Enabling Field-Level Connectivity in Rural Digital Agriculture with Cloud-Based LoRaWAN

Joshua K. Bailey[1], Yaguang Zhang[1,2], Andrew Balmos[3], Fabio A. Castiblanco[3], Jingwen Zhang[4], Dennis Buckmaster[1], James Krogmeier[3], Mark G. Allen[4], and David Love[3]

[1] Purdue University, Department of Agricultural and Biological Engineering,
225 S University St, West Lafayette, IN, USA

[2] Purdue University, Department of Agricultural Sciences Education & Communication,
915 W State St, West Lafayette, IN, USA

[3] Purdue University, Elmore Family School of Electrical and Computer Engineering,
465 Northwestern Ave, West Lafayette, IN, USA

[4] University of Pennsylvania, Department of Electrical and Systems Engineering,
200 S 33rd St, Philadelphia, PA 19104

A paper from the Proceedings of the
16th International Conference on Precision Agriculture
21-24 July 2024
Manhattan, Kansas, United States

Abstract

The widespread adoption of next-generation digital agriculture technologies in rural areas faces a critical challenge in the form of inadequate field-level connectivity. Traditional approaches to connecting people fall short in providing cost-effective solutions for many remote agricultural locations, exacerbating the digital divide. Current cellular networks, including 5G with millimeter wave technology, are urban-centric and struggle to meet the evolving digital agricultural needs, presenting a significant hurdle to rapid rural connectivity development. In this paper, we explore alternative and cost-effective solutions that extend beyond conventional cellular networks. Our previous investigation encompasses innovative approaches such as follow-me drone data relay, fusion-based predictive beamforming, Long-Range Wide Area Network (LoRaWAN), and edge computing. Notably, this paper highlights the potential of LoRa technology in IoT applications, showcasing extensive coverage, low power consumption, and cost-effectiveness, albeit with a limitation in data rate. Furthermore, we present the features and success of projects including the Purdue Open Ag Technology and Systems (OATS) Center Data Stations (PODs), the ISOBlue telematics and mobile compute platform, and Avena, an open-source software stack that each effectively reduce data size to enable decentralized, network-agnostic communication through opportunistic transmissions. We demonstrate cloud-based LoRaWAN as a practical and

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 16th International Conference on Precision Agriculture. EXAMPLE: Last Name, A. B. & Coauthor, C. D. (2024). Title of paper. In Proceedings of the 16th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

low-cost solution for field-level connectivity and evaluate scalability under three scenarios: Wi-Fi-connected gateways, cellular data-connected gateways, and options for scenarios where neither Wi-Fi nor cellular coverage are available. Additionally, we address resiliency and security aspects of on-farm LoRaWAN deployments, including gateway replacement, cybersecurity threat responses, and existing measures for continued sensor data flow to ensure uninterrupted operations, particularly when automated devices are in use. Digital agriculture will involve a hybrid approach of telecommunication technologies, each customized for specific applications and reflecting a nuanced set of trade-offs. Cloud-based LoRaWAN is a promising means to address connectivity challenges in rural areas, paving the way for the seamless integration of next-generation digital agriculture technologies.

Introduction

Throughout history, agricultural technologies have played a crucial role in connecting people, especially farmers, to the land. From the first use of traditional tools to the adoption of horsepower and eventually the development of machinery, technological advancements have reshaped the way we view and understand agriculture, ultimately deepening the relationship between farm and farmer. In the age of digital agriculture, which is characterized by the use of precision and data-driven technologies to assist farmers in making site specific, real-time management decisions (MacPherson et al., 2022), there is new potential to connect farmers to the land through data. Making this connection is now more important than ever, as farmers face pressures from multiple angles. With continued population and consumption growth leading to increases in the global demand for food (Godfray et al., 2010), farmers need to be able to produce more. At the same time, farming has become more expensive across the board due to rising input costs (Brunelle et al., 2015) including higher machinery pricing, stringent regulations creating compliance burdens (Hou & Li, 2017), labor shortages stressing farms' bottom lines, and environmental shifts impacting the availability of key inputs such as water. All these factors are making it more important than ever for farmers to analyze each decision daily.

In order to analyze each decision, farmers need reliable data across their operations. Internet of Things (IoT), broadly defined by systems of devices, software programs, sensors, and other technologies that are able to exchange information and data via the internet, has notable applications in agriculture to help achieve this by providing site-specific, real-time data (Dhal et al., 2023). Through the use and integration of various IoT devices such as soil sensors and weather stations, farmers can obtain real-time monitoring insights that aid with informed decision-making and efficient resource allocation to maximize crop productivity (Farooq et al., 2022). In livestock settings, livestock monitoring systems can provide insights on livestock behavior, health, and living environment. From an operational perspective, sensors such as GPS trackers, fuel tank monitors, energy meters, and storage metrics help with the effective management of farm assets on the go. Additionally, automated devices such as smart irrigation valves and automated feeders enable farmers to act on data collected with remote access and control.

Despite significant developments and growing interest in IoT applications in agriculture, several challenges impede widespread adoption, with connectivity being a major issue (Zhang et al., 2021). This problem affects not only IoT but also rural communities worldwide. The digital agriculture sector urgently needs low-cost, field-level connectivity to test and deploy current and next-generation technologies at scale. Traditional connectivity solutions are often insufficient for remote agricultural locations, exacerbating the digital divide. Current cellular networks, including 5G, are urban-centric and struggle to meet rural needs, hindering rapid rural connectivity development (Zhang et al., 2022). Our previous research explored alternative, cost-effective connectivity solutions beyond conventional cellular networks, such as follow-me drone data relays (Zhang et al., 2023), fusion-based predictive beamforming (Lee et al., 2024), Long-Range Wide Area Network (LoRaWAN), and edge computing. This study highlights the potential of LoRa technology in offering extensive coverage, low power consumption, and cost-effectiveness, despite its limited data rate. We also demonstrate the success of edge computing in projects such as ISOBlue and Avena (Balmos, 2022; Wang, 2020), which reduce data size and enable decentralized, network-agnostic communication. This approach greatly enhances digital agriculture functionalities.

Previous work done by the OATS team on farm-level LoRaWAN deployments have included the Purdue OATS DataStation (PODs) (i.e., a "PC-based system") and a Pi- Enabled Adaptation of the PODs (pea-POD) (i.e., Raspberry Pi Based System), however the goal was more to demonstrate the capabilities of LoRaWAN and the custom open-source software stack (presented later), showcasing cloudless, internetless, and internet-connected configurations (Schreck, 2023). Moving forward, we view the value of having cloud-based systems to be imperative for efficiently providing data on the go for modern farming operations. We opt to move as many components as possible from being physically in the field and on the same tripod as the gateway to being more spread out/indoors or entirely hosted in cloud computing space to reduce the risk of both physical and cyber vulnerabilities, which can cause the loss of important historical data and network configuration settings. Lastly, utilizing cloud-based systems enables less hands-on requirements with automated backups and easier maintenance (i.e. server hardware doesn't become outdated/run out of storage), as well as flexible cost structures where the user only needs to pay for the amount of resources they use.

