

# AN EXPANDABLE UAV-WSN SYSTEM FOR PRECISION AGRICULTURE WITH DEDICATED WEATHER-HARDENED HARDWARE

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*The paper presents a UAV-WSN hybrid system for large-scale agricultural data acquisition. It features a network of terminal nodes and a central node communicating with a data-collecting UAV. Multiple sensor networks are distributed across the field, utilizing a custom communication protocol with ad-hoc device registration, acknowledgments, and integrity checks to optimize energy-efficient data transmission in noisy environments. Key contributions include a custom electronic circuit and a novel protocol with safety and energy-saving features. A field experiment validated the system, achieving approximately 100 days of end-node operation, demonstrating its scalability and efficiency for real-world agricultural monitoring.*

**Keywords:** data transmission; sensor network; precision agriculture; sensor node; unmanned aerial vehicle; message integrity checking.

## 1. Introduction

With an ever-increasing population size and new challenges brought about by an unstable climate, fundamental changes should also be made in the agricultural sector. Rapid advances in computational technologies enable unseen-before techniques in industry and agriculture, ranging from adopting new and safer chemicals [1] to integrating software and sensors. As with all other industries, agriculture has evolved through the ages, using the newest technologies available at the time and integrating them into pre-existing workflows [2].

The main motivating factor behind this work is the principle of modular and expandable network design, where a sensing node can offer thorough functionality with minimal overhead. By making use of such devices, farmers can build expandable sensor networks that can be integrated into their existing workflows for prolonged periods. Large-scale agricultural operations require many sensors placed throughout the field, making efficient data collection an important task. Developing a dedicated wireless protocol, based on an open and connectionless protocol like ESP-NOW, for IoT (Internet of Things) devices would incentivize farmers to adopt such new technologies. Making the process of registering new devices and expanding the network's coverage a simple one, farmers can either monitor smaller, localized areas or cover large fields by using multiple networks. Replacing the requirement for an internet connection with a different technique for data collection,

such as drones, would simplify integration and help farmers study their crops. UAVs have seen growing popularity in recent years and have made their way into multiple industries, including agriculture. Their ability to quickly reach hardly accessible areas, cover large distances, and scan large surfaces has proven to be a key advantage for remote data acquisition. Another advantage that UAVs have for agricultural studies is the nature of their non-intrusive interaction with the crops.

While household applications for IoT networks can benefit from a wide array of protocols, technologies, and vendors, industrial and agricultural applications have needs that might not be covered by off-the-shelf products. Agricultural applications require hardy devices that can operate in remote conditions with no access to the internet, and slow intervention from a farmer should network issues arise. To solve these issues, devices should be weather-resistant, have acceptably long functioning lives, be able to work without an active internet connection, and implement communication protocols suited for environments with high attenuation or large distances between nodes.

Considering that agricultural fields often cover large areas without internet connectivity, farmers have been deterred from adopting sensing devices to monitor their crops owing to the laborious task of collecting the data. UAVs can eliminate this hurdle, making data collection much easier and quicker. Moreover, they can be used for crop surveillance, early detection of damage, periodical crop evolution surveys, or harvest planning, making drones multi-purpose vehicles that are becoming more common.

## **2. Related Works**

The field of wireless sensor networks (WSNs) has many approaches concerning sensor design, network arrangement, and communication protocols. These variables depend on the type of crop studied, the specific metrics desired by the researchers, the degree of inclusivity that the device can have, or the size of the studied area. The authors in [3] developed a compound UAV–leaf sensor network for measuring leaf temperature using a UAV and a leaf sensor, both equipped with infrared thermometers. A UAV carrying a mobile sink (MS) to capture data from a ground network comprised of multiple sensing nodes is presented in [4]. This forms a separate Zigbee network and gathers soil data collected by a coordinator.

While the previous studies have the sensing nodes placed on or above the ground, some applications use underground sensing nodes, usually on large field crops [5]. An underground sensor network based on LoRa-WAN for long-range communication between subterranean devices is used in [6]. User-centred approaches integrate sensors and networks with graphical interfaces for enhanced interaction, such as a sensor node paired with a GUI for mobile applications [7].

