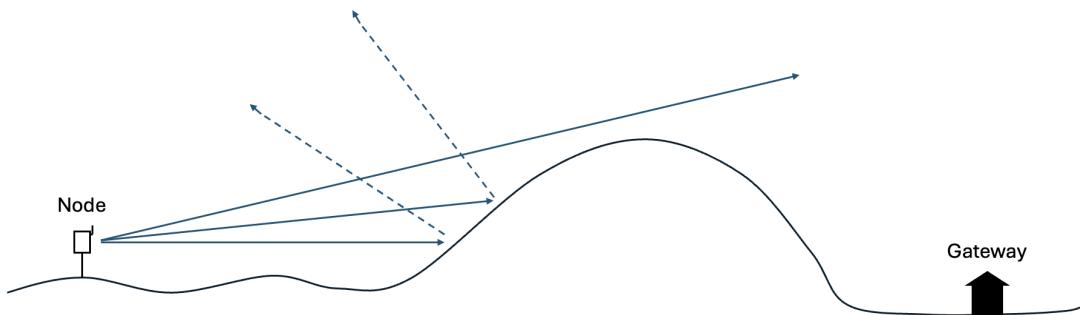


Figure 31: Illustration of LoRa radio propagation between node and receiver with blocking terrain

If a repeater is placed on the top of the hill not only would the LoRa signal reach the gateway receive signal but the repeaters increased elevation would give a significant boost to its range as the total area with a line of sight to the repeater would be vastly increased.

The range that this repeater allows is what sets the design of my network apart from commercial options and is discussed in more detail in the next section..

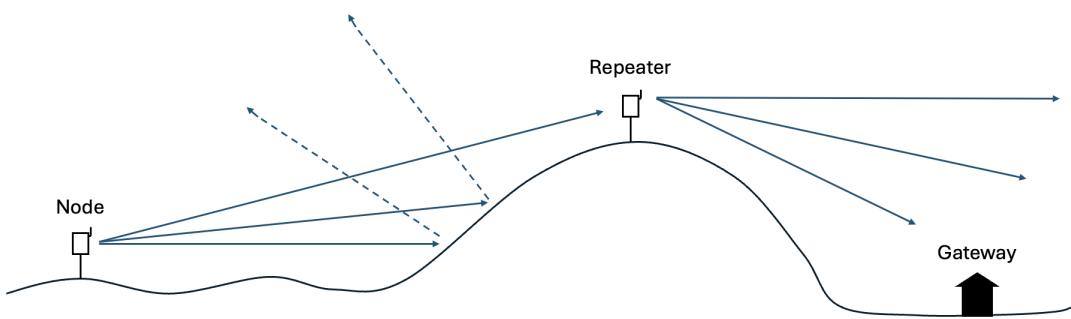


Figure 32: Illustration of LoRa radio propagation with a repeater included

15.1.4 Reset behaviour

As covered briefly in Chapter 8, the reset behaviour of the challenger is inconsistent after a brownout or complete power outage. Essentially if the power of the sensor nodes is cut off at night then it is not guaranteed that the node will restart the code.py program in the morning. This is in spite of the fact that I modified the safemode.py behaviour of circuitpython with the recommended code for remote solar power applications. As this ultimately appears to be a firmware issue there is not an obvious or easy solution for this.

With enough time I would probably rewrite all of the challenger software in Micropython and see if that firmware behaves in a more useful way on power outage. Unfortunately the issue was picked up fairly late in development and it was unrealistic to perform a refactor of this scale with the time left.

15.2 Quantitative comparison with commercial alternatives

I will now compare the performance of my LoRa weather station to prebuilt options available to purchase. A breakdown of costs for Agriscanner is included in Appendix A.

	Agriscanner Network	SenseCAP S2120[39]	Decentlab Eleven Parameter[40]	HOBO weather station kit[41]	SparkFun Arduino weather kit[42]
Number of sensors	4	8	11*	6	7
Sensor accuracy	Hobbyist	Hobbyist	Professional	Professional	Hobbyist
Communication type	LoRa	LoRa	LoRa	Mobile network	WiFi
Update frequency	1 minute	1 hour	10 minutes	1 hour	1 minute
Readings per hour	60	1	6	10	60
Power source included	Yes	Yes	Yes	Yes	No
Power source	Solar	Solar	Solar	Solar	–
Batteries recharge?	Yes	No	No	Yes	–
Reported battery life	replace ~ 3 years	154 days	Several months	replace 3–5 years	–
Reported range	–	2–10 km	2–10 km	Anywhere with 4G	–
Estimated range	2.4–20 km	1.2–10 km	1.2–10 km	–	10–50 m
IP rating	~ IP65	IPX6	IP66	IP66	None
Ongoing payment?	–	–	–	Yes – mobile plan	–
Ongoing costs p.a	£0	£0	£0	£132	£0
Cost per sensor node	£177	£287	£3,272	£4,138	£130
Cost per repeater	£93	£0	£0	£0	£0
Cost per gateway**	£66	£122	£122	£0	£0
Battery cost p.a.***	£7	£10	£30	£20	£0
Total cost****	£520	£706	£6,696	£8,418	£260

* Sensors missing from Agriscanner: Solar radiation, rainfall, barometric pressure, vapor pressure, dew point, wind direction, tilt sensor, lightning strike count / distance

** For SenseCAP and Decentlab models the lowest cost gateway available is sensecap m2 at £122

*** Battery cost assumptions are detailed in Appendix C.

**** Includes sensors, repeater, gateway, and estimated first-year battery + ongoing costs.

Table 3: Comparison of weather-station options.

15.2.1 Benefits of my weather station

- **Cost:** At £520 the Agriscanner weather stations are the lowest cost option among waterproof, long-range systems. While the SparkFun kit is cheaper, it is not suitable for outdoor deployment due to its exposed electronics and, since it relies on WiFi, its range would be insufficient in an agricultural setting. It will therefore not be discussed further. The two professional systems (DecentLab and HOBO) are over ten times the price of my system and are therefore not comparable.

