OATSMobile: A Data Hub for Underground Sensor Communications and Rural IoT

Fabio A. Castiblanco[1], Byunghyun Lee[1], Ashwin Natraj Arun[1], Andrew Balmos[1], Sneha Jha[2], James V. Krogmeier[1], David J. Love[1], Dennis Buckmaster[2]

(1) Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, 47907, U.S.A

(2) School of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN, 47907, U.S.A

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Abstract

Wireless Underground Sensor Networks (WUSNs) play a crucial role in precision agriculture by providing information about moisture levels, temperature, nutrient availability, and other relevant factors. However, the use of radio-frequency identification (RFID) devices for WUSNs has been relatively unexplored despite their benefits such as low power consumption. In this work, we develop a hardware platform, called OATSMobile, that enables radio-frequency identification (RFID) communications in WUSNs. OATSMobile is a mobile platform that carries a sensor reader for scanning underground RFID tags and is equipped with communication modules to transport collected data. In addition to collecting RFID data, our edge computer collects machine location and speed from a Real Time Kinematics (RTK) GPS device, soil moisture from externally installed LoRaWAN sensors, and ground-to-antenna height from a Wi-Fi enabled LiDAR sensor. Data is automatically transferred over the cell network to an Avena–based data pipeline for analysis and processing. With OATSMobile, we investigated the feasibility of RFID communications in the Ultra High Frequency (UHF) band for WUSNs. We evaluated the impact of soil moisture and temperature on RFID scanning performance by randomly placing corn seed sized RFID tags in soil blocks of different drainage classes at 2.5 cm depths and measuring the Received Signal Strength Index (RSSI) and scanning success rates at different stages of the corn growing season. The nominal antenna height was 32 cm above ground, and the machine traveled at 0.44 m/s. As a result, we confirmed that 152 out of 282 tags were detected, for an overall success rate of 53.9%. Other results, such as the impact of soil moisture, antenna height, and machine speed impact will be discussed in this paper. Finally, we outline pathways for developing communications frameworks for WUSNs applied to precision agriculture.

Keywords.
Edge-computing, WUSN, wireless, underground, soil propagation, RFID, IoT, UHF, event data streaming, precision agriculture

Introduction

Wireless Underground Sensor Networks (WUSNs) involve deploying sensors below the soil surface to collect and transmit data via wireless links. These networks have potential applications in fields like agriculture for soil moisture monitoring, environmental science for studying subsurface conditions, and engineering for monitoring the health of underground infrastructure. WUSNs offer the advantage of minimal environmental disruption and reduced exposure to above-ground hazards. However, they face challenges such as higher signal attenuation and difficulty in maintenance due to limited access. Advanced communication techniques like magnetic induction (MI) are often used to enhance data transmission through soil. Currently, we can find WUSNs in different applications such as:

- Food Supply Chain Produce Tracking: Using sensors installed in produce transportation containers, distribution of produce can be improved by reducing food waste and tracking spoiled batches of produce in the supply chain (Pal & Kant, 2018)
- Internet of Underground Things (IoUT): Different materials and water content in soil present a challenging media for wireless communications. Applications such as tracking of underground objects allow use cases such as rescue operations and oil and gas reservoir monitoring (Saeed et al., 2019).
- Soil pH evaluation: By using radio waves emitted by public AM radio broadcasts, pH in soil can be estimated by calculating phase disturbances in waves due to propagation in the air-soil interface, allowing a noncontact method for pH measurement (Uchida et al., 2019).
- Soil moisture sensing: Radio waves in the UHF ISM band can be used to estimate soil moisture by detecting changes in the Received Singal Strength Indicator (RSSI) of reflected signals. This approaches provides extended coverage when compared to traditional methods of spot based moisture probing measurements (Hossain et al., 2022) (Liedmann et al., 2018).

Recently, communications systems have been added to agricultural vehicles and farm machinery to enable applications that external systems or platforms. These systems utilize a combination of GPS modules for asset tracking and accurate timing, wireless communications such as cellular and satellite backhauls to enable real-time data transfer and remote monitoring. This connectivity supports precision farming practices by allowing vehicles to receive field data, adjust operations based on real-time information, and synchronize activities with other machines. Enhanced communication capabilities ensure more efficient field operations, optimize resource use, and improve decision-making processes in modern agriculture.

Radio Frequency Identification (RFID) is a technology that leverages backscatter communications to identify and track transponders or tags attached to objects. Tags employed in RFID have a small footprint and can harvest energy emitted from interrogation devices, making them ideal for underground communications scenarios, where battery replacement in transponders is challenging due to difficult sensor retrieval. Some applications of RFID in underground communications include the use of underground tags to locate non-metallic objects (Zhu et al., 2024), structural health monitoring (SHM) in underground mining (Lasantha et al., 2023), among others.