By integrating these research findings, we propose cloud-based LoRaWAN as a practical, low-cost solution for field-level connectivity. We evaluate its scalability under three scenarios: Wi-Fi-connected gateways, cellular data-connected gateways, and options for areas without Wi-Fi or cellular coverage, suggesting hybrid approaches tailored to specific farm needs. Additionally, we address resiliency and security aspects of on-farm LoRaWAN deployments, including gateway replacement, cybersecurity threat responses, and existing measures for continued sensor data flow to ensure uninterrupted operations, especially when using automated devices.

Considering the connectivity challenges and the need for sensor data in modern farming, the objectives of this work were to:

1. Explain principles of LoRaWAN as a connectivity solution and the benefits for sensing in agricultural production systems.
2. Provide hardware setups for remote LoRaWAN applications.
3. Propose a cost-effective open-source software stack enabling data flow and insights.
4. Illustrate case studies for LoRaWAN applications deployed in orchards and fields.

LoRaWAN-Centered Networking Solutions for Farming Operations

LoRa (Long Range) is a spread spectrum modulation technique developed by Semtech utilizing chirp spread spectrum (CSS) technology (Semtech Corporation, 2024), constituting the device layer and physical layer responsible for modulating data collected (i.e., from a sensor), converting it to digital (RF) signals, and transmitting the data to a central point or gateway (Schreck, 2023). As a Low Power Wide Area Network (LPWAN) technology, some key features of LoRa include its low-power consumption and long-distance connectivity (up to 10 km (Aihara et al., 2019)), albeit at a lower data rate (Haxhibeqiri et al., 2018). Table 1 shows a comparison of LoRa with five other connectivity options.

Table 1. Comparison of six wireless connectivity options (Balmos, n.d., personal communication, July 1, 2021).

	Cellular	**Wi-Fi**	**Cat-M1**	**NB-IoT**	**Bluetooth**	**LoRa**
Range	Long	Short	Medium	Long	Very short	Long
Power (Battery usage)	High	High	Medium	Medium	Low	Low
Capacity (Devices per gateway)	Medium	Medium	High	High	Medium	Low
Cost	High	Low	Medium	Medium	Low	Low
Data rate	Very high	Very high	Medium	Low	Low	Very low

In order to increase capacity, the LoRa Alliance developed LoRaWAN, which stands for Long Range Wide Area Network, and is a communication protocol built on top of the LoRa physical layer specifically for IoT applications (LoRa Alliance, 2024). LoRaWAN is a good selection for many agricultural settings because it covers vast amounts of land and can potentially connect thousands of sensors per gateway. The tradeoff of lower data rate for lower power end devices is a strange compromise for many physical layers, but is critically important for agriculture because in-field sensors do not necessarily provide real-time data; measurement periods of 15, 30, 60 minutes or even longer is often sufficient for slowly changing applications like soil moisture sensing, nutrient uptake monitoring, or hourly atmospheric condition measurements. Therefore, these sensors do not need large data rates because they have long periods of time between samples to transmit the data that they do collect. As a result, LoRaWAN sensors can achieve long lifespans, some having been noted to last for up to 10 years on a single 1000mAh battery (Abdelfadeel, 2020). This reduced need for continual servicing is a critical practical factor in cropping systems because the difficulty of accessing and the lengthy process of servicing sensor nodes distributed over a large area like a farm is a major blocker to adoption.

LoRaWAN operates in the unlicensed radio spectrum, enabling LoRaWAN gateways to be operated without any professional licenses, similar to how anyone can purchase and activate a Wi-Fi router. The costs to operate LoRaWAN are on the same order of magnitude as other unlicensed networks (e.g. WiFi). In other words, LoRaWAN can be deployed as a private network without needing to cooperate with or inform anyone else; however, the LoRaWAN standard was built around a vision that either a cooperative network of private installations and/or large managed public networks would eventually make LoRaWAN access a purchasable commodity like cellular networks of today. We feel that entities like rural wireless internet providers and utility or agricultural cooperatives may eventually grow to coordinate and operate such a cooperative LoRaWAN network for heavy agricultural areas.

The LoRaWAN protocol connects sensors to gateways, then to cloud or edge devices, and finally to applications (Schreck, 2023), Figure 1 illustrates a typical LoRaWAN network architecture.

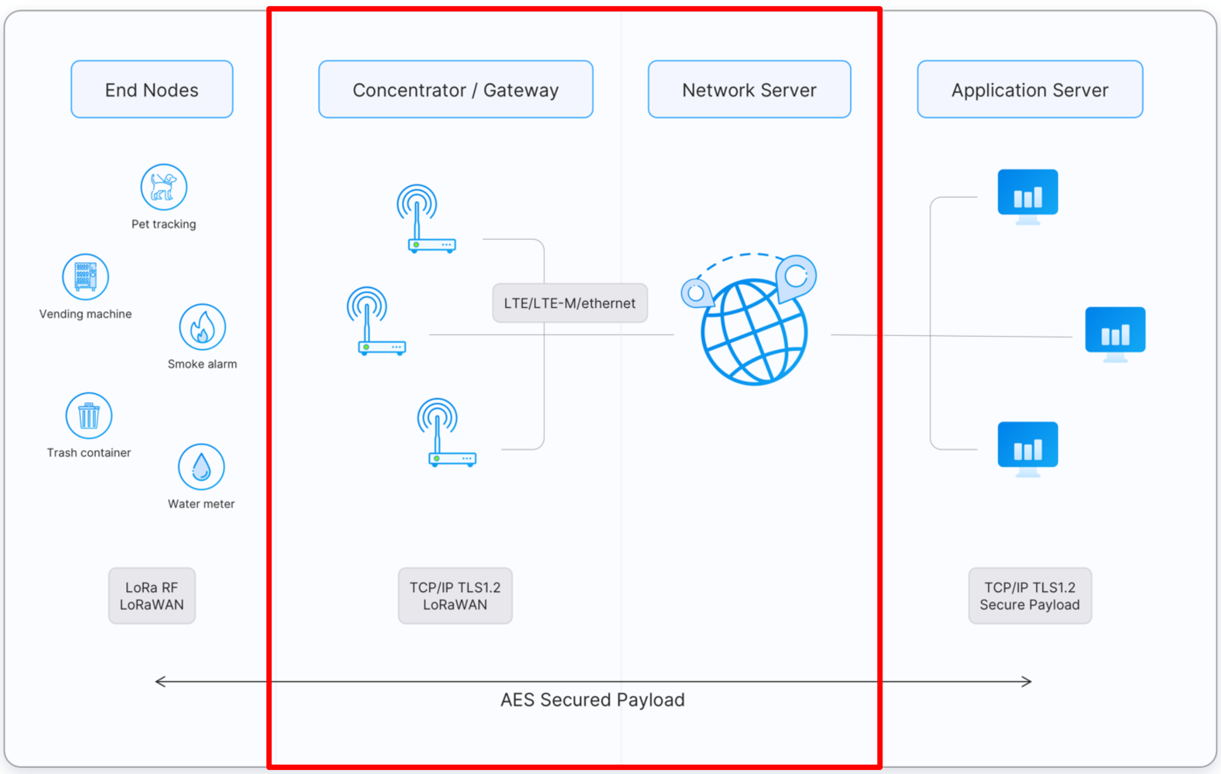


Fig 1. LoRaWAN network architecture (The Things Network, 2024), red box indicating focus area of this paper.