A smart automated watering system based on soil pH sensors was developed in [8]. Other communication protocols and techniques have been explored as well, for example, a WSN based on devices using the OpenThread protocol [9]. As for other approaches to network sensor data collecting, [10] proposed a new framework for collecting sensor data from a network using a low-cost UAV with optimal drone placement. The team behind [11] developed a multi-layer sensing network for data collection, distribution, and processing.

In the field of WSN, considerable effort is being devoted to developing energy-efficient and stable protocols. A protocol aimed at reducing redundant transmissions was simulated in [12]. A work targeting improvements in security and throughput was tested in MATLAB in [13], and a clustering technique to reduce duplicate data was evaluated using the Castalia simulator [14].

The paper proposal is to use sensing networks paired using a custom protocol with unmanned aerial vehicles (UAVs) to enable efficient and large-scale data collection meant to improve the currently employed cultivation practices. The principle of a multi-sensing node with multiple networks that can cover large areas has applications across various crop types, allowing farmers focused on a diverse range of crops to gather data best suited to their specific needs. This provides flexibility for sensor networks to respond to seasonal requirements with ease and collect wide-ranging amounts of data. To achieve this, a custom communication protocol was designed, aimed at ensuring stable operation in noisy or high attenuation environments, as well as custom electronics and hardware optimized for outdoor operation. Both end nodes and central nodes are battery-powered, allowing prolonged functioning that is independent of their proximity to a power source. The device's housing was chosen such that the electronics can safely work in wet or dusty settings. Software safeguards and antenna choice are aimed at minimizing data loss.

### **3. Materials and Methods**

#### ***3.1. Conceptual Model***

An overview of the network topology as it can be deployed in a real-world scenario is presented in Fig. 1. Multiple such networks could be used to cover larger areas. In the network pictured, five end nodes were connected to a central node. Due to the limitation of the ESP-NOW protocol's routing table, which has a fixed memory size allocated for directly paired connections, the maximum number of end nodes that can be associated with the central node is 20. End nodes are configured to only stay awake for short periods of time, namely, to perform measurements and send the data over to the central node. The latter is responsible for collecting the data and passing it over to the UAV, thus acting as a manager and bridge between the sensing end nodes and the vehicle responsible for data forwarding to the farmer.

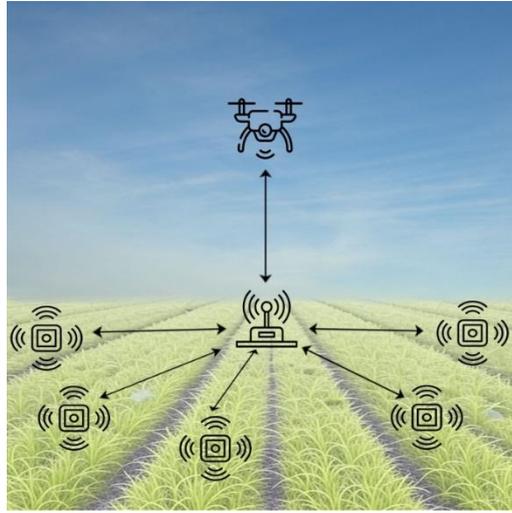


Fig. 1. UAV-WSN System Topology

### 3.2. Sensing Nodes Used

Sensing nodes are built on a custom printed circuit board (PCB) and each uses an ESP32 microcontroller. To boost the node's coverage and extend its range, the proper antenna for outdoor operation must be chosen [15, 16]. For this circuit, a SubMiniature version A (SMA) connected dipole with linear vertical polarization and 4 dBi gain operating in the 2400 MHz frequency band was chosen.

To allow for external sensor connections, digital and analogue connectors are exposed outside the housing containing the internal circuitry of the node. Power to the sensing nodes is provided using three rechargeable 18650-type batteries, each with a 3500mAh capacity. The current firmware allows the use of Inter-Integrated Circuit (I2C) and analogue sensors as provided in Table 1.