The main goal of this work is to assess the feasibility of employing commercial passive RFID systems for communications between vehicles and underground sensors in precision agriculture scenarios. The contributions of this work can be summarized as:

- A system model for communications between underground sensing systems and vehicles centered in edge computing.

- An event driven pipeline that integrates data flows from disparate sources into a data stream oriented to underground communications channel assessment.
- An analysis of underground back-scatter communications for RFID systems in the 900 MHz UHF ISM band
- An assessment of the viability of RFID for communications in applications of precision agriculture in underground sensor networks.

System Setup

In this section we introduce OATSMobile as a mobile communications platform for in-field wireless underground sensor networks and edge-computing fleets based on agricultural vehicles.

OATSMobile: Communications on agricultural vehicles

OATSMobile serves as a communications hub for rural IoT applications as a platform for edge computing in agriculture. Based on agricultural machinery, OATSMobile integrates the edge computing capabilities of ISOBlue with an array of wireless communication systems. This integration enables the collection, processing, and streaming of data from diverse sensor networks in precision agriculture scenarios. By leveraging local data processing capabilities, OATSMobile reduces the burden of data transmission demands prevalent in rural areas, where stable real-time data streams can be challenging to achieve. Moreover, equipped with advanced communication radios, OATSMobile extends the reach of existing communication backhaul infrastructure through machine-to-machine communications (Castiblanco et al., 2023).

In this work we introduce OATSMobile as a platform for Underground to Aboveground (UG2AG) and Aboveground to Underground (AG2UG) communications. Here, an agricultural machine outfitted with an RFID interrogation node is used to scan a crop field embedded with RFID tags deployed underground. This setup serves binary presence identification purposes, enabling the detection of objects or properties within a designated environment.

Figure 1. The OATSMobile system. Based on a 2016 Lee-Agra sprayer, equipped with multiple communications devices and sensor systems for enabling communications with in-field sensors and other computing assets in rural environments.

The ISOBlue Edge Computer

ISOBlue is the OATS Center approach for rural telematics, in which embedded computers connected to agricultural vehicles interact with machine sensor data streams found in the Controller Area Network (CAN) bus in ISOBUS compliant vehicles (Layton et al., 2014).Throughout the years, ISOBlue has been constantly upgraded to accommodate and innovate in digital agriculture, evolving from an affordable machine data logger to an edge-computing device capable of interacting with multiple data sources, such as RFID interrogation devices, or cameras for operator action pattern recognition data collection activities (Wang et al., 2020). With the addition of wireless networking hardware, ISOBlue can establish links with data sources that interface through Wi-Fi links, and at the same time, it can create temporary ad hoc wireless links with other machines, making it possible to exchange data with other edge-computers.

Figure 2 shows the current iteration of the ISOBlue edge-computer used on this work. This edge-computer is based on the UDOO X86 Ultra single board computer, based on the x86 architecture found in common computing devices such as laptops, desktop computers and servers. It also features a weatherproof IP68-rated enclosure for protecting electronics of ISOBlue. Further hardware and software details can be found in Table 1.

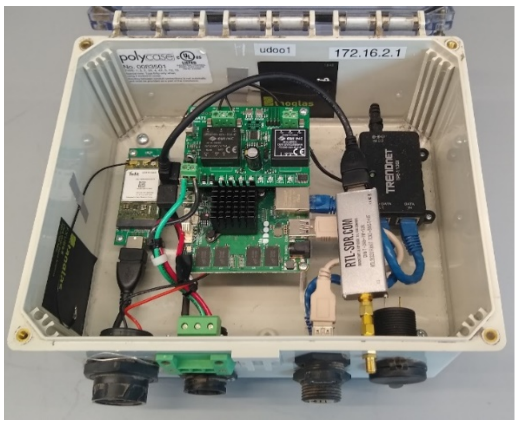

Figure 2. The ISOBlue edge-computing device. A network-based architecture allows to extend the functionalities in a modular approach.

Table 1. Hardware specifications of the ISOBlue edge-computer

	Specifications
CPU	Intel Pentium N3710 @ 2.56GHz
RAM	8 GB
Storage	128 GB M.2. SATA SSD
Operating System	Fedora Linux CoreOS 39 amd64
Hardware Interfaces	USB 3.0, Gigabit Ethernet

Communications in the OATSMobile system

OATSMobile features communications with multiple sensor systems interfacing via both wired and wireless sensor networks. Figure 3 illustrates a bus representation of the sensor networks available in the system. This bus architecture supports the incorporation of new data sources in a modular approach, making OATSMobile a scalable platform for multiple combinations of sensing devices in precision agriculture scenarios.