The only system with similar characteristics under £1,000 that I could find is the SenseCAP device. However, with a cost per node roughly 50% higher, my nodes still provide better value. If additional nodes were deployed, this price difference would become even more significant.

- **Frequency of readings:** My sensor nodes collect and transmit readings every minute, providing the Agriscanner webapp with effectively live data. By contrast, most alternative options only provide hourly readings, leaving actual conditions between measurements unknown.

- **Battery recharging:** My nodes use rechargeable 18650 batteries, which I conservatively estimate will last around three years (the same battery chemistry as mobile phones) before requiring replacement. Of the alternatives, only the HOBO system features a rechargeable battery. Both SenseCAP and DecentLab rely on disposable alkaline batteries, requiring regular replacement and therefore more frequent maintenance.
- **Range:** As explained in Section 15.1.3, my weather station network benefits from the inclusion of a repeater. This enables significantly greater range than the other models could provide, particularly in hilly terrain.

I also doubt whether either the SenseCAP or DecentLab systems could achieve a substantial range improvement under the same test conditions. In the UK, LoRa transmission power is subject to a strict regulatory cap (see Section 9.1.1). Since my system already operates at this maximum power, commercial products cannot exceed it. Even with a superior antenna, transmit power would need to be reduced proportionally, as antenna gain also counts towards the effective radiated power. It is therefore highly unlikely that these alternatives would achieve a range advantage sufficient to offset the benefits of a repeater in my system.

15.2.2 Drawbacks of my weather station

- **Number of sensors:** One of the clearest drawbacks of the Agriscanner system is the lower sensor count: only four sensors compared with seven to eleven on competing systems. However, the Challenger microcontrollers in my sensor nodes still have spare GPIO ports, so adding additional sensors would be straightforward. The cost of many sensors is also not prohibitive (for example, a UV index sensor is only £6).
- **Sensor accuracy:** Professional systems use higher-grade sensors with tighter accuracy specs. For example, the DecentLab unit specifies air temperature accuracy of $\pm 0.6^\circ\text{C}$, whereas the DHT11 used in mine is only rated to about $\pm 2.0^\circ\text{C}$.
- **Reset behaviour:** As noted in Section 15.1.4, the node firmware can behave unreliably after a full battery drain. While I cannot purchase the other devices in this list to confirm this directly, it is unlikely that the other units would exhibit the same behaviour, especially because their firmware will be built specifically for remote solar powered applications.
- **Other factors:** The other devices bring other non-tangible benefits besides their technical specification. For example, warranties, formal testing, vendor support etc. Professional systems commonly offer long-term maintenance and firmware updates beyond the initial purchase, which my prototype solution obviously does not offer.

15.3 Conclusion on hardware performance

While the weather station network has shown promising results as a low cost and long range solution, the unreliable reset behaviour holds it back from being 100% deployment ready. So far the weatherproofing of the external devices has been encouraging, though testing has been limited due to unusually dry weather and a longer deployment in wetter and colder conditions is needed. The outages seen during the current deployment appear to be an issue specific to the private garden they are in and would be much less likely in an open field environment; however, this does emphasise the need for more extensive site surveys prior to installation. Overall, if the reset behaviour can be addressed and a small number of additional sensors are added, the complete system would be well suited for long term unattended deployment on a farm.

16 Web-app evaluation

This Chapter will evaluate the usability of the Agriscanner webapp using results from a System Usability Scale (SUS) survey that was carried out via online form in late August.

16.1 Procedure

Before the main section of the survey, participants were asked to consent to standard University of Bristol privacy wording (see Appendix D). To avoid stricter GDPR handling I did not record identifiable information (e.g. name, email, age), which may have also encouraged more honest responses. I also made sure to ask what device they were viewing the project on (either mobile or desktop) as I wanted to test whether there was any difference in usability between the two.

Participants were then asked to perform a set of four representative tasks in the webapp. Each task involved collecting a piece of information from a specified chart, such as finding the temperature for a particular node at a a specified time (tasks list shown in Appendix D). Once the tasks were completed, I asked participants to submit these answers via multiple-choice questions.

Next, the survey presented a standard 10-question SUS, which is a Likert-scale questionnaire commonly used to report on the usability of software systems [43]. The SUS gives a score from 0 to 100, where a higher score indicates that a system is more usable. A "good" SUS score is generally regarded as anything above 68 [44].

Finally, there was an optional textbox for participants to fill out asking for feedback on bugs or features they would like to see. I included this to generate user stories for future development (Section 16.5).

By asking participants to perform the same tasks and collecting their answers, I ensured everyone completed a valid interaction with the webapp before rating it. This standardises the experiment context and reduces uncontrolled variance that can arise from an open "try out my website" approach. Because I recorded the task responses, I could also compare them to the correct answers, providing an additional objective metric (task success) to complement the SUS.

In total, 15 participants completed the survey. Participants were recruited mainly from friends, family and other students on my course.

16.2 Hypotheses

16.2.1 Hypothesis 1

The sample SUS score will be greater than the benchmark value of 68

Statistic to test: One-sample, right-tailed Wilcoxon signed-rank test¹.

Null and alternative hypotheses:

$$H_0 : m = 68 \quad \text{vs} \quad H_a : m > 68,$$

where m is the population median.

16.2.2 Hypothesis 2

The SUS scores for users on mobile will not differ significantly from those on desktop.

Statistic to test: Two-sample, two-tailed Mann-Whitney U Test¹.

¹For rationale and sources on statistical testing refer to Figure 40 in the Appendix

Null and alternative hypotheses:

$$H_0 : \text{the two populations are equal} \quad H_a : \text{the two populations are not equal.}$$

16.3 Results

This section summarises the key results from the survey. Refer to Table 8 in the Appendix for data per participant.