LoRaWAN Hardware

The following subsections detail reference hardware setups for cloud-based LoRaWAN infrastructure that take advantage of existing farm resources. Connectivity options of Wi-Fi, Cellular, and low orbit satellites are presented. These implementations utilize RAKwireless Edge Pro gateways for their ability to be powered over ethernet, their size and range capabilities, and outdoor rating (Schreck, 2023). These have a relatively simple dashboard for initial gateway configuration. It is important to note that LoRaWAN gateways achieve better coverage when mounted higher, but the tradeoff is they can be more difficult to access, and if something were to happen to a gateway or antenna during a busy season when a farmer is relying on actionable data, this could be problematic.

Internet Service-Connected LoRaWAN Gateways

In farming operations where existing Internet service is accessible, e.g., home, office, shop, LoRaWAN gateways can be connected directly. Both direct connect to an ethernet source or wireless via Wi-Fi is supported. In this configuration, the existing internet connection will be used for communicating with the rest of the LoRaWAN software hosted in the cloud. The table below outlines the costs associated with this deployment strategy, not including shipping. A deployment within North America, or any area that utilizes the same operating rules, is assumed. Mounting equipment is site-specific and should be specified as needed.

Table 2. Wi-Fi-Connected LoRaWAN Gateway Costs (North America).

Manufacturer	Component	Description	Approx. Cost	URL
RAKwireless	LoRaWAN Gateway	Channel: 8 Channels, LTE: Without, Frequency: US915	$372.00	Link
RAKwireless	8dBi Antenna	Connector Type: N-Type Male, Frequency: 900-930MHz	$60.00	Link
PackYard	Sealing Tape	0.8mm Thickness	$12.98	Link
MOOKEERF	Antenna Cable	10FT	$17.99	Link
MOOKEERF	Lightning Arrester	N-Type Male to N-Type Female	$16.99	Link
MAXLIN CABLE	Long Ethernet Cable	50FT (can be more or less)	$24.99	Link
Vabogu	Short Ethernet Cable	1.5FT (can be more or less)	$3.99	Link
		Total	**$508.94**	

Although the RAKwireless Edge Pro gateway is outdoor rated and a 5.8dBi antenna can be mounted directly to it, our approach placed the gateway inside to ensure smooth operations throughout seasons with the antenna outside and mounted on an accessible area (such as a low roof) for better serviceability if necessary. To construct this setup, the gateway (inside) should be placed as close to the antenna location as possible since a greater cable length will decrease the distance of connectivity (we aim for 10 ft or under, but slightly over is acceptable). If a metal roof is present, a rule of mounting the antenna two times its height is recommended, so for the 8dBi fiberglass antenna which is 3 ft in length, this means the base of the antenna should be 6 ft above the peak of the roof. Consulting with a local contractor could be beneficial for determining the optimal configuration depending on specific scenarios. A complete build guide is available on the GitHub page below for steps to installing this setup (OATS Center, 2024).

While this setup may require additional steps and the help from local contractors, especially for threading the antenna cable through a wall or ceiling and potentially threading the long ethernet cable through walls to the Internet source, the cost over time is comparatively lower since an existing internet connection is being used and won't require additional fees for data uplink.

Cellular-Connected LoRaWAN Gateways

In the event pre-existing Internet is not an option but cellular coverage is available, LoRaWAN gateways can be connected via a data plan. In our trial installations, we have used with good success the low-cost, IoT specific data plans offered by Sixfab which support flexible pricing across multiple devices (in this case, gateways) and carriers (Sixfab, 2024). In applications where Power over Ethernet (PoE) can't be used, an alternative energy source must be utilized. A Solar Powered Remote IoT4Ag Network Gateway (SPRING) was configured and deployed to provide continuous cellular-based LoRaWAN connectivity in remote areas. Although new versions of gateways are being released that consolidate gateways with solar panels directly, we used the RAKwireless Edge Pro and RAKwireless solar panel and battery kit as they were already on the market, reasonably priced, had good power/energy capacity, and weren't solely used for backup power. Some notable features include the battery's long service life span of 10 years with daily use, the battery's ability to charge under 0°C, the solar panel's ability to operate in extreme temperatures (-40°C to +85°C), and the solar panel's peak power of 80 W (RAKwireless, 2024). To support the weight of the battery pack and solar panel, a sturdy tripod system is used. The table below outlines the costs associated with this deployment strategy, not including shipping, for a deployment within North America, or any area that utilizes the same operating rules. Not included are any site-specific grounding equipment.

Table 3. Cellular Data-Connected LoRaWAN Gateway Costs (United States).

Manufacturer	Component	Description	Approximate Cost	URL
RAKwireless	LoRaWAN Gateway	Channel: 8 Channels, LTE: With LTE Cat4 (EG95-NA) for North America, Frequency: US915	$402.00	Link

RAKwireless	8dBi Antenna	Connector Type: N-Type Male, Frequency: 900-930MHz	$60.00	Link
National Hardware	U-Bolt (2)	5/16" x 2" x 3-1/4" Zinc	$3.00	Link
PackYard	Sealing Tape	0.8mm Thickness	$12.98	Link
MOOKEERF	Antenna Cable	6FT	$15.99	Link
RAKwireless	RAK Battery Plus	Variant: RAK Battery Plus & Solar Panel Kit, Country: United States	$817.00	Link
YardGard	Fence Post	Steel Chain Link Fence Post, 8' H 1-5/8" W	$26.99	Link
WiMo	Tripod	Mast Tripod, 7FT Spread	$279.99	Link
WiMo	Tripod Feet	Tripod Foot Plates	$89.99	Link
American Earth Anchors	Tripod Anchor (3)	9-inch Penetrator	$21.51	Link
American Ground Screw Mfg & Supply Store	Ground Screw	22" Ground Anchor	$39.99	Link
		Total	**$1,769.44**	

For the deployment of a SPRING, a complete build guide is available on GitHub (OATS Center, 2024). Although this setup is meant to be secured to the ground, a key feature of SPRINGs is their mobility. A farmer may only need to collect data during certain times of the year (e.g., planting, growing, harvesting) and would prefer to protect their equipment in others (e.g., winter). Therefore, by simply loosening the fence post from the ground screw and tripod, it's possible to transport the critical SPRING components as one unit to and from the deployment location. The ground screw and tripod may be left out or collected and redeployed at a later date or new location.

Low Orbit Satellite Internet-Connected Solutions for Remote Areas

In scenarios where traditional internet access methods such as cable, fiber, or cellular are not readily available in remote areas, the emerging low-cost satellite communication technology exemplified by the low orbit satellite connections offered by Starlink (Ahmmed et al., 2022) presents a viable solution for providing backhaul communication. Subsequently, a variety of wireless communication technologies, including Wi-Fi, private 5G, and LoRa/LoRaWAN can be deployed to establish a local area network managed by farmers, thereby facilitating field-level connectivity. Nonetheless, potential technical challenges on the farmers' end may pose a hindrance, particularly concerning the establishment and maintenance of the local network that disseminates the backhaul connection across expansive areas of interest.