Serial-based Communications

OATSMobile features communications with wired serial sensors interfacing through the USB bus available on ISOBlue. Devices compatible with the Linux kernel can be easily interfaced through hardware drivers, which allow easy access to sensor data from serial-enabled devices. In our setup, a GPS PPS device reports timing signals over the USB bus for accurate synchronization of devices connected to the internal sensor network based on TCP/IP communications.

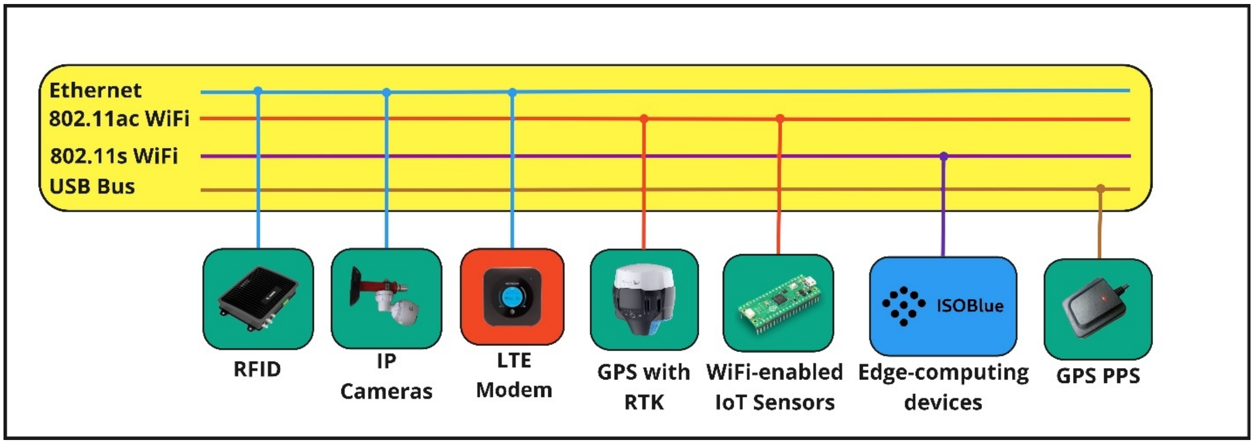

Figure 3. Communications with data sources in the OATSMobile system. By featuring multiple networks and data buses (yellow), OATSMobile can communicate with a variety of sensors (green), other edge-computers in a fleet (blue), and network backhaul devices (red), such as LTE modems for access to commercial backhaul networks.

TCP/IP-based Communications

TCP/IP Networks form the backbone of high-bandwidth data communications in OATSMobile. Local Area Network technologies such as Ethernet (IEEE 802.3) and Wi-Fi (IEEE 802.11) enable both wired and wireless communications with external hardware data sources. The system includes a Power over Ethernet (PoE) network switch, which allows external hardware to receive both power and connectivity through a single cable.

For instance, the wired network setup allows ISOBlue to interface with a Zebra FX9600 RFID interrogation device, which scans RFID tags on the Ultra High Frequency (UHF) ISM band. Similarly, ISOBlue can connect to wireless backhauls via external ethernet-enabled modems. For internet access, a NETGEAR Nighthawk LTE Modem is used to connect to a commercial cellular LTE backhaul. Additionally, ISOBlue is connected to a commercial IP camera to access video streams from cabin operation events using the RTSP protocol over ethernet.

In the same way, ISOBlue can connect to Wi-Fi enabled devices, such as a Real-Time Kinematics (RTK) GPS device, which delivers centimeter-grade corrected GPS fixes for precise location tracking during scanning operations. Additionally, common IoT wired sensing devices can be converted to Wi-Fi enabled units using an RP2040 microcontroller board equipped with a Wi-Fi chip. By embedding code that interfaces with the Avena software stack over a Wi-Fi network, it is possible to establish longer-range communications with sensors originally designed for short-distance serial communications. Table 2 shows a summary of the networks found in the OATSMobile system.

Table 2. Networks of the OATSMobile system

Network	Implementation	Purpose	Bandwidth
Ethernet	NETGEAR PoE Gigabit Switch	Internal high bandwidth wired communications between edge computing devices, RFID interrogation modules, imaging systems, and LTE backhauls	1Gbps
2.4 GHz WiFi	MediaTek MT7612U 802.11 b/g/n WiFi adapter	Internal high bandwidth wireless communications between edge computing devices, and wireless-enabled data sources	150 Mbps
2.4 GHz Mesh WiFi	MediaTek MT7610U 802.11 b/g/n WiFi adapter operating in Mesh mode	Backhaul communications for edge computing	150 Mbps
LTE Cellular	NETGEAR Nighthawk LTE modem	Backhaul link to the internet via a cellular network	Variable, depending on network coverage

Avena: An event-based software framework

Avena is a software framework designed for data interoperability among disparate data sources and computational instances in IoT environments. Built as a collection of open-source technologies, Avena integrates data flows at various levels. Ranging from sensing devices in precision agriculture scenarios, to remote computing instances running software implementations of algorithms for enhanced decision-making in agricultural operations. At the foundational level, Avena uses the GNU/Linux operating system in edge-computing nodes, where software running in the kernel space abstracts hardware functions, providing software interfaces to access data from multiple hardware sensors and actuators.