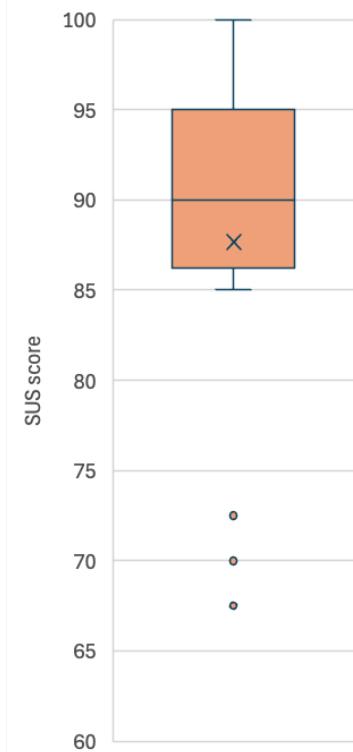


Figure 33: Box and whisker plot showing range of SUS scores from participants

Metric	Value
Maximum	100.0
Quartile 3	95.0
Median	90.0
Mean	87.7
Quartile 1	86.3
Minimum	67.5

Group	N	Mean SUS
Desktop	7	84.3
Mobile	8	90.6

Table 5: Mean SUS score by device

Table 4: Summary statistics for SUS

Figure 33 shows a tight distribution of values between the first and third quartiles, with most participants giving favourable ratings. There were also a smaller number of lower ratings shown as outliers, with a minimum score 67.5.

Table 4 shows the key metrics from the survey. The mean score of 87.7 is well above the benchmark of 68 and indicates a high perception of usability for the Agriscanner webapp. A one-sample Wilcoxon signed-rank test confirmed that the median SUS score was significantly greater than 68 ($p = 0.0004$), allowing for the rejection of the first null hypothesis H_0 .

Table 5 indicates that participants using mobile devices gave slightly higher usability ratings (90.6) than those on desktop (84.3). However, a two-sample Mann-Whitney U test revealed no statistically significant difference between the two groups. ($p = 0.105$). Therefore, the second null hypothesis H_0 could not be rejected at the 5% significance level.

Question no.	Incorrect answers	Percentage incorrect
1	3	20%
2	1	7%
3	1	7%
4	0	0%
Overall percentage incorrect		8%

Table 6: Number of incorrect answers for task quiz

Performance in the assigned tasks was generally good (Table 6), with participants answering incorrectly only 8% of the time. Questions 2, 3 and 4 were answered correctly by almost all participants, with only one participant failing on 2 and 3. The first question proved the most difficult to perform accurately with 3 candidates failing. I decided to plot the SUS score given against the percentage of correct answers (see E) however with an R^2 value of 0.0066 there was effectively zero correlation between the two; even if there was some correlation the small sample size and ceiling effect from so many respondents getting perfect scores would make this difficult to detect.

16.4 Discussion and limitations of results

With a very high mean (87.7) and median (90) SUS score, the results here suggest a high degree of usability. A one-sample Wilcoxon signed-rank test helps confirm that the median score of my sample is significantly greater than the benchmark of 68 and cannot be attributed to randomness with $p < 0.001$. This provides quantitative evidence that the frontend development choices I have taken (Chapter 13) have given my webapp excellent perceived usability. This point is further reinforced by the very high task completion rate (92%). The fact that users could not only perceive the system as easy to use but could also operate it efficiently with minimal guidance validates the chosen design approach—particularly the emphasis on a minimal, low-distraction interface.

Additionally, the data suggest that usability on mobile devices is no different to that on desktop devices. A two-sample Mann-Whitney U test revealed no statistically significant difference in usability ratings between mobile and desktop users with $p > 0.05$.

Not all the data were positive however: Two participants gave scores close to the benchmark level of 68 and one respondent gave a score below this point. With such a small sample it is important not to dismiss these as outliers. Fortunately, many participants left detailed feedback on usability issues they encountered (Figure 39)- including all three who gave lower scores (Figure 38). These comments provided useful insight into specific usability issues, such as the difficulty with date selection which directly explains the 20% failure rate on the first task. This qualitative feedback was then used to generate the feature requests compiled in Table 7.

There are a number of important limitations to these findings. The sample was small and non-random so the results are not necessarily representative of the wider population. Because I knew many participants personally, social-desirability bias was likely to have inflated ratings. Likewise, a high proportion of computer-science students in the sample means these participants may have been more familiar with web interfaces than the general public, which could also have contributed to the higher SUS scores. While I measured the completion rate for the user tasks I

did not measure the time taken to do this. Even if users successfully completed the tasks it may have taken a long time to do so, which would have been a valuable metric to include here.

In conclusion, while the limitations of the sample mean the results cannot be broadly generalised, they still provide a strong, positive indication of the webapp's usability. An exceptionally high SUS score and a high task completion rate demonstrate that the core design of the application succeeded in its aims. Further, the evaluation has successfully identified specific feedback from users, which provides a clear path to improving usability further.

16.5 User stories from SUS survey

Based on the qualitative feedback, several key themes emerged. The most frequently mentioned issues have been summarised in Table 7 and translated into user stories to guide future development.