Hybrid Approach

It's highly possible that more than one of these hardware setups will be needed to effectively cover all of a farm's acreage with LoRaWAN connectivity. For example, a farm might have a gateway connected to a Wi-Fi router, but the signal is unable to reach beyond a forest line to further acreage. Another farm might have multiple locations, some with cellular coverage and some without. In these instances, a scalable and cost-effective combination of the three hardware setups can be used, considering accessibility and LoRaWAN coverage distance. Additionally, cooperative neighbors could join forces, deploying LoRaWAN gateways that expand area covered across multiple properties, together sharing in the increased coverage and robustness.

To evaluate LoRaWAN coverage distance and determine the need for more than one gateway, simple range testing can be conducted. In prior field experiments, we utilized a Clover Agriculture Sensor (TEKTELIC, 2024) and monitored the Signal Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) values for an indication of signal strength and quality via our Chirpstack server (discussed in the software section) while moving the sensor further from the gateway location in incremental distances and multiple directions (i.e., coordinal directions or in the general direction of where sensors will be deployed). Additionally, LoRaWAN GPS trackers such as Oyster3 for LoRaWAN (Digital Matter, 2024) can be driven further from a gateway location while monitoring a dashboard visualization platform, such as Grafana (discussed in the software section), until connection is lost. While there are specific tools available for testing LoRaWAN network range, using devices that will be implemented at the site in the future is a cost-effective method for validation, and eliminates the device-specific performance variations. The height above ground of the test device is a critical parameter to not ignore, as well as considerations if the device will be further covered by crops as the growing season continues.

An example (hypothetical) coverage map for a farm is shown below, assuming the deployment of a Wi-Fi connected gateway and an additional cellular-connected SPRING. An actual coverage map would display more heat map-style characteristics and less of a perfect circle shape, with greater coverage in open areas and less coverage where barriers (such as forest groves or heavy terrain) are present.

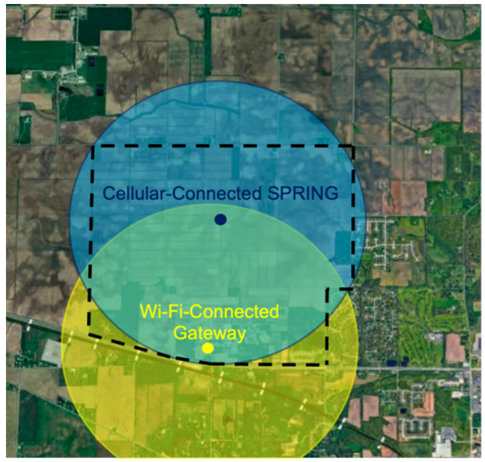


Fig 2. Hypothetical coverage map of farm with two gateways.

At each new gateway site, whether as an initial site or for expanding coverage, decisions can be made for determining which of the three hardware setups to implement. In summary, if local fixed Internet service is available and the antenna can be mounted within a close distance to the gateway, an Internet connected gateway will be the least expensive choice, while providing reliable coverage. If it is not, cellular (if available) via a SPRING is the best option. Finally, if there is no reliable cellular connection, then a low orbit satellite internet option (if available) may be required.

Hardware Resiliency and Risk Considerations

The resiliency and risk considerations for LoRaWAN-based systems in agricultural scenarios are fundamentally crucial, especially as the data they provide becomes fully integrated with day-to-day management decisions and farming operations. Here we list some hardware related scenarios that can affect system stability and methods for preventing and/or dealing with them:

- Loss of power to gateway: A backup power supply, such as a generator, can be used until the power source is restored or replaced.
- Loss of Internet service: Specific to the Internet-connected gateway setup, a gateway with LTE can be purchased instead. For everyday use, the gateway would use the local Internet service, but in the event that it is not available due to an outage or other issue, the gateway would switch over to the cellular modem to continue talking with the cloud. We have not independently verified this failover mechanism, and it will be the subject of future work.
- Gateway and/or antenna damage: Due to the relatively inexpensive nature of the hardware, we suggest holding a backup gateway, antenna, and cabling to allow for swift replacement. This would most likely present after an extreme weather event such as heavy winds or lightning strikes.

The nature of LoRaWAN itself provides robustness for upholding communication even when facing challenging scenarios. Once configured, LoRa-based sensors “blindly” broadcast messages, and all gateways within range will receive them for processing. This means that for any of the three hardware scenarios in which a gateway is rendered unusable, sensor data can continue to be received once the issue is fixed without having to reconfigure each individual sensor. Additionally, sensors within range of other gateways will also collect the broadcasted message, providing resiliency against any particular gateway failing.

In the event of a cyber-attack that compromises the network, especially when automated devices are being used, LoRaWAN gateways can be unplugged to mitigate damage. It is also recommended to maintain a physical backup mechanism for utilizing automated devices, such as a handle for turning a device on/off so that operations can continue manually. Having a comprehensive strategy for dealing with worst-case scenarios that can disrupt the normal use of IoT technologies is highly recommended.

Software Stack for Efficient Data Flow

Avena is an open-source software framework developed to overcome long-standing challenges in agricultural edge computing such as vendor lock-in and incompatibility (Balmos et al., 2022). Early work with Avena centered around supporting cloud connectivity for ISOBlue, an open-source edge-computing device capable of collecting and transmitting machine sensor data from the Controller Area Network (CAN) bus, as well as recording machine position data over GPS (Balmos et al., 2022). Avena was later integrated into the Purdue OATS DataStation (PODs) project, which implemented computing into LoRaWAN gateways for cloud-less data collection, storage, and processing of LoRaWAN sensor data (Schreck, 2023).

Along with the prior steps of physically deploying the RAKwireless Edge Pro gateways, sensors must be associated to the network through a web-based user interface. A complete build guide for setting up the Avena software framework is available on the GitHub page below (OATS Center, 2024). The following sections outline the data pipeline for LoRaWAN use cases.

Once individual sensor transmissions arrive at a gateway, it transfers them to our customized open-source data pipeline that will associate, decrypt, transform, and store the data. For SPRINGs that happens on a remote server, or cloud, and results in dashboard visualizations accessible from any Internet-connected device. Dashboards may either be publicly available or protect by authentication. The main components of this data pipeline, shown schematically in Figure 3, are described below:

- NATS: A messaging system that implements interest-based communications between software services and hardware. (https://nats.io/)
- Chirpstack: An open-source LoRaWAN gateway network server that implements a LoRaWAN network across all of your deployed gateways. (https://www.chirpstack.io/) Verified and decrypted sensor messages are exported over Message Queuing Telemetry Transport (MQTT) for further processing within the data pipeline.
- Benthos: A system integrator that transforms sensor data streams, preparing them for storage, applying calibration factors, and any other processing required. (https://www.benthos.dev/)
- Prometheus: Collects health metrics from all services. (https://prometheus.io/)
- Timescale DB: A timeseries database that stores all sensor data permanently. (https://www.timescale.com/)
- Grafana: An open-source data visualization and monitoring tool. Custom monitors can be defined, which result in notifications within a variety of external systems, e.g., SMS, email, online chatting tools. (https://grafana.com/)

It's also important to note that users can choose any data visualization option and/or customize the framework for their specific use cases. A user may select Grafana due to its open-source nature or a commercial application, such as Power BI, a business analytics platform offered by Microsoft, if the insights the platform provides with its analytics are needed.