The Avena software stack features software from the following open-source projects to implement several functions of the data pipeline:

- **NATS**: A messaging system used in the Avena ecosystem to manage data flows and implement interest-based communications between services and computing nodes. It includes a compatibility layer with the MQTT protocol, facilitating integration with commercial IoT devices that support this protocol and offering a plug-and-play experience. NATS enables software services to publish data as messages, typically representing event signals with small payloads that reflect observations or measurements from sensors. Additionally, NATS can organize data flows into streams, grouping flows that share a common context for more efficient data management.

- **WireGuard:** A Virtual Private Network (VPN) protocol that establishes secure links between endpoints in an Avena network. It allows the implementation of overlay networks by abstracting all underlying connections between edge-computing and cloud-computing instances. This abstraction allows simple connections between software services running in different computing endpoints.

- **Benthos:** A software tool for data stream transformations. It allows subscribing to data streams and converting data from atomic message formats into entries suitable for long-term storage systems. The transformations are user-defined, providing flexibility by enabling the conversion of streams into various views for interoperability across multiple use-cases reliant on the same data stream. For example, in the Avena implementation for OATSMobile, messages from data streams are transformed into table rows for storage in a Database Management System (DBMS).

- **PostgreSQL:** A relational database management system (RDBMS) designed for the long-term storage of event data. Based on SQL, it offers a scalable platform for managing event data storage. With the integration of TimescaleDB, a software extension for PostgreSQL, the system is further optimized for performing fast queries on time-indexed tabular data. This enhancement makes it particularly suitable for rapid querying needed in visualization and analysis applications.

- **Grafana:** A data visualization engine that supports the integration of multiple data sources. This software is particularly effective in handling real-time data streams from IoT devices using the MQTT protocol, as well as sourcing data from long-term storage via predefined queries in databases. Within the OATSMobile system, Grafana is used to visualize data stored in a PostgreSQL database, enhancing the ability to monitor and analyze key metrics effectively.

- **Jupyter:** A web application that enables interactive data science and scientific computing, primarily based on the Python programming language. Jupyter leverages powerful data science tools from libraries such as Pandas and SciPy, enabling in-depth analysis of event data from long-term databases for research and educational purposes. Within the OATSMobile system, Jupyter is utilized to analyze experiment data, providing insights into the performance of Wireless Underground Sensor Networks (WUSNs) implemented with commercial RFID systems.

Figure 4 illustrates the interactions among the various components of the Avena ecosystem within OATSMobile. Data originates from various sources, with each device transmitting sensor signals to ISOBlue via different hardware interfaces. Specifically, GPS data streams are captured in NMEA string format by **gpsd**, a system service that interfaces with a network socket exposed by the RTK device. Subsequently, **gps-nats**, an Avena Hardware Abstraction Service (HAS) (Balmos et al., 2022), publishes these GPS signals in JSON format to the NATS message queue.

In the case of RFID reading events, the commercial RFID interrogation device publishes event data in JSON format over the MQTT protocol. This data is seamlessly integrated into the system through NATS' MQTT compatibility layer, aggregating it into the contextual stream of the system. Similarly, other sensor streams from Avena-compatible devices are published to the NATS message queue and then aggregated into the same contextual stream. This stream groups all relevant signals into a single flow, enhancing data synchronization across computing endpoints. This setup provides connectivity fault tolerance by queuing messages locally before transferring them to remote computing endpoints for transformation and storage, as per user-defined requirements for the data payloads.

Table 3 provides a detailed description of the hardware used by each data source within the OATSMobile system, along with the Avena topics where all signals of interest are exposed. These topics adhere to NATS message semantics, where message levels are organized by context, data source, and signal of interest, respectively. The ">" symbol is used as a wildcard to capture all signals available from each data source. For more information on NATS subject semantics, refer to (Quevedo, 2018).