Category	Mentions	User story
Calendar with date-range selection	4	As a user I want the ability to select date ranges so that I can quickly jump to past dates without repeatedly clicking through days.
Clearer way to find compare graph	2	As a user I want the compare graph to be more explicitly signposted so that I can easily find it when trying to compare nodes
Human readable soil moisture readings*	1	As a user I want an option to view soil moisture in a human readable format (e.g. wet/dry) so that I can understand what the sensor values mean.
Tooltip granularity on chart	1	As a user I want smoother control when using the tooltip without snapping to a particular minute so that I can select more precise times reliably.
Way to export data	1	As a user I want a way to export weather data to a CSV file so that I can have offline access to it.
Switch between measurements without going back	1	As a user I want a control from within each sensor section (temperature, humidity etc) that allows me to switch between measurement types quickly so that I don't have to return back to the home page between each navigation.
About page	1	As a user I want an "About" page describing the project and the data sources so that I understand the context of the data.
Specific issue with chart	1	As a user I want the Y axis to align with my screen properly so that no text is cut off and I can read the labels

*This has now been implemented on the webapp

Table 7: Compiled feature requests from survey

17 Machine learning model evaluation

Section will compare machine learning models prediction to the actual sensor data and the general forecast and conclude on whether model is appropriate for application

17.1 Methodology

18 Future work

Future improvements for weather station and app

19 Closing remarks

Brief conclusion

References

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Part V

Appendices

A Breakdown of costs

Category	Name	Units	Cost (£)	Total cost (£)	Units per component				
					Sensor node 1	Sensor node 2	Repeater	Gateway	Difference
Electronics	Electronics iLabs Challenger RP2040 LoRa (868MHz)	4	20.80	83.20	1	1	1	1	-
Electronics	Electronics Solar Power Management Module for 6V-24V Solar Panel	3	9.70	29.10	1	1	1	-	-
Electronics	RS485 Wind Speed Transmitter	2	43.20	86.40	1	1	-	-	-
Electronics	Capacitive Soil Moisture Sensor	2	4.00	8.00	1	1	-	-	-
Electronics	Monocrystalline Silicon Solar Panel	3	9.90	29.70	1	1	1	-	-
Electronics	Electronics 2-Channel RS485 Module for Raspberry Pi Pico	2	7.50	15.00	1	1	-	-	-
Electronics	Electronics 9V Step-Up Voltage Regulator U3V40F9	2	9.60	19.20	1	1	-	-	-
Electronics	18650 Lithium-ion Rechargeable Cell - 2500mAh 3.7V 30A	5	3.99	19.95	2	2	1	-	-
Electronics	Raspberry Pi	1	33.60	33.60	-	-	-	1	-
Electronics	iLabs LoRa Antenna (EU868)	4	5.53	22.12	1	1	1	1	-
Electronics	Electronics DHT11 Temperature-Humidity Sensor	2	3.90	7.80	1	1	-	-	-
Electronics	Electronics Half size breadboards	3	2.00	6.00	1	1	1	-	-
Electronics	Electronics 5 Meters of Black 3 core cable	1	5.00	5.00	0.50	0.50	-	-	-
Electronics	Electronics Battery storage case	5	1.00	5.00	2	2	1	-	-
Electronics	Assorted (M-M, M-F, F-F) jumper cables	1	6.00	6.00	0.25	0.25	0.25	0.25	-
Enclosure	IP65 junction box	3	12.18	36.54	1	1	1	-	-
Enclosure	Small IP55 junction box	2	4.20	8.40	1	1	-	-	-
Enclosure	Wooden posts (2m)	3	17.00	51.00	1	1	1	-	-
Enclosure	Gravel board	1	8.50	8.50	0.5	0.5	-	-	-
Enclosure	Plastic box with screw on lid	1	5.00	5.00	-	-	-	1	-
Enclosure	Steel spur post supports	3	8.95	26.85	1	1	1	-	-
			512.36	176.69	176.69	92.55	66.43	-	-

Figure 34: Table of component costs

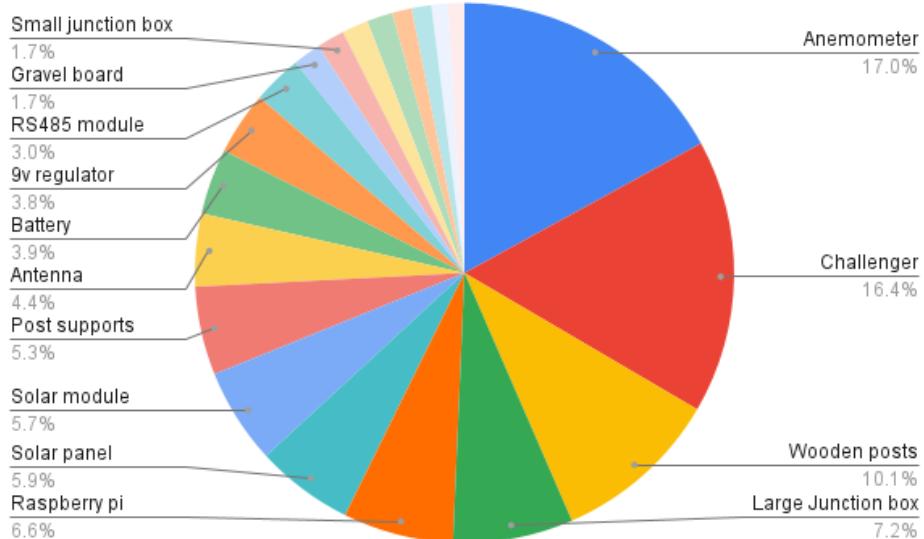


Figure 35: Chart to visualise relative cost of components

B Interview excerpt with Small Brook Farms owners

Interviewer: So you would need a weather station to observe very local weather, I expect. What you're saying is that the BBC website weather is not necessarily relevant to you?

Speaker 1: No, No , so there's another site which is in Sanford and we can have conversations - we're what? - 5 miles apart 10 miles?

Speaker 2: Yeah. So the other side of that hill there like a mile away you get a different sort of weather, but even on this side of the [apple orchard] as opposed to that side of the [apple orchard] like the wind can be less than whatever else, its very localised. But you know you if you then go on that side of the valley, it doesn't rain on this side. So like to be actually useful, yeah, [weather monitoring] sort of has to be [based on] the farm.