Table 1

Available Sensors

Device Name	Parameters
Sensirion SHT40	<ul style="list-style-type: none"> <li>• Temperature [°C]</li> <li>• Humidity [%]</li> </ul>
Vishay VEML7700	<ul style="list-style-type: none"> <li>• Ambient light [lux]</li> </ul>
SR PASSIVES 100k NTC	<ul style="list-style-type: none"> <li>• Temperature [°C]</li> </ul>

### 3.3. UAV Used

From inspecting soil quality to assessing crops' overall health and productivity [17], rotary-wing aircraft are used from small-scale monitoring to mapping or treatment applications [18]. The drone used for this work is the Hexsoon Edu 450 UAV equipped with a Matek F405 flight controller in the configuration

presented in Fig. 2. Mission planning and drone control were achieved using ArduPilot's open-source Mission Planner software, communicating via User Datagram Protocol (UDP) with the flight controller. To simplify communication with the central node and efficiently gather data, a small ESP32-based board implementing the same ESP-NOW communication protocol was attached to the frame.



Fig. 2. The UAV Used for Collecting Data

The proposed use case scenario for this network architecture is a multi-sensing node multi-network approach in which many central nodes, each managing multiple end nodes, are spread across large surfaces to monitor crops. The UAV is explored as a solution for the problem of collecting network data in areas with no GSM coverage or with very poor reception. Moreover, as terrain can become inaccessible during wet periods, UAVs can be used for data collection when such a task would be difficult for humans.

#### **4. System Implementation**

This section describes the implementation of the communication protocol defined, the hardware designed for the sensing nodes, and the integration of the UAV. ESP-NOW was chosen as the wireless communication protocol as it combines the reduced power consumption offered by BLE with ranges greater than Wi-Fi, with low latency and low packet loss [19]. Owing to the connectionless nature of ESP-NOW, regardless of the central node's loss of power, network integrity is not permanently affected. Considering the network's resilience to disconnects, the choice was made to proceed with a battery-powered central node. A mechanism of acknowledgements is implemented between the end nodes and the

central nodes, where should a sensing node not receive a response about a specific transmission, it should attempt three retransmissions.

#### 4.1. Inter-Node Communication

The chosen command format for this ESP-NOW implementation is outlined in Fig. 3. The 250-byte command was divided into a 244-byte payload and a 6-byte header consisting of one byte for command ID, which can provide up to 255 commands, an acknowledgement byte, and four bytes reserved for a 32-bit cyclic redundancy check (CRC32). Acknowledgements can be individually set for each transmission, allowing for retries in unfavourable environments.

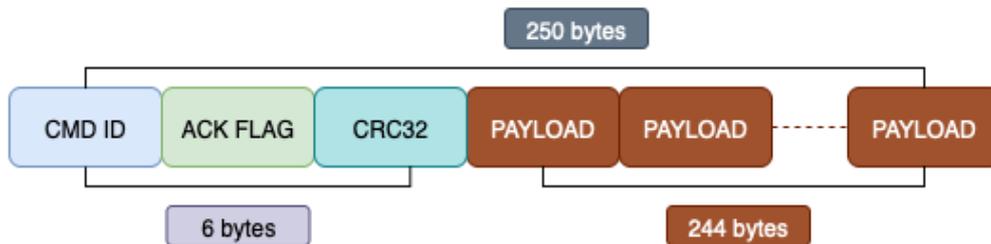


Fig. 3. Command Structure

#### 4.2. Network Formation and Data Transmission

Networks can be formed on the fly, and new end nodes can be added at any time. To achieve this, network formation is built around the end nodes publishing their identity to a central node through broadcast messages. Fig.4a illustrates the end-node registration command format, where the CMD ID byte has the value of hexadecimal 0x00, the ACK FLAG byte is 0x01, and the payload is the device's own MAC address. Registered end node addresses are written in persistent memory so that, where a crash to occur, end node connections are not lost. Fig.4b illustrates the Sensor Data Send command format for transmitting measurements from end nodes to the central node, featuring CMD ID with value 0x04 and a payload with the decodable data structure.