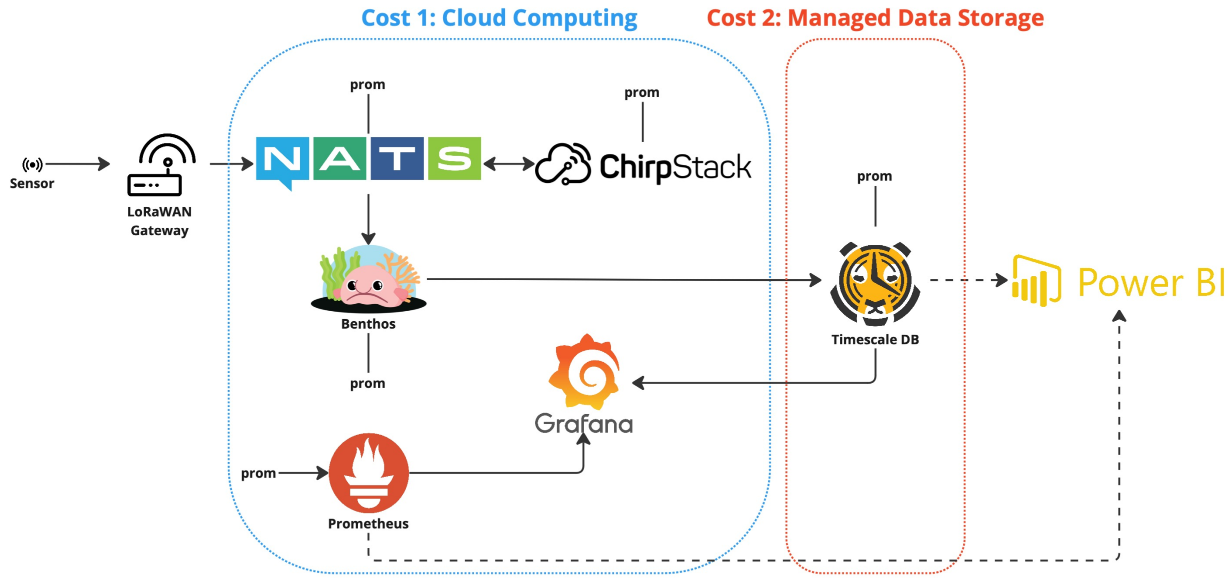


Fig 3. Open-source data pipeline design for IoT systems including two main cost categories.

Example Costs for Hosting the Data Pipeline

As an example breakdown of costs for hosting the data pipeline, Cost 1 is the cost of utilizing a managed cloud service for NATS, Chirpstack, Benthos, Prometheus, and Grafana. Our main purpose for choosing a cloud service over a physical option is for hedging against the risk of something happening to a physical server/computer that could cause loss in historical data collected and the configuration settings of the network, but cloud services also offer numerous advantages including the ability to scale up as more storage space is needed over time, resource efficiency from cloud providers managing underlying infrastructure, and cost efficiency from cloud services often following a pay-as-you-go model. From our estimates for using DigitalOcean as a cloud service for a virtual machine, it would cost $4-$6/month for 10-25 GiB of storage. This can be lower however, as a user can turn on/off components depending on when the system is in use (such as during the growing season vs. winter months) to save money on storage use.

Cost 2 is the cost of paying for Timescale DB as a managed service. Timescale DB could also be included in the Cost 1 category but since Timescale DB is the permanent data storage hub for all sensor data collected, we're opting to pay extra so automatic backups can be made to alleviate potential pressure on the user to constantly keep track of this, not to mention the added layer of security to protect the data. If Timescale DB were to be kept in the Cost 1 category, the overall cost would be around $12/month for 50 GiB of storage, while Timescale DB in the Cost 2 category would amount to $39/month for 50 GiB of storage plus the Cost 1 costs. However, it's important to keep in mind that these estimates are only meant to give an idea of the cost and capacity of these options. The costs will start out much lower due to how both managed service providers only require payment based on storage used and will only increase over time as more data is collected, more devices are used, and/or more acres are covered.

Software Resiliency and Security Considerations

As previously indicated in hardware, there are methods for preventing or dealing with software reliability and security issues. Some of these are:

- Grafana promptly sends alerts if issues occur with any element of the data pipeline architecture, allowing for timely action. Examples could include services suddenly stopping (due to bugs, errors, connectivity issues, etc.), data streams suddenly disappearing; in general, any part of the software stack that unexpectedly stops working.
- Cyber threats of data sniffing: In general, all things within the Avena architecture are

connected via a WireGuard (https://www.wireguard.com/) network. This ensures that all communication is secure, even between the gateways and various cloud-hosted software components. In addition, any user with an authenticated connection to the same WireGuard network can remote access all hardware devices and software services without having to risk exposing them directly to the public internet.

- Cyber threats to data pipeline components: Secure passwords should be used and regularly updated for accounts.

Case Studies

Two case studies are presented to demonstrate progress and real-world scenarios of cloud-based LoRaWAN deployments. The first was a collaboration with a commercial apple farm in New York interested in testing LoRaWAN in an orchard setting, utilizing various sensors and a Wi-Fi-connected gateway (included to show the direction of this work). The second was a multi-user effort among the IoT4Ag Engineering Research Center members: Purdue University, the University of Florida, and the University of Pennsylvania, to support experimental deployments of air batteries as a power source for subsurface sensing.

Wi-Fi-Connected LoRaWAN Gateway at Commercial NY Apple Orchard

To provide a lean way of testing basic LoRaWAN coverage at a commercial NY apple farm, a spread-out version of the pea-POD (Raspberry Pi-Enabled Adaption of the Purdue OATS DataStation) was constructed. A RAKwireless Edge Pro gateway and antenna were mounted on a tripod, brought outside the farm’s main shop area, and then connected to a Wi-Fi source and power supply inside the shop via a 50 ft ethernet cable and PoE injector. The gateway remained on the tripod at ground level for the duration of experimentation. Inside the shop, a Raspberry Pi was configured to host Chirpstack as the network server and interfaced with the gateway over Wi-Fi using a static IP. For data visualization and storage, ThingsBoard Cloud (ThingsBoard, 2024) was purchased, which in essence served as the rest of the software components in Avena albeit with less capacity and flexibility.

Since the apple farm utilized drip irrigation for watering various blocks of orchard during summer months, the first experiment conducted involved placing three Clover Agriculture Sensors in the three irrigation zones closest to the gateway. Data on ambient temperature, relative temperature, soil temperature, light intensity, and gravimetric water content was collected and visualized in ThingsBoard, as shown in Figure 4, and monitored by farm managers over the course of three weeks.

To evaluate the scalability of the LoRaWAN network and address concerns of IoT scalability given the orchard setting and dense presence of trees, range testing was conducted where an Oyster2 for LoRaWAN GPS tracker was attached to a farm UTV (Figure 5) and the three Clover Agriculture Sensors were driven in three opposing directions to the furthest irrigation zones of the farm’s primary location (Figure 6). The sensors were left for a few hours and data was collected and displayed in the ThingsBoard dashboard. Figure 7 shows the visualization for the GPS path traveled and the relative locations the sensors were deployed (in red). The sensor in the top right corner was moved further past the locust grove noticeable in the upper region of the satellite image but data eventually stopped transmitting, suggesting a SPRING may need to be deployed to cover areas of the farm beyond that barrier.