Source: Transcript no.28 of site visit (9 May 2025)

C Battery cost assumptions

- **Agriscanner Network:** Replace 5 (2 per sensor node, 1 for repeater) Li-ion batteries every 3 years at a cost of £20 $\Rightarrow \approx$ £7 per annum.
- **SenseCAP S2120:** Three AA batteries per node, replaced twice a year (total 12 batteries) \approx £10 per annum.
- **Decentlab Eleven Parameter:** Two C batteries per node, replaced four times per year (total 16 batteries) \approx £30 per annum.
- **HOBO weather station kit:** Replace lead-acid for each node battery every 4 years at a cost of £80 $\Rightarrow \approx$ £20 per annum.

D System usability survey

System usability survey for Agriscanner website

B I U ↵ X

This questionnaire contains 14 questions. The first four consist of a mini quiz to help the user get an idea of the website's functionality. The remaining 10 are a standard system usability survey (SUS)

Steps before answering this survey:

Go to the website <https://agrisanner.onrender.com>

Perform actions and note down answer. If you cannot perform the action then move to the next.

- 1) To the nearest degree what was Node 2's temperature at 14:00 18 August 2025?
- 2) To the nearest 1m/s what was Node 1's gust speed at 13:00 26 August 2025?
- 3) Go to wind speed and change the graph to compare mode. What colour is Node 2 gusts represented by?
- 4) What is the forecast for humidity at 6am tomorrow for Node 1?
- 5) Feel free to use the website more extensively after this to get a better feel for it

Study information sheet

Results from this study will give a metric for the usability of the website linked above. The website collates and displays weather data that is collected from two custom weather stations (Node 1 and Node 2) built for this project. These weather stations are designed for use in agriculture where actual field conditions can differ from the general forecast. They give farmers more accurate information to better inform their decision making.

Consent wording

"I hereby fully and freely consent to my participation in this study

I understand the nature and purpose of the procedures involved in this study. These have been communicated to me on the information sheet accompanying this form.

I understand and acknowledge that the investigation is designed to promote scientific knowledge and that the University of Bristol will use the data I provide for no purpose other than teaching and research.

I understand the data I provide will be anonymous. No link will be made between my name or other identifying information and my study data.

I understand that the University of Bristol may use the data collected for this study in a future research project but that the conditions on this form under which I have provided the data will still apply.

I agree to the University of Bristol keeping and processing the data I have provided during the course of this study. I understand that this data will be used only for the purpose(s) set out in the information sheet, and my consent is conditional upon the University complying with its duties and obligations under GDPR."

Figure 36: SUS survey wording

List of tasks for users:

1. To the nearest degree, what was Node 2's temperature at 14:00 18 August 2025?

2. To the nearest 1 m/s, what was Node 1's gust speed at 13:00 26 August 2025?
3. Go to wind speed and change the graph to compare mode. What colour is Node 2 gusts represented by?
4. What is the forecast for humidity at 06:00 tomorrow for Node 1?

E Additional SUS materials

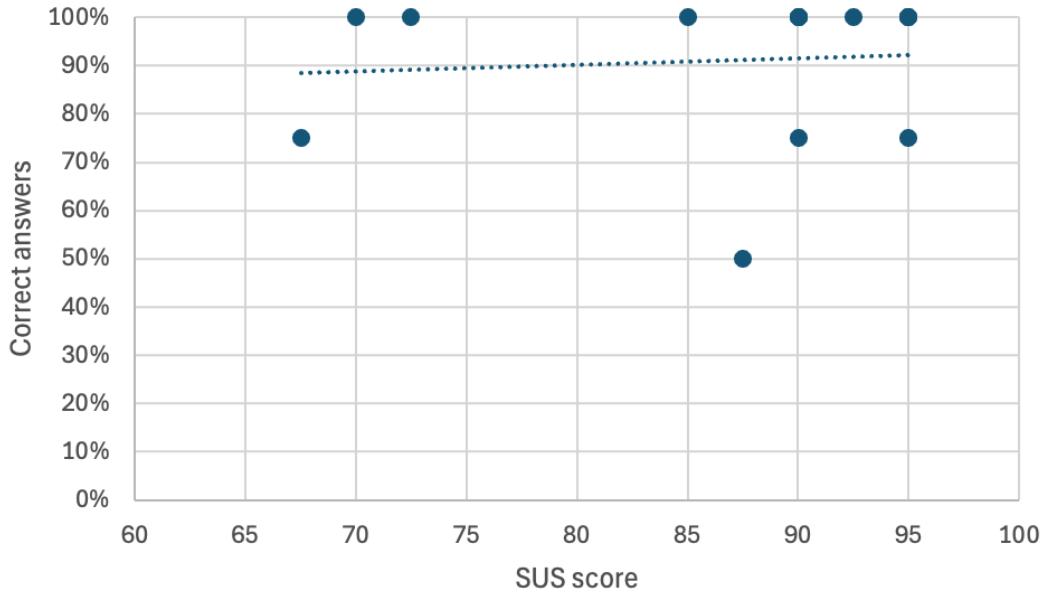


Figure 37: Graph to show SUS score vs percent of correct answers ($R^2 = 0.0066$)

responder_num	sus_score	correct_answers	type
1	90.0	75%	desktop
2	92.5	100%	mobile
3	95.0	100%	mobile
4	70.0	100%	desktop
5	90.0	100%	mobile
6	90.0	100%	desktop
7	87.5	50%	desktop
8	95.0	100%	mobile
9	95.0	75%	mobile
10	95.0	100%	desktop
11	72.5	100%	desktop
12	67.5	75%	mobile
13	100.0	100%	mobile
14	90.0	100%	mobile
15	85.0	100%	desktop

Table 8: Raw SUS scores and correct answer percentage from survey

"I found it very hard to get to a specific time on the graph - the granularity of the cursor moving seemed to make it hard to choose my time - I ended up with 14:01 for the first question as I couldn't get the cursor to stay at 14:00. But as a weather nerd I loved it."