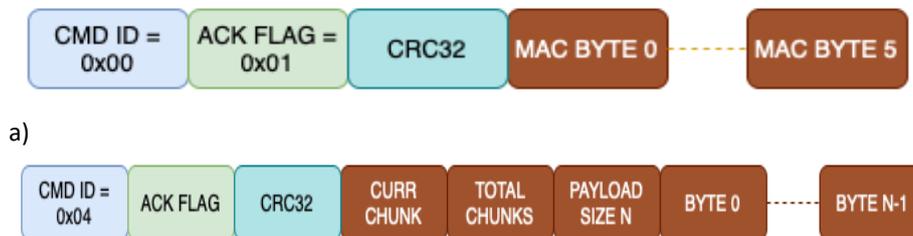


Fig. 4. Commands for Sensor Nodes. a) End Node Publishing and b) Sensor Data Send

For payloads exceeding 244 bytes, multiple packets are employed, with the first two payload bytes indicating the total chunk count and the current chunk index.

### 4.3. Persistent Data Storing

To efficiently organize data within the flash storage of the central node, a flash system library was written. Fig. 5 showcases the chosen file structure of the central node's stored data. A central DATA file contains all the subdirectories for all nodes, whereas connected end nodes' information is stored in a NODES.txt.

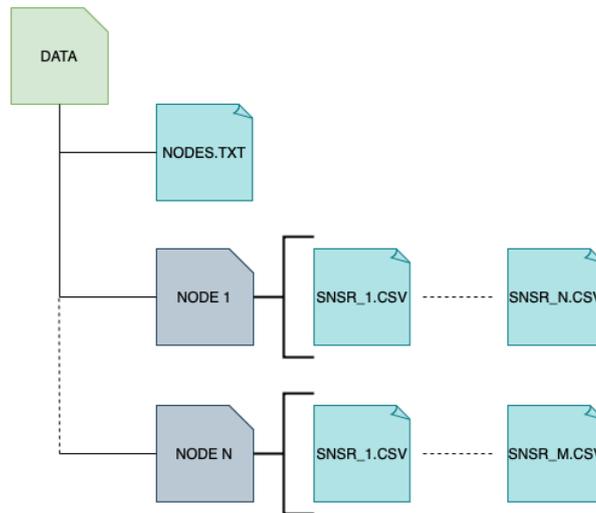


Fig. 5. Central Node Flash Structure

Each end node has its subdirectory where all the sensor data is separately logged. This simplifies access to the sensor data and makes it easier to forward each end node's measurements individually to the UAV. Actual sensor measurements are stored in individual files in a comma-separated values (CSV) format for easy processing by the end user.

### 4.4. Sensor Node Implementation

A dual-core ESP32 stood as the basis for this design, mainly for making use of ESP-NOW as a communication protocol. This microcontroller has other significant benefits, such as affordable price for the modules compatible with IPEX antenna connectors, high availability, and acceptable power consumption for the deep sleep operating modes of the end nodes. Fig. 6a shows the PCB, which was designed to use three batteries while easily fitting in a sealed housing. Fig. 6b shows the weather-hardened box meant to protect the electronics from the elements. It is sealed to an IP68 rating and can safely withstand the dust, rain, and watery environments commonly found in agricultural fields.

Central nodes have the responsibility to manage network traffic, log data, and act as a bridge between UAVs that gather measurements and the end nodes that are responsible for data collection. As the end node might transmit data with varied frequency and UAVs might pass at any moment, central nodes need to always be ready to receive messages from any possible source. To facilitate this, central nodes are always awake and responsive to queries from all peers. Built around the ESP-32 microcontroller and the same core electronic design, central nodes implement the same communication rules as all other devices in the network, but have additional features required for network management.