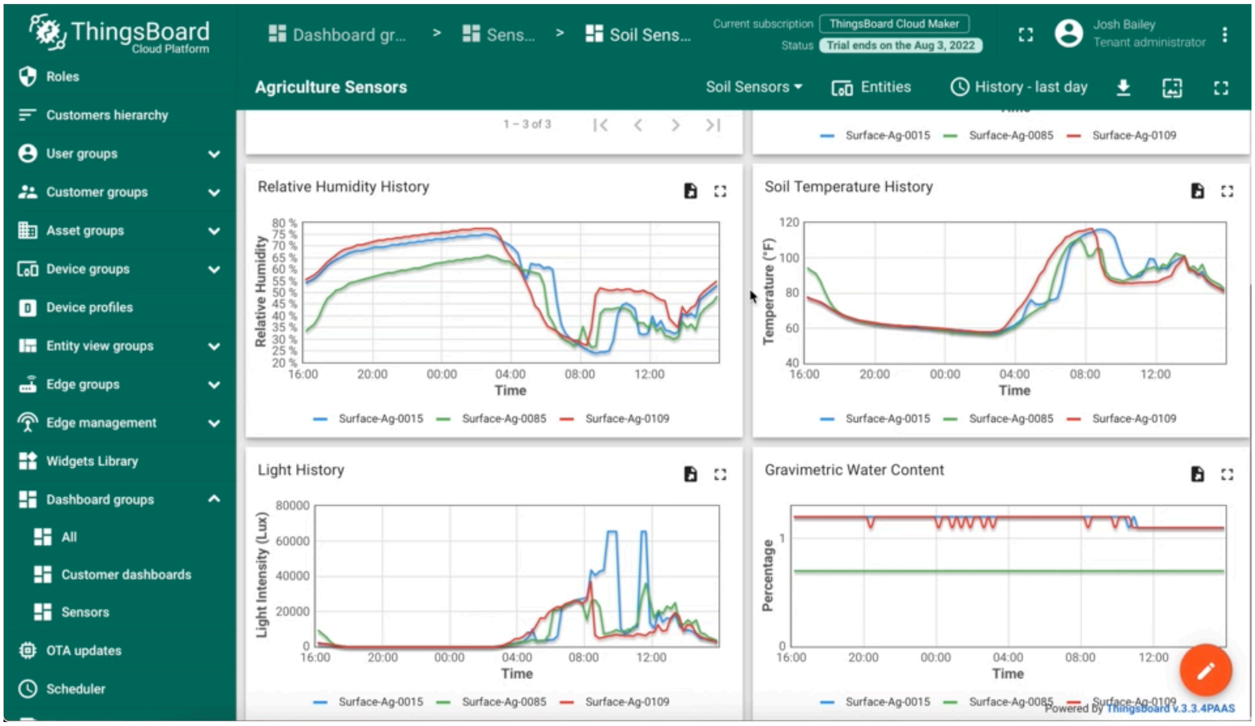


Fig 4. ThingsBoard dashboard view of three Clover Agriculture Sensors

Fig 5. Oyster GPS tracker on UTV

Fig 6. Three Clover Agriculture Sensors deployed (a), (b), and (c) from left to right.

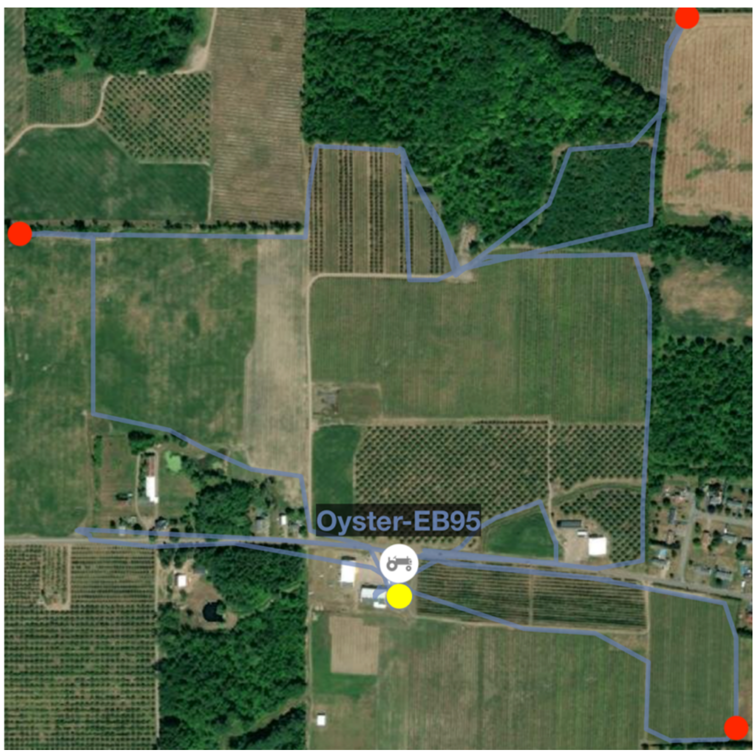
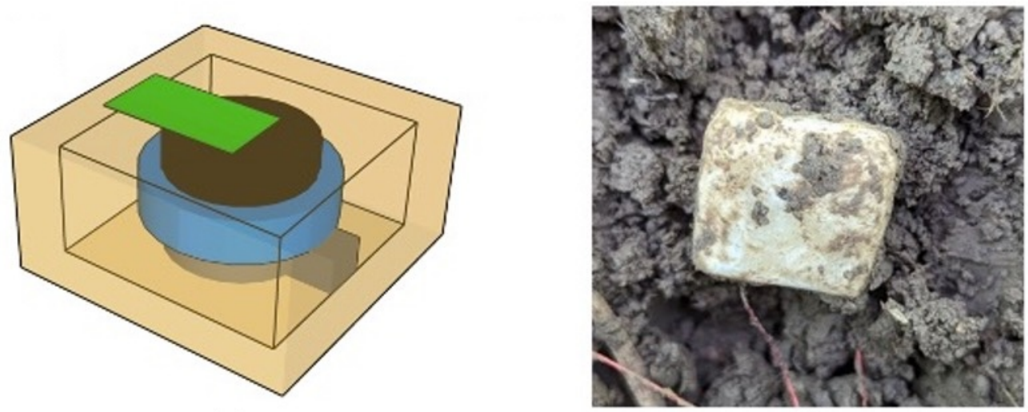


Fig 7. Gateway location (yellow), GPS path recorded (blue), relative locations of sensors deployed (red).

Cellular Data-Connected LoRaWAN Gateway at University of Florida Research Farm

Subsurface sensing platforms distributed throughout the soil enable the real-time monitoring of the soil environment for precision agriculture. Many of these sensing platforms require energy resources for data collection and communication. Wax-encapsulated biodegradable Zn-air batteries have been reported as promising candidates for their biodegradability and long operational lifetime under the soil as shown in Figure 8 (a) (Zhang, J. & Allen, M. G., 2022). To evaluate their performances in the natural environment, these batteries were integrated with the LoRaWAN communication system via interface circuits, in which the batteries were connected to a load resistor, with the working voltage collected hourly under the designed current load. The integrated system had been initially installed at West Lafayette, Indiana, and a similar setup was later implemented at Quincy, Florida with the SPRING LoRaWAN module as shown in Figure 8 (b). For both rounds of the air battery field tests, the battery voltage data was successfully collected in real time, which demonstrated the functionality of the system.