Table 3. Data sources of the OATSMobile system

	Data Source	Purpose	Hardware Interface	Avena Topic
GPS PPS	Navisys technology, Ublox 8 GNSS Receiver	Machine location tracking and accurate time and synchronization via PPS	Serial USB	machine.gps.>
RTK-corrected GPS	Emlid RS2+ Multi-band RTK GNSS Receiver	Precise machine location tracking with centimeter precision	TCP over WiFi	machine.gps.>
RFID	Zebra FX9600 RFID interrogation device	RFID tag identification via UHF communications	TCP over Ethernet	machine.rfid.>
LiDAR	TFMini Plus LiDAR distance detection module	Above ground RFID antenna height tracking	TCP over WiFi via an RP2040 microcontroller	machine.lidar.>
Camera	Ubiquiti UniFi IP Camera	Operation and field event image capture	UDP over Ethernet	machine.video.>

RFID Back-scattering in Soil

Radio Frequency Identification (RFID) is a wireless communication technology primarily used to identify tags using radio frequency (RF) energy. It operates on the principle of backscattering communication, where devices reflect and modulate an incoming RF signal to transmit data. This method is particularly useful for devices with limited or no power sources, as it reflects incident RF energy to communicate, making RFID-based sensors ideal for low-power applications. The RF energy is generated by the RFID reader and incident on the RFID tags. The RFID tags reflect and modulate this RF energy, encoding it with information that is transmitted back to the RFID reader.

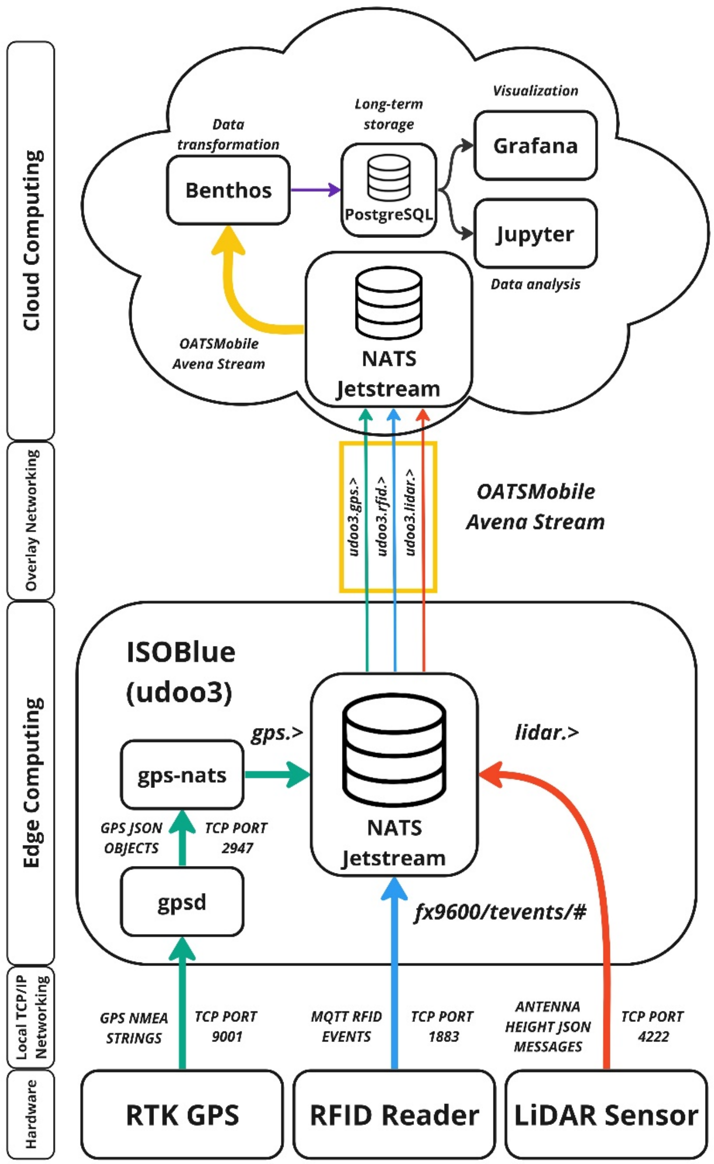

Figure 4. An Avena-based data pipeline for the OATSMobile system. Each data source publishes its own event-data stream (highlighted with color) to other components of the Avena environment in OATSMobile. Sensor event streams are indicated using the NATS and MQTT message topic semantics.

In this study, we employ RFID tags to enable underground sensing using backscattering communications. The system consists of an RFID reader above ground and RFID tags buried underground in the fields. The underground communication channels differ significantly from terrestrial wireless channels, incorporating both aboveground-to-underground (AG2UG) and underground-to-aboveground (UG2AG) components. Since part of the communication occurs through soil, there are additional refractive losses and losses due to soil moisture, alongside power loss due to the distance between the reader and the RFID tag. Before conducting field trials with RFID, we conducted a theoretical link-budget analysis to determine the maximum read ranges of RFID underground, aiding in identifying the optimal planting depth of our tags in the soil. In our experiment, we place our RFID antennas 30 cm aboveground. The maximum RFID read range for this setup at 5% soil moisture is 44 cm. This assumes ideal conditions where the antenna and the tag are in the same line.