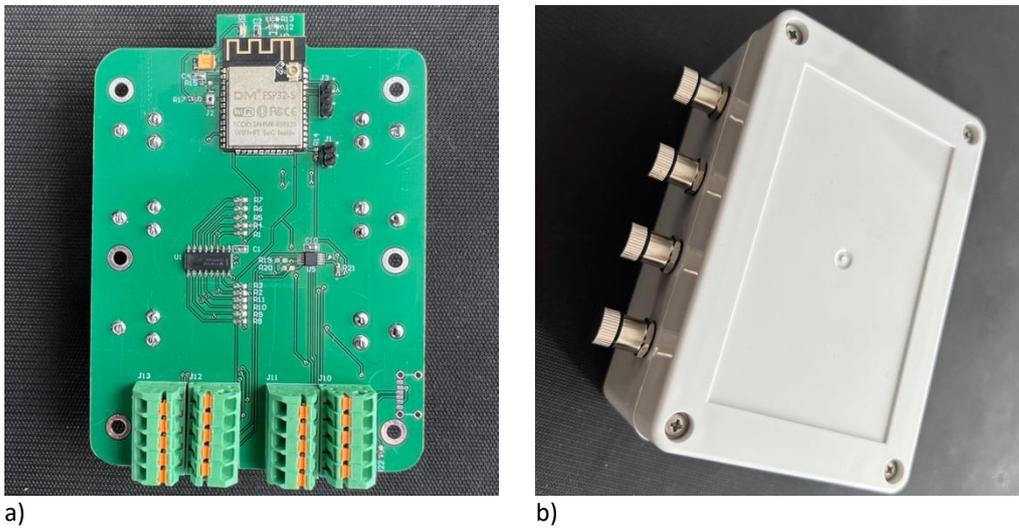


Fig. 6. Sensing Node: a. Front Side of the PCB; b. Weatherproof Housing

To integrate the UAV for data collection, a small board using the same ESP32 microcontroller as the network nodes was attached to the drone frame and powered from the flight controller. Data transfer was made using the same protocol as the rest of the network. For the files stored by the central node as shown in Fig. 5, the *Sensor Data Send* command shown in Fig. 4 b) was used to handover the data.

## 5. Experimental Results

### 5.1. Experimental Setup

A real-world field experiment was designed and performed to validate the network's functionality. A local field was chosen, and a network comprised of five end nodes and a central node was dispersed throughout it. For this experiment, each of the end nodes was equipped with the same sensor configuration: a digital Sensirion SHT40 [20] temperature and humidity sensor, a digital Vishay

VEML7700 [21] ambient light sensor, and an analogue SR PASSIVES 100k NTC [22] soil temperature sensor.

Sensors were placed an average of 20 meters away from the central node, thus covering an area of approximately 700 square meters. Each end node performed a set of measurements at five-minute intervals. This measurement frequency equates to 288 measurements per end node sensor per day. One exception to this was the analogue temperature sensor, which had a measurement frequency of 90 minutes due to the soil's high thermal inertia, causing the temperature to vary at a significantly lower rate than ambient air [23].

To end the experiment, a data collection flight had to be performed to validate the transmission from the central node to the UAV. At the end of the 72-hour-long experiment, an imaging flight was performed using the Hexsoon UAV equipped with an additional payload containing an ESP32 microcontroller responsible for managing communication with the central node using the same protocol as the other devices in the network. Upon reaching the hovering point, the UAV initiates a transfer request to the central node, and data is transmitted using ESP-NOW and the proprietary communication protocol defined. To try and guarantee a maximum transfer success rate, all messages passed between the UAV and the central node use acknowledgements. The data collected by the drone is not processed on board but rather stored on an SD card for offloading and analysis.

## 5.2. Data Analysis

After the experiment ran for 72 hours, the data was collected by the UAV and analysed. To validate the proper workings of the protocol and the fitness of the chosen hardware, the data collected was analysed for its size, the correctness of the measurements, and the total messages lost and recovered. To validate the energy profile of the boards, they were tested for their power consumption. Post-flight, the UAV-collected files were offloaded and analysed for size to assess the central node's flash storage capacity for measurements. File sizes depend on the number of records and the number of metrics for each node, varying between 10.158 bytes for the SHT40 sensor and as low as 312 bytes for the soil NTC. For the total duration of the experiment, a sensing node with the specified sensor configuration required a total amount of 15.695 bytes of memory. The memory requirement for such sensing nodes varies depending on the chosen measurement frequency and the total number of end nodes in the network.