(a) (b)

Fig 8. (a) The schematic of the wax-encapsulated Zn-air battery (Zhang, J. & Allen, M. G., 2022); (b) a battery that was deployed in the field at West Lafayette, Indiana.

The LoRaWAN gateway used in Florida was first configured and added to the Avena platform running on a server at Purdue University in Indiana before assembly of the SPRING took place onsite in Florida. Once the SPRING was set up (Figure 9), soil moisture began reporting data immediately after being deployed without any further configuration required. Several weeks later, air batteries were deployed with similar results. The experimental devices were monitored in real-time by the research team located in Indana, Pennsylvania, and Florida through a Grafana-based dashboard visualizer for the air battery data, shown in Figure 10.

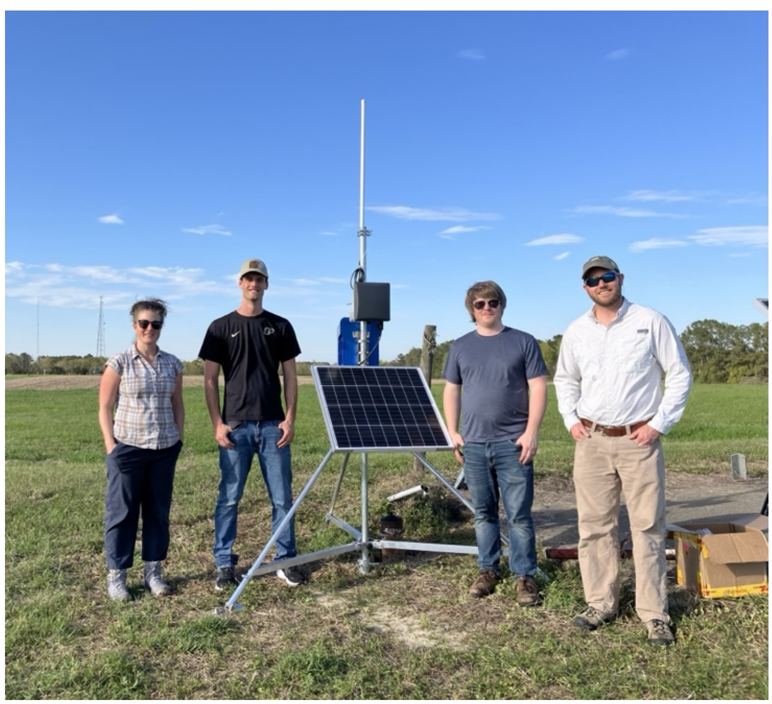


Fig 9. IoT4Ag members pictured with SPRING deployed in Quincy, Florida.

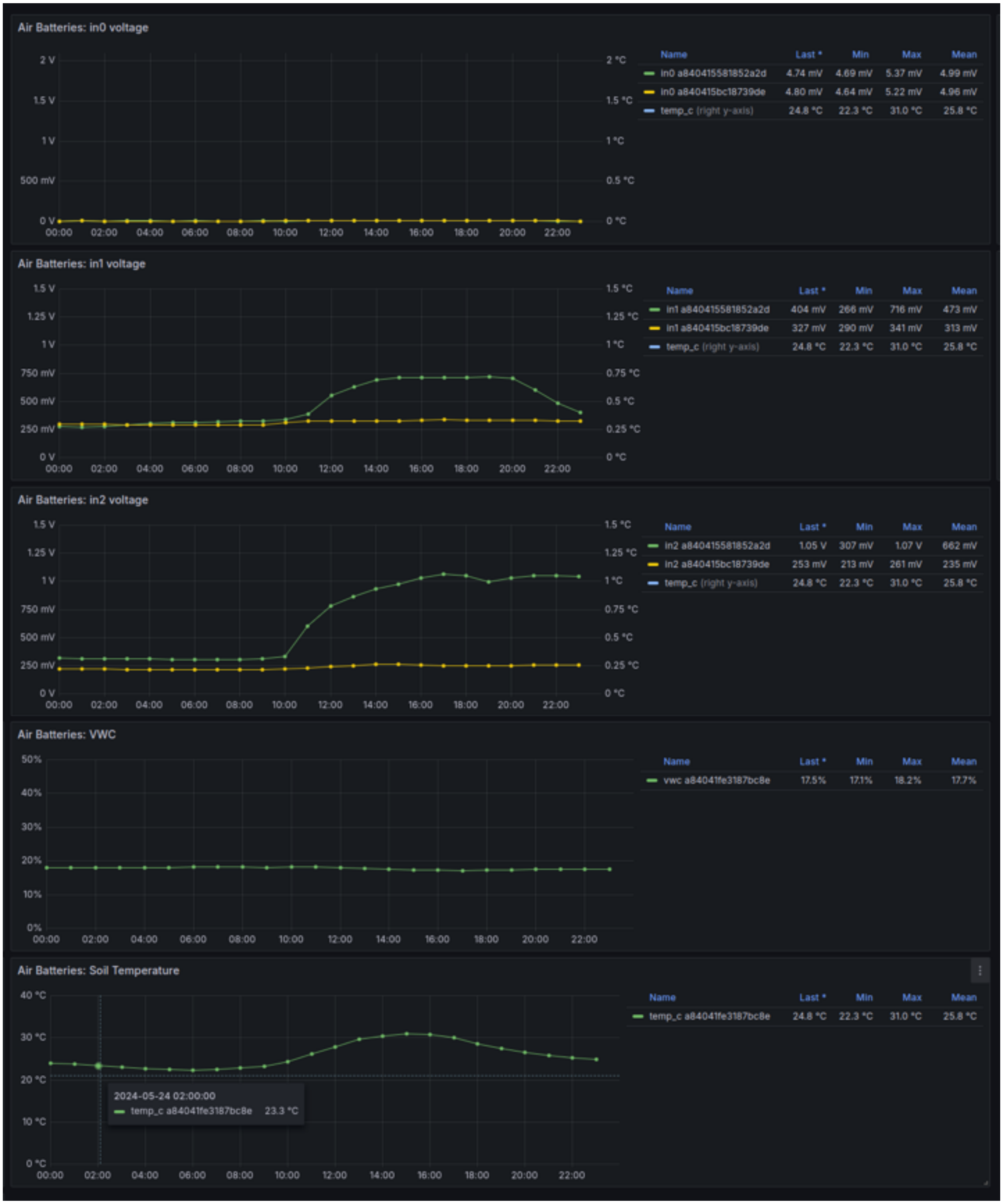


Fig 10. Grafana dashboard visualization of air battery data.

Summary

Farmers need data now more than ever to manage their operations efficiently, given the multitude of pressures they face. However, connectivity in rural areas has historically been an issue in enabling this. LoRaWAN has great potential for providing low-cost field-level connectivity for IoT applications in agricultural settings, given its wide area coverage, low-power consumption, and gateway capacity for connecting thousands of devices. Building on previous LoRaWAN projects such as PODs, three hardware setups were presented for on-farm cloud-based LoRaWAN deployments in scenarios where: local Internet is available, cellular coverage is available, and when neither a local Internet nor cellular connection is available so that low orbit satellite internet-connected solutions could be utilized. The open-source software stack Avena was then illustrated as a means for efficient data flow, enabling flexibility and user choice to maximize actionable insights from the collected data. For both hardware and software, resiliency and risk/security were considered to outline measures and recommendations for ensuring uninterrupted LoRaWAN network coverage and safeguarding digital assets. Finally, two case studies were presented to demonstrate the capabilities of a Wi-Fi-connected LoRaWAN deployment at a commercial New York apple orchard and a cellular-connected SPRING at a Florida research farm. Looking ahead, we anticipate a hybrid approach involving a tailored mix of telecommunication technologies for specific applications, reflecting a nuanced set of trade-offs. Our proposed cloud-based LoRaWAN solution stands out as a promising avenue for overcoming connectivity challenges in rural areas, paving the way for the seamless integration of next-generation digital agriculture technologies.