The reading process of an underground RFID tag involves several steps. First, the RFID reader generates an RF wave that propagates through the AG2UG wireless channel and reaches the

RFID tag. If the RF received power at the tag exceeds the tag activation threshold, the RFID tag is activated. The tag then backscatters the incident RF wave, embedding it with information via load modulation. This backscattered wave travels through the UG2AG wireless channel and reaches the RFID reader. The received signal at the RFID reader can be successfully decoded if its strength exceeds the reader's sensitivity threshold. Unlike terrestrial RFID tags, reading underground RFID tags is more challenging due to the additional path loss through soil, requiring both the received power at the tag and the reader to be above specific thresholds.

Materials and Methods

In this work, we used OATSMobile as a platform for collecting experimental data of the performance of an RFID system used for UG2AG and AG2UG communications, characterized by the Received Signal Strength Index (RSSI) recorded at the interrogation device in the system. This section summarizes the experimental considerations for evaluating the feasibility of RFID communications applied to communications with underground sensors in precision agriculture applications.

Experiment Testbed

This experiment was deployed at the Purdue Agriculture Center for Research and Education (ACRE) testbed, using a plot of 0.22 acres (9.1m x 96m) to evaluate the performance of RFID communications. In this plot, three soil drainage classes were identified: poorly drained, somewhat poorly drained, and moderately well drained, according to the SSURGO soil database.

The experimental testbed creates the conditions of corn crops, in which passive underground tags are deployed next to plants, in which variations in soil moisture occur due to several factors, such as root water intake in plants, water evaporation, precipitation, and soil drainage, among others.

Figure 5. Research plot planter used to plant the small tag units (left). Small RFID tags compared to regular corn seeds (center), and a large RFID tag featuring a weatherproof enclosure, for deep underground communications testing (right).

To assess the feasibility of using RFID for underground sensing, RFID tags of two sizes were used. Figure 5 illustrates the two types of tags used in the study. The first type includes small epoxy-coated tags, measuring 6mm in diameter, which were planted alongside corn seeds at a depth of 2.54 cm (1 inch) using a research plot seed planter. These small tags enable the evaluation of sensing technologies that can be deployed with current planting technology. Their size, smaller than regular corn seeds, simplifies the deployment process without the need for specialized tools. Additionally, large weatherproof RFID tags (140mm x 433mm) were used to explore scenarios involving communication with deep RFID sensors. These tags were manually planted at a depth of 20 cm (7.87 inches). In total, 276 small tags and 6 large tags were deployed, making up a population of 282 tags for the experiment.

To scan the RFID tags in the soil, the Zebra FX9600 RFID transponder equipped in the OATSMobile system was used, featuring six antennas to enable multi-antenna connectivity. The transponder module's transmit power was configured to +33 dBm, in compliance with FCC section 15.247 transmission regulations. The antennas are strategically mounted to allow RFID tags planted along the corn rows to be simultaneously read by two antennas. This arrangement increases the likelihood of tag detection, thereby enhancing the overall read rate.

Experiment Design

This work is based on the hypothesis that soil moisture decreases the performance of underground RFID communication systems. The main plot was subdivided into 60 smaller plots, each measuring 5m x 3m. We categorized the soil drainage classes of the field into blocks, ensuring that soil moisture levels were consistent within each block. The experiment considered several variables: soil moisture, plant population, and above-ground antenna height. Each block contains at least three replications of three different plant populations, with each plot containing four randomly placed RFID tags. Additionally, each plot has four rows of corn with varying plant populations as specified in the replications. Key metrics evaluated in the study include RSSI, soil moisture, and machine location during the scanning process.

Data Collection

Data variables such as RSSI from the reflected signals of the tags, GPS machine location, and above-ground antenna height were recorded using the OATSMobile system. Additionally, soil moisture was monitored at several points within the main plot using 18 Dragino LoRaWAN-enabled soil moisture sensors. These sensors transmitted volumetric water content (VWC) measurements every 15 minutes to the testbed's LoRaWAN infrastructure. Subsequently, this data was integrated into the Avena data pipeline, contributing to the data streams from the OATSMobile system.

Scanning activities were conducted once a week throughout the corn crop's growing season, spanning a total of eight weeks. Each scanning session involved mobilizing the OATSMobile vehicle to the field and performing six scanning passes. A "pass" refers to the vehicle traveling through the field to perform an operation. During each scanning session, each pass covered one-third of the experimental plot, ensuring the entire plot was scanned twice per session. The vehicle's speed was consistently maintained at 0.45 m/s (approximately 1 mph), and the antenna height was initially set to 32 cm at the start of each pass.