The graphs shown in Fig. 7 highlight the measurements performed by one of the selected end nodes. For each of the equipped sensors, the graph plots the 72-hour data collection period, showcasing the variation in soil temperature, ambient temperature and humidity, and sunlight intensity. The subplot in Fig. 7a expresses the evolution of ambient temperature over the 72 hours, with a high plateau hit around the noon hours. Similarly, Fig. 7b shows the relative humidity of the

ambient air. Fig. 7c displays the soil temperature progression at 10cm depth throughout the 72 hours of the experiment. Fig. 7d illustrates the global radiation variation for the duration of the experiment.

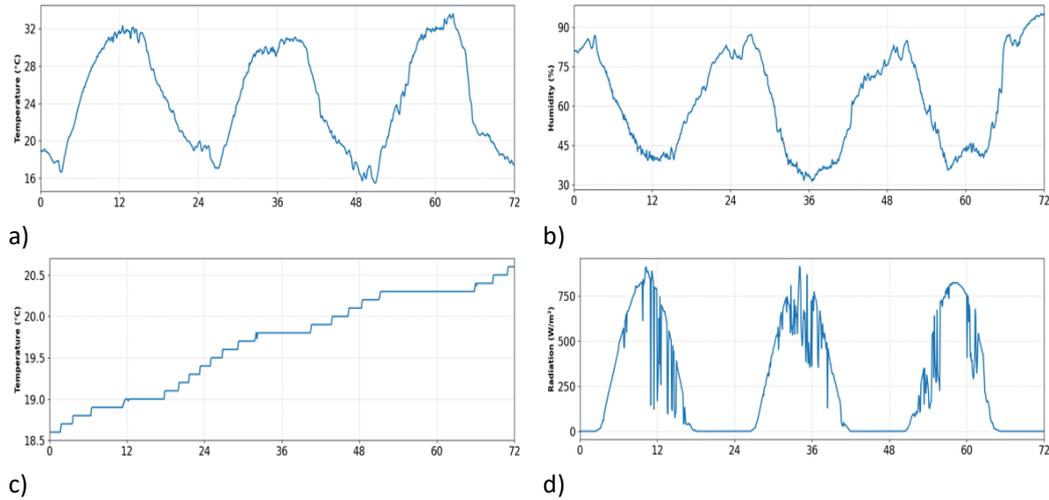


Fig. 7. End Node Data Over 72 Hours: a) Ambient Temperature [°C]; b) Humidity [%]; c) Soil Temperature [°C], and d) Global Radiation [W/m<sup>2</sup>].

Energy consumption is an important factor when designing the circuit and deciding on the battery size and case constraints. The largest consumer of energy in such a system is its microcontroller, and the overall current draw during operation and sleep depends on the circuit design, chosen sleep mode for the microcontroller, and frequency of measurements. To evaluate the board's energy consumption, an end node was powered from a power supply, and the instant readings every 100 milliseconds were logged over one hour of normal network operation. The end node's peak current draw was reached during transmission with a value of 129 mA, while the deep sleep mode of the microcontroller requires 15  $\mu$ A. For the duration of the measurement, the average power consumption sat at 4.25 mA. Given that the end node is equipped with three batteries totalling 10500 mAh, an estimated 100 days of use can be obtained. A slower measurement frequency would reduce the average consumption rate even more, thus increasing the period between battery charges or replacements.

The same procedure was applied for the central node's power evaluation, and the current draw sat at 131 mA during active transmission. As the central node manages communication with five end nodes, each transmitting messages at five-minute intervals, more peaks were registered. Idle consumption for the central node during waiting periods sat at 95 mA, with the average throughout the measurement being 103 mA. This average power consumption results in a 102-hour functioning period using the same 10500 mAh three-battery setup.