Acknowledgments

This work was supported in part by the NSF-funded IoT4Ag project (EEC-1941529). Partners are University of Pennsylvania, University of Florida, University of California – Merced, and University of Arizona.

This material is based upon work supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, through the Northeast Sustainable Agriculture Research and Education program under subaward number FNE23-034.

Thank you to Ian Small and Rebecca Barocco for assisting with deploying and testing of the SPRING modules at Quincy and Live Oak, Florida.

References

Abdelfadeel, K. Q., Zorbas, D., Cionca, V., & Pesch, D. (2020). $FREE$—Fine-grained scheduling for reliable and energy-efficient data collection in LoRaWAN. *IEEE Internet of Things Journal, 7*(1), 669-683. https://doi.org/10.1109/JIOT.2019.2949918

Adelantado, F., Vilajosana, X., Tuset-Peiro, P., Martinez, B., Melia-Segui, J., & Watteyne, T. (2017). Understanding the limits of LoRaWAN. *IEEE Communications Magazine, 55*(9), 34-40. https://doi.org/10.1109/MCOM.2017.1600613

Aihara, N., Adachi, K., Takyu, O., Ohta, M., & Fujii, T. (2019). Q-Learning aided resource allocation and environment recognition in LoRaWAN with CSMA/CA. *IEEE Access, 7*, 152126-152137. https://doi.org/10.1109/ACCESS.2019.2948111

Ahmmed, T., Alidadi, A., Zhang, Z., Chaudhry, A. U., & Yanikomeroglu, H. (2022). The digital divide in Canada and the role of LEO satellites in bridging the gap. *IEEE Communications Magazine, 60*(6), 24-30.

Balmos, A. (n.d.). Meet LoRa, your new best friend [PowerPoint slides]. OATS Center. https://oatscenter.org/Images/project-lora-balmos.pdf

Balmos, A. D., Castiblanco, F. A., Neustedter, A. J., Krogmeier, J. V., & Buckmaster, D. R. (2022). ISOBlue Avena: A framework for agricultural edge computing and data sovereignty. *IEEE Micro, 42*(1), 78-86. https://doi.org/10.1109/MM.2021.3134830

Brunelle, T., Dumas, P., Souty, F., Dorin, B., & Nadaud, F. (2015). Evaluating the impact of rising fertilizer prices on crop yields. *Agricultural Economics, 46*(6), 653-666. https://doi-org.ezproxy.lib.purdue.edu/10.1111/agec.12161

Dhal, S., Wyatt, B. M., Mahanta, S., Bhattarai, N., Sharma, S., Rout, T., Saud, P., & Acharya, B. S. (2023). Internet of Things (IoT) in digital agriculture: An overview. *Agronomy Journal, 116*(3), 1144-1163. https://doi.org/10.1002/agj2.21385

Digital Matter. (2024). Oyster LoRaWAN. Digital Matter. https://www.digitalmatter.com/devices/oyster-lorawan/

Farooq, M. S., Javid, R., Riaz, S., & Atal, Z. (2022). IoT based smart greenhouse framework and control strategies for sustainable agriculture. *IEEE Access, 10*, 99394-99420. https://doi.org/10.1109/ACCESS.2022.3204066

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science, 327*(5967), 812-818. https://doi.org/10.1126/science.1185383

Haxhibeqiri, J., De Poorter, E., Moerman, I., & Hoebeke, J. (2018). A survey of LoRaWAN for IoT: From technology to application. *Sensors, 18*, 3995. https://doi.org/10.3390/s18113995

Hou, D., & Li, F. (2017). Complexities surrounding China's soil action plan. *Land Degradation & Development, 28*(7), 2316-2322. https://doi.org/10.1002/ldr.2741

Lee, B., Marcum, A. C., Love, D. J., & Krogmeier, J. V. (2024). Fusing channel and sensor measurements for enhancing predictive beamforming in UAV-assisted massive MIMO communications. *IEEE Wireless Communications Letters*.

MacPherson, J., Voglhuber-Slavinsky, A., Olbrisch, M., et al. (2022). Future agricultural systems and the role of digitalization for achieving sustainability goals: A review. *Agronomy for Sustainable Development, 42*(70). https://doi.org/10.1007/s13593-022-00792-6

OATS Center. (2024). OATS Center GitHub profile. GitHub. Retrieved from https://github.com/oats-center

RAKwireless. (2024). RAK battery plus RAK9155. RAKwireless. https://store.rakwireless.com/products/rak-battery-plus-rak9155?variant=42576088531142

Schreck, A. B. (2023). The application of LoRaWAN as an Internet of Things tool to promote data collection in agriculture (Master's thesis). Purdue University Graduate School. https://doi.org/10.25394/PGS.22693036.v1

Semtech Corporation. (2024). What is LoRa? Semtech. https://www.semtech.com/lora/what-is-lora

Sixfab. (2024). Pricing. Sixfab. https://sixfab.com/pricing/

TEKTELIC. (2024). Clover agriculture sensor. TEKTELIC. https://tektelic.com/products/sensors/clover-agriculture-sensor/

The Things Network. (2024). LoRaWAN architecture. The Things Network. Retrieved from https://www.thethingsnetwork.org/docs/lorawan/architecture/

ThingsBoard. (2024). PaaS. ThingsBoard. https://thingsboard.io/products/paas/

Wang, Y., Liu, H., Krogmeier, J., Reibman, A., & Buckmaster, D. (2020). ISOBlue HD: An open-source platform for collecting context-rich agricultural machinery datasets. *Sensors, 20*(20), 5768.

Zhang, J., & Allen, M. G. (2022, June 5-9). In-soil biodegradable Zn-air batteries. In *Solid-State Sensor, Actuator, Microsystems Workshop* (pp. 310-313). Hilton Head Island, South Carolina.

Zhang, Y., Krogmeier, J. V., Anderson, C. R., & Love, D. J. (2022, October). Overcoming the digital divide by large-scale coverage analyses for mmWave cellular networks. In *2022 56th Asilomar Conference on Signals, Systems, and Computers* (pp. 1190-1194). IEEE.

Zhang, Y., Krogmeier, J. V., Anderson, C. R., & Love, D. J. (2023). Large-scale cellular coverage simulation and analyses for follow-me UAV data relay. *IEEE Transactions on Wireless Communications*.

Zhang, Y., Love, D. J., Krogmeier, J. V., Anderson, C. R., Heath, R. W., & Buckmaster, D. R. (2021). Challenges and opportunities of future rural wireless communications. *IEEE Communications Magazine, 59*(12), 16-22. https://doi.org/10.1109/mcom.001.2100280