From all scanning activities, the following numbers of data points were recorded:

- 2,915,568 RTK GPS location points.
- 637 RFID tag reading events.
- 2,803,642 above-ground LiDAR distance points.
- 144,827 VWC (Volumetric Water Content) measurement points.

Experiment Results

For the experiment, we obtained the following results:

- 152 out of 282 tags were successfully scanned, accounting for a success rate of 53.9%.
- 146 out of 276 small tags were successfully scanned, accounting for a success rate of 52.9%.
- 6 out of 6 large tags were successfully scanned, accounting for a success rate of 100%.

In the subsequent figures, we will present some of the results derived from the experiment.

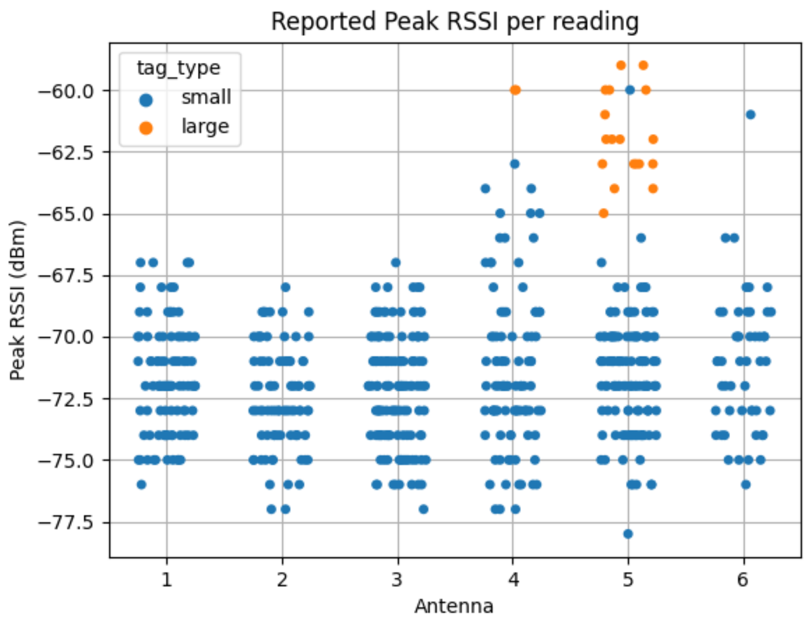

Figure 6. Distribution of the RSSI measured per antenna. Readings from small tags

Figure 6 presents a histogram for each antenna, depicting the distribution of measured RSSI values per antenna and tag type. This visualization helps determine the dynamic range for each antenna, calculated as the difference between the highest and lowest recorded RSSI levels. For antennas 1, 2, 3, 5, and 6, using small tags, the RSSI levels range from approximately -67dBm to -77dBm, resulting in a dynamic range of 10dB. Antenna 4 shows a broader dynamic range of 14dB, with RSSI levels varying from -63dBm to -77dBm. Regarding the large tags, antenna 5 exhibits RSSI levels between -59dBm and -65dBm, with a dynamic range of 6dB.

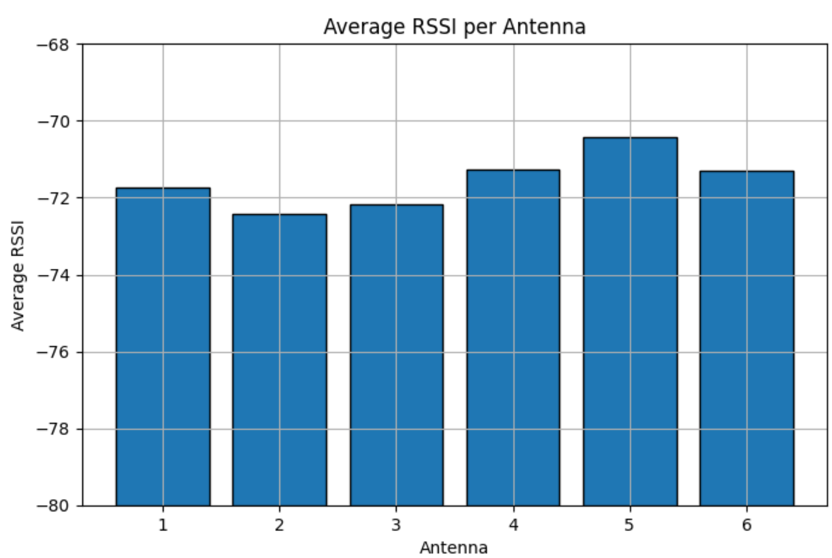

Figure 7. Average reported RSSI per antenna.