"I found it annoying having to click to get to the required date. Also I don't understand from the website alone what the project is about or where the data is from - maybe an about page would be nice :)"

"Sorry wasn't sure where the compare graph is but the website looked really nice!"

Figure 38: Feedback from participants with lower SUS scores

"The soil moisture readings surprised me - I expected them to go up with rain (increased moisture) but they went down. I think this is counter-intuitive and there should either be some explanation of the what the measurements mean, or preferably there should be an option to convert to a more human understandable description like very dry/dry/slightly moist.../wet/very wet/saturated"

"When selecting the date (specifically when clicking the arrows to move forwards and backwards in time) it would be useful to have a calendar display to travel to past dates quicker."

"Extra features: - Date picker instead of having to navigate past each day
- Export feature to export data in bulk (e.g. to a csv) - Ability to select a time period (specific dates) instead of just a day view"

"I think when switching dates, it should support selecting a date from the calendar rather than only moving forward or backward to the nearest dates."

"Being able to navigate directly between measurements (e.g. temp, humidity etc.) while on [sic]"

"Finding the "compare" option was the hardest part. But didn't take long."

"Great website- simple layout and easy to use!"

"No bugs seen, but on wind graph some of the y axis text was slightly cut off on my screen. I'm on a laptop"

Figure 39: Feedback from participants with higher SUS scores

Both the Mann Whitney U and Wilcoxon Signed Rank test were selected for this data because the SUS score is derived from Likert items. Likert items are ordinal (e.g. strongly disagree) and so nonparametric statistical testing is typically preferred [45]

The Mann Whitney U statistical test score was calculated in an Excel sheet I made using the procedure described in [45] and the result cross-verified using the website in [46] which is also the source of the p-value. Results: $U = 13.5$, critical value = 10 p=0.10524. Parameters: two-tailed, 0.05 significance

Due to the complexity of calculating it, the one-sample Wilcoxon Signed Rank Test score was calculated in Excel using a modified template from the source in [47] and cross-verified with the website in [48]. Results: $W^+ = 119$ z = 3.3361, critical value = 1.6449 Parameters: right-tailed, 0.05 significance

Figure 40: Note on statistical testing

F Nielsen's nine usability heuristics [49]

- Simple and natural dialogue
- Speak the user's language
- Minimize user memory load
- Be consistent
- Provide feedback
- Provide clearly marked exits
- Provide shortcuts
- Good error messages
- Prevent errors

G How LoRa works

As this paper is not a technical study of radio communication I will opt for a brief summary of the principles behind LoRa. With this in mind I have based much of the information from the excellent video lecture in [50] that itself draws upon the paper in [51].

The reason LoRa modulation is different to traditional modulation techniques is the use of a "chirp" as the key to transmitting packets. A more traditional technique might involve a frequency shift key; that is a single frequency represents several bits. These unique frequencies are called symbols as they represent data, like letters in the alphabet. In the below graph we see

three simplified symbols that represent binary values, the combination of these symbols makes a packet:

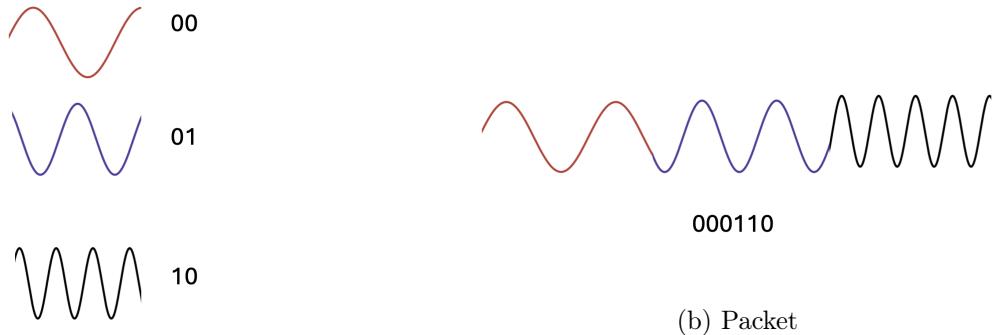


Figure 41: Traditional radio modulation with frequency symbols

In traditional modulation, symbols always have flat unchanging frequency (as can be seen from the fact the wave separation never changes). LoRa symbols instead have changing frequencies that have a waveform like the below.

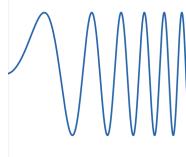
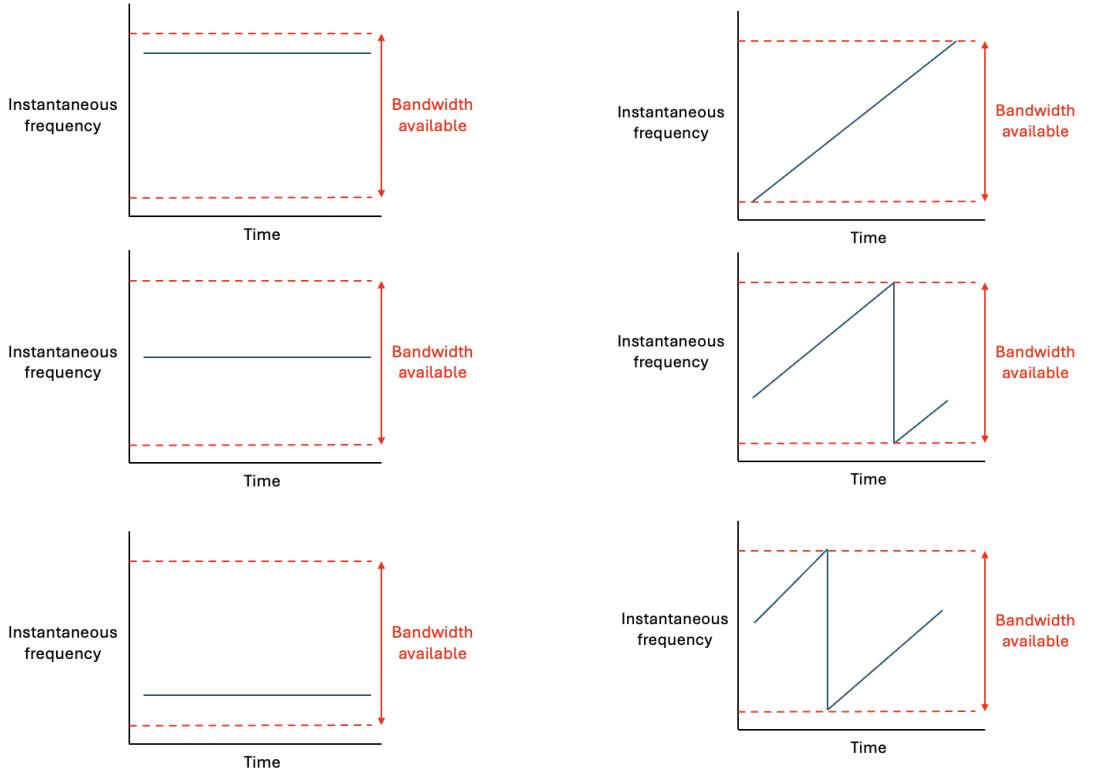