### **5.3. Data Loss Reduction**

To evaluate the network's resilience to data loss, the experiment was run with an additional layer of statistical data collection meant to evaluate the number of messages lost and their cause. If an end node received a response indicating a CRC32 mismatch, or no response at all, a counter dedicated to each event would be incremented. Throughout the experiment, a total of 1524 messages were sent. Of the total messages sent, seven were failed messages, and 63 retransmissions took place. These 63 retries represent 51 messages that required one or two retransmissions, and which would have been lost otherwise. The CRC32 integrity check, together with the retransmission mechanism, helped reduce the rate of message failure from 58 to seven, or a reduction from 4% to 0.48%.

## **6. Discussions**

As other state-of-the-art approaches focus on building conceptual solutions for sensor measurements in agriculture, this work produced a real sensing network. The choice of a custom circuit design enables modularity and reduced size of the electronic board, and the custom communication protocol gives flexibility to measure data with configurable frequency. The battery-powered device displays low energy consumption and can gather data for the lifetime of most crops, even at five-minute acquisition intervals, with a low packet loss that would not prevent farmers from obtaining detailed measurements.

While most approaches make use of off-the-shelf communication protocols, such as Zigbee or Wi-Fi, the main contribution of this work lies in developing a novel and dedicated protocol for inter-device communication paired with custom hardware optimized for reducing lost packets. In contrast with simulation-based evaluations in [12-14], our field-deployed network extends on prior work and reveals practical challenges such as packet loss through signal attenuation caused by environmental factors and the need to consider battery drainage and active transmission time to conserve energy. As such, the need for supplemental integrity verification mechanisms and retransmission rules arose, achieving stable operation under real conditions. This method proved to be very reliable at transmitting data and preserving network integrity over prolonged periods of use. Another contribution lies in developing a registration procedure that simplifies end node additions and reduces the risk of network corruption, a common pitfall of IoT protocols. As the central node allows new devices to register themselves with no prior setup, an existing network can easily be augmented with new unregistered end nodes by simply placing them within transmission range to the central node. Data collection with UAVs using the same communication protocol as the rest of the network is another innovative feature of the proposed network architecture, allowing for rapid gathering of measurements. With off-the-shelf protocols, data

collection is a cumbersome task that either requires storing the data on the network manager's local storage and retrieving it manually or ensuring an active internet connection. Maintaining an active internet connection for data uploading to the cloud is especially cumbersome in agricultural applications, as most agricultural fields are low-signal areas and data transmission in such environments incurs a hefty energy penalty through a higher required transmission power and frequent retransmissions. By incorporating data retrieval within the protocol's design and using UAVs, networks can be placed anywhere, irrespective of an internet connection or ease of access to the central node.

Unlike commercially available IoT devices, which use ESP32's built-in antenna, an effort has been made to design the PCB such that a dedicated omnidirectional antenna can be used to augment the radio communication. Efforts made to implement integrity checks, retransmission attempts, and choosing the right antenna have proven to make the proposed network stable, significantly reducing the number of packets lost. These features together allow for greater communication distances than were employed in this experiment, but with higher message loss. While most approaches produce a concept only, without building a complete network that can safely operate while exposed to the elements, the custom circuit design allowed the use of a weatherproof housing that can withstand the usual outdoor conditions found on most types of crops.

## 7. Conclusions

The viability and real-world operation of a distributed wireless sensor network were proven by developing a custom communication protocol based on ESP-NOW. Additionally, data collection using a UAV was also tested and proven as an effective means of remotely gathering data. The battery life of the devices was proven to be around 100 days, even with a five-minute interval between sensor acquisitions. A sealed circuit housing was also validated as the correct approach for encapsulating the electronics. Replacing the default antenna with one having greater gain and the development of retransmission mechanisms and message integrity checks have resulted in a significant lowering of transmission failures. A procedure to enrol new devices was developed, thus simplifying the steps required to augment the network compared with other common IoT protocols.

Future directions of this work aim to further improve the sensing node design by exploring other, more energy-dense battery solutions or solar panel additions for further prolonging the operational lifetime of the network. Developing the mesh capabilities of the protocol would tap into the potential of enlarging the network beyond its current maximum size and allow for more complex routing.

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