Figure 7 displays the computed average RSSI for each antenna. The data indicate that the average RSSI per antenna fluctuates around -72dBm. Antenna 2 records the lowest average RSSI at -72.4dBm, while antenna 5 exhibits the highest average RSSI at approximately -70.4dBm.

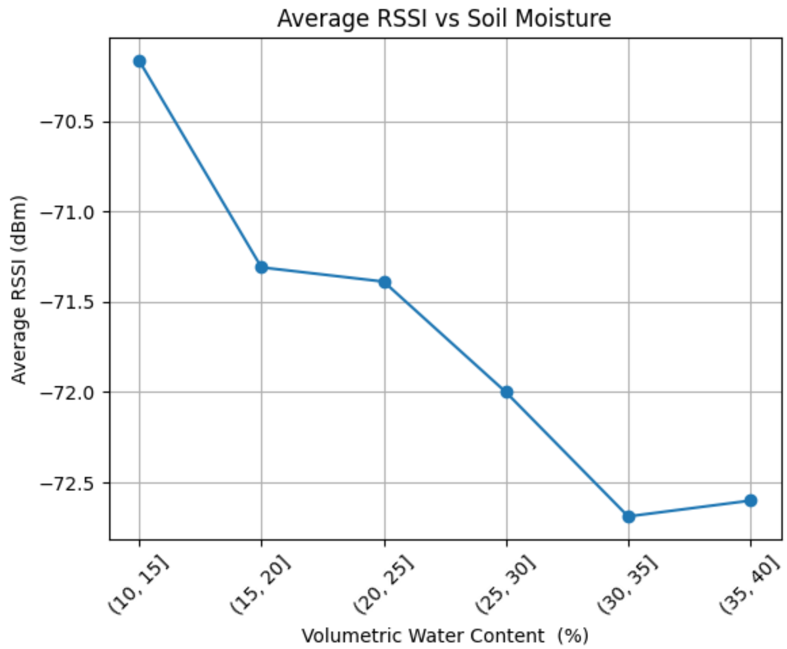

Figure 8. Average RSSI for different levels of volumetric water content in soil.

Figure 8 shows the relationship between the average Received Signal Strength Indicator (RSSI) values and varying levels of soil moisture, measured as volumetric water content (VWC) in percentages. The x-axis categorizes the soil moisture into ranges from 10-15% up to 35-40%, while the y-axis represents the average RSSI in dBm.

Discussion

Figure 6 illustrates the RSSI measurements from RFID tags captured at each of the six antennas. We observe that the RSSI values for the small tags are consistently around an average of –72.5 dBm across all six antennas. In contrast, the average RSSI for the large tags is approximately –62.5 dBm, significantly higher than that of the small RFID tags. This difference can be attributed to the large tags having bigger antennas and being manually planted with a flat orientation, with the tag antennas facing upwards. This orientation ensures better alignment with the radiation pattern of the RFID reader, resulting in higher gain and less signal loss, despite the tags being planted deeper.

Additionally, it can be observed that the lower bound of the dynamic ranges is -77 dBm, which is close to the transponder sensitivity (-80dBm). Thus, the performance of the system featuring small tags can be close to the operational limits of the equipment in use. Increasing the transmission power on the transponder may increase the reading success rate, as having

Figure 7 displays the average RSSI for the small tags across each of the six antennas in the system. The average RSSI recorded at each antenna is approximately -72.5 dBm. This consistency in RSSI values across different antennas underscores the robustness of our experimental setup and demonstrates reliable results throughout the growing season, despite varying weather conditions and corn growth.

Figure 8 illustrates the average RSSI for varying volumetric water content (VWC) levels in the soil. A noticeable decreasing trend in RSSI is observed as the VWC increases. This trend aligns with the established theory that higher VWC levels in soil increase signal attenuation. Therefore, this confirms that the RSSI decreases due to increased signal losses associated with higher soil moisture.

Conclusion

OATSMobile serves as a model for edge computing and automated data collection on agricultural vehicles, enabling the integration of multiple data sources in precision agriculture scenarios. Leveraging the Avena software stack, it effectively synchronizes data flows between edge and cloud computing endpoints, facilitating resilient data transfers. This is particularly beneficial in rural communications where commercial backhauls are intermittently available. Additionally, OATSMobile can be utilized to explore new communication approaches, such as RFID for underground communications. However, the development of underground sensor networks interfacing with agricultural vehicles still faces challenges. Factors like low RSSI from return signals in RFID may limit some potential applications of passive underground sensor networks. Nonetheless, some of these limitations are derived from current regulatory measures, which restrict the power in communications devices. The system performance could be improved by updating the current regulations to consider the case of vehicles communicating with underground sensor networks.

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