Figure 42: LoRa symbol showing changing frequency ("Up-chirp")

This change in frequency is what gives the wave form the name "chirp". If traditional frequency symbols were thought of a sound they would be similar to morse code beeps while LoRa would be more similar to siren or *chirping* bird. LoRa has both rising and falling chirps (up-chirps and down-chirps).

Different LoRa symbols are then distinguished by the point in time of a discontinuity. LoRa symbols are always delivered over a known length of time, so different symbols include a reset back to the starting frequency at a different point in time.

A way to graphically show this discontinuity in LoRa and compare it to frequency shift modulation is by using instantaneous frequency graphs:



(a) Frequency shift symbols

(b) LoRa symbols, note shifting discontinuity

Figure 43: Comparison of frequency shift and LoRa modulation

Once these symbols hit the receiver, the receiver must work out which symbol it was. In frequency shift modulation this is achieved by performing a correlation test against every symbol received. However this is computationally difficult and requires a low signal-to-noise ratio to work effectively. The benefit of chirps is that due to a mathematical transformation that will not be further discussed (Fast Fourier transform), the correlation can be computed much more easily and with less powerful hardware.

H IoT enabling technologies

This supplementary section lists the key technological developments that have contributed to the viability of my project.

1. Efficiency improvements in microchips - breakthroughs in microchip fabrication have led to smaller more efficient chips with improved performance.
2. Lithium-Ion batteries improvements - continuous improvements in the energy density of lithium-ion batteries has made it possible to power devices for long periods without mains power.
3. Low-power long-range radio - new radio communication techniques such as LoRa allow for data transmission over several kilometres using a fraction of the power required by traditional mobile or Wi-Fi technologies.
4. Affordability of solar panels - since 1970 the price of solar panels has decreased to 1/500th

of its original cost [52] making solar a viable power source for IoT systems.

5. Growth of hobbyist embedded systems - since the release of accessible platforms such as Arduino in 2005, the growth of hobby level embedded systems has lowered the barrier to entry to create IoT systems.
6. Accessible cloud computing and hosting - Cheap and available web hosting has allowed application level systems to be more easily developed.

I CircuitPython sensor node 1 code example

```

import time
import board
import busio
import digitalio
import adafruit_rfm9x
import adafruit_dht
import analogio

DEVICE_ID = 1
RADIO_FREQ_MHZ = 868.0
WIND_REQUEST = bytes([0x02, 0x03, 0x00, 0x00, 0x01, 0x84, 0x39])

# Initialise LORA radio and settings
try:
    spi = busio.SPI(board.RFM95W_SCK, MOSI=
                      board.RFM95W_SD0, MISO=board.
                      RFM95W_SD1)
    cs = digitalio.DigitalInOut(board.
                                 RFM95W_CS)
    rst = digitalio.DigitalInOut(board.
                                 RFM95W_RST)
    rfm9x = adafruit_rfm9x.RFM9x(spi, cs,
                                  rst, RADIO_FREQ_MHZ)

    rfm9x.tx_power = 13
    rfm9x.spreading_factor = 7
    rfm9x.signal_bandwidth = 125_000
    rfm9x.coding_rate = 5
    rfm9x.enable_crc = True
    rfm9x.implicit = False

except Exception as e:
    rfm9x = None
    print("ERR: Lora module", e)

# Initialise UART and settings
try:
    uart = busio.UART(tx=board.GP16, rx=
                       board.GP17, baudrate=9600, timeout
                       =0.2)
except Exception as e:
    uart = None
    print("ERR: UART", e)

# Initialise the soil moisture sensor
try:
    moisture_pin = analogio.AnalogIn(board.
                                       A0)
except Exception as e:
    moisture_pin = None
    print("ERR: moisture pin", e)

# Initialise DHT11 temperature humidity
# sensor
try:
    dht_device = adafruit_dht.DHT11(board.
                                      A1)
except Exception as e:
    dht_device = None
    print("ERR: dht11", e)

# Returns raw soil moisture reading
def get_raw_moisture(pin):
    try:
        raw = pin.value
        return raw
    except:
        return None

# Returns wind speed sensor using MODBUS
# protocol
def get_wind_speed():
    if uart:
        try:
            uart.write(WIND_REQUEST)
            time.sleep(0.2)
            response = uart.read(16)
            if response:
                if len(response) >= 5 and
                   response[0] == 0x02 and
                   response[1] == 0x03:
                    value_raw = response[3]
                    << 8 | response[4]
                    return value_raw / 10.0
            else:
                print("Bad format error
                      ")
                return None
        else:
            print("No response error")
            return None
    except:
        print("Unknown error")
        return None
    print("Bad UART error")
    return None

def find_err(value):
    if value is None:
        return "ERR"
    else:
        return value

counter = 0

while True:
    t_sum = h_sum = w_sum = 0.0
    s_sum = 0
    t_n = h_n = s_n = w_n = 0

```

```

min_counter = 0
w_max = 0

while min_counter < 10:
    if dht_device:
        try:
            t_reading = dht_device.
                temperature
            if t_reading is not None:
                t_sum += float(
                    t_reading)
                t_n += 1
        except Exception:
            pass
        try:
            h_reading = dht_device.
                humidity
            if h_reading is not None:
                h_sum += float(
                    h_reading)
                h_n += 1
        except Exception:
            pass
        s_reading = get_raw_moisture(
            moisture_pin)

        if s_reading is not None:
            s_sum += s_reading
            s_n += 1

        w_reading = get_wind_speed()

        if w_reading is not None:
            w_sum += float(w_reading)
            w_n += 1
            if w_reading > w_max:
                w_max = w_reading
                min_counter += 1
                time.sleep(6)

if t_n != 0:
    t_avg = t_sum/t_n
else:
    t_avg = None
if h_n != 0:
    h_avg = h_sum/h_n
else:
    h_avg = None
if s_n != 0:
    s_avg = s_sum/s_n
else:
    s_avg = None
if w_n != 0:
    w_avg = w_sum/w_n
else:
    w_avg = None
w_max = None

payload = f"{{DEVICE_ID},{find_err(t_avg)}," \
        "}{find_err(h_avg)},{find_err(" \
        "s_avg)},{find_err(w_avg)},{ \
        find_err(w_max)},{counter}"
try:
    rfm9x.send(payload.encode("utf-8"))
    print(f"Sent packet {payload}")
except Exception as e:
    print("Failed to send packet: ", e)
counter += 1

```

J Typescript API endpoint code for node data insert

```

app.post('/api/database/insert-node-data',
  async (req: Request, res: Response) =>
  {
    const {
      device_id,
      packet_id,
      temperature,
      humidity,
      soil_moisture,
      wind_speed,
      gust_speed,
      rssi0,
      rssi1,
      snr0,
      snr1,
    } = req.body;

    try {
      const query = `INSERT INTO node_data
        (node_deployment_id, farm_id,
         packet_id, temperature, humidity,
         soil_moisture, wind_speed, gust_speed
         , rssi0, rssi1, snr0, snr1,
         node_name)
      VALUES (
        (SELECT id FROM node_deployment WHERE
         node_name = $11 ORDER BY ts DESC
         LIMIT 1),
        ${farm_id},
        ${node_deployment_id},
        ${packet_id},
        ${temperature},
        ${humidity},
        ${soil_moisture},
        ${wind_speed},
        ${gust_speed},
        ${rssi0},
        ${rssi1},
        ${snr0},
        ${snr1},
        ${device_id}
      )`;
      await pool.query(query, values);
      res.status(200).json({ status: 'success' });
    } catch (error) {
      console.error(error);
      res.status(500).json({ error: 'failed to insert to database' });
    }
  });

```

K Python code to train machine learning model

```

import pandas as pd
import numpy as np
import lightgbm as lgb
import joblib as jl
import m2cgen as m2c
from sklearn.metrics import
    mean_absolute_error, mean_squared_error

VALIDATION_PERCENT = 0.2
NODE_ID = 1
TARGET = 'temperature'

NODE_PREFIX = 'node_' + f'{NODE_ID}'
TARGET_COL = NODE_PREFIX + '_' + TARGET

# Read the csv and make it into pandas
# datafram
data_frame = pd.DataFrame(pd.read_csv(
    NODE_PREFIX + '_training_data.csv'))

# Remove sensor data other than the target
cols_to_remove = ['ts']
for col in data_frame.columns:
    col_name = str(col)
    if col_name != TARGET_COL and col_name.
        startswith(NODE_PREFIX):
        cols_to_remove.append(col_name)

data_frame = data_frame.drop(columns =
    cols_to_remove)

# Set the split for training and validation
# data
cut_off_index = int(round((1-
    VALIDATION_PERCENT) * len(data_frame),
    0))

# Define the data
training_data = data_frame.iloc[:-
    cut_off_index]
validation_data = data_frame.iloc[-
    cut_off_index:]

# Define the features used for prediction
features = ['day_sin', 'day_cos', 'year_sin',
    'year_cos', 'temp', 'pressure',
    'humidity', 'uvi', 'clouds', 'wind_speed',
    'wind_gust', 'rain_1h', 'snow_1h']

# Initialise LGBM with following parameters
training_model = lgb.LGBMRegressor(
    n_estimators=250,
    learning_rate=0.05
)

# Fit the model using features and target
# data
training_model.fit(
    training_data[features],
    training_data[TARGET_COL],
    eval_metric='rmse',
    eval_set=[(validation_data[features],
        validation_data[TARGET_COL])],
    # Stop running training after 50
    # iterations of no improvement
    callbacks=[lgb.early_stopping(50), lgb.
        log_evaluation(20)]
)

# If it ends from best iteration get the
# date from this
best_iteration = getattr(training_model, "
    best_iteration_", None)
if best_iteration:
    prediction = training_model.predict(
        validation_data[features],
        num_iteration=best_iteration)
else:
    prediction = training_model.predict(validation_data[
        features])

#Console log useful stats
print("Mean absolute error:",
    mean_absolute_error(validation_data[
        TARGET_COL], prediction))
print("Root mean squared error:", np.sqrt(
    mean_squared_error(validation_data[
        TARGET_COL], prediction)))
print("Features used:", training_model.
    booster_.feature_name())

#Export final model to JS
javascript_final_model = m2c.
    export_to_javascript(training_model)

with open(f'{TARGET}{NODE_ID}.js', 'w') as
    f:
    f.write(javascript_final_model)

```