The International Society of Precision Agriculture presents the
16th International Conference on
Precision Agriculture
21–24 July 2024 | Manhattan, Kansas USA

Recovery Mechanism for Real-Time Precision Agriculture Sensor Networks: A Case Study

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

Abstract.

Variable rate technologies are lagging behind other precision agriculture technologies in terms of famer adoption, and sensor networks have been defined as a necessary step to implement these improvements. However, the gap between availability and adoption of said systems point to issues in cost, flexibility, and reliability. In rugged outdoor environments, where systems like these are useful, it is common for sensor networks to lose connectivity to a monitoring interface, even if data collection is still occurring. This paper presents a provisionless passive recovery system for sensor networks to retrieve data lost during a break in real-time connection, without physical access to the device or prior knowledge of the sensor network configuration. The recovery mechanism was used in the Sensor Collection and Remote Environment Care Reasoning Operation (SCARECRO) system at Sandpoint Organic Agriculture Center (SOAC), a heritage apple orchard in Idaho. The mechanism operates through a central agent (in SCARECRO, the middle agent), which keeps track of all incoming records and their source (sensor or gateway). If a previously reporting sensor has not been heard from for a set period of time, the agent logs a dead period. When connection is reestablished, the central agent forms a dead period request by retrieving all dead period logs from the database before sending them to the gateway. This dead period request is sent to the local gateway collector, which searches its local database for records matching the specified time and sensor(s) before sending it to the middle agent in chunks for processing and uploading to the main database. Upon receiving the first chunk of data from the gateway, the middle agent marks the dead period as finished by adding the reconnection time to the original dead period log. The real-time connection for this system was tenuous, with a directional antenna mounted to two thin bamboo poles to reach the WiFi connection point at the orchard's cider house, roughly 400 feet from the gateway. Data was analyzed from 4 sensor types (each reporting every 5 minutes) in the orchard over a period of 104 days from July 1st, 2023, to October 12th, 2023. During this period, there were 67–79 outages, adding to a total of 328.0-470.8 hours of total downtime. Across the 4 sensors, the outlined recovery mechanism was responsible for recovering 28.4%-33.63% of the missing data, comprising 12.0-16.7% of the total collected. This case study illustrates the necessity of having a recovery mechanism for real-time systems.

Keywords.
data recovery mechanism, SCARECO, orchard, open-source, data collection

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Introduction

Background

Precision agriculture, as defined by the International Society of Precision Agriculture (ISPA), represents a strategic approach to agricultural management. It involves the comprehensive gathering, processing, and analysis of temporal, spatial, and individual plant and animal data. This data is then integrated with other relevant information to facilitate informed decision-making. The overarching goal is to leverage estimated variability in agricultural systems to enhance resource utilization efficiency, productivity, quality, profitability, and sustainability of agricultural production (International Society of Precision Agriculture, 2021).

Among the large collection of precision agriculture technologies are wireless sensor networks (WSNs), which play a pivotal role in capturing real-time data from agricultural environments. WSNs allow farmers to access vital information regarding various growth parameters such as temperature, humidity, rainfall, and light levels and serve as a critical component in irrigation management, enabling precise monitoring of crop growth stages, optimal harvesting timing determination, and accurate calculation of fertilizer requirements (Kumar and Ilango, 2018). However, despite their importance, variable rate technologies and remote sensing often remain underutilized within the agricultural sector (Lowenberg-DeBoer and Erickson, 2019). This underutilization poses significant challenges to maximizing the benefits of precision agriculture.

This paper aims to delve into the factors behind the underutilization of these crucial technologies, focusing on the prevalence of data loss. Specifically, it will assess the effectiveness of a data recovery mechanism within an installation of the Sensor Collection and Remote Environment Care Reasoning Operation (SCARECRO), deployed at the Sandpoint Organic Agriculture Center (SOAC) over a four-month period. By addressing this issue, the research seeks to propose the solution of a data recovery mechanism that can enhance the effectiveness and reliability of wireless sensor networks, thereby advancing the broader adoption of precision agriculture practices.

Significance

While the principles of precision agriculture have been well-established, the practical implementation of these strategies often encounters barriers, hindering their widespread adoption. Sensors play a major role in various precision agriculture implementations. The value of assorted weather and environmental parameters is important in precision agriculture to increase the quality and quantity of the crop. In soil alone, temperature, moisture, water level, and conductivity impact crop growth, but a single sensor simply cannot measure all the parameters of soil (Kumar and Ilango, 2018). Given that soil and environmental properties fluctuate over time, data collected at one time may not hold relevance throughout entire crop seasons. To ensure precise application of agricultural inputs, it is essential to obtain accurate data at consistent intervals (Imam, Choudhary, and Sachan, 2015). Wireless sensor networks (WSNs) represent a cornerstone technology within precision agriculture, offering real-time data collection and analysis capabilities crucial for informed decision-making, allowing for the collection of diverse datapoints. However, the underutilization of WSNs in agricultural contexts remains a prevalent issue, limiting their potential to revolutionize farming practices.

At the heart of this challenge lies the persistent problem of data loss within WSN deployments. Inaccurate or incomplete data undermines the reliability of agricultural management decisions, ultimately impeding efforts to optimize resource allocation, enhance productivity, and ensure sustainability. Addressing this issue is not only essential for maximizing the efficiency of precision agriculture practices but also for mitigating the environmental impact of agricultural activities. By investigating the effectiveness of a data recovery mechanism within the SCARECRO sensing system at the Sandpoint Organic Agriculture Center (SOAC), we aim to bridge the gap between theory and practice in precision agriculture. Our findings have the potential to inform best practices for WSN implementation, empowering farmers and stakeholders with the tools and knowledge necessary to embrace innovative agricultural technologies.

Furthermore, by analyzing the effectiveness of data recovery, this research contributes to the broader discourse regarding sustainable agricultural practices. Given the susceptibility of WSNs to communication loss, especially when deployed in harsh outdoor environments (Mafuta, et al, 2013), the study of more resilient data recovery systems becomes imperative. By addressing this fundamental challenge, this case study aims to lay the groundwork for a more sustainable future characterized by the adoption of more resilient and resource-efficient precision agriculture systems.

Methods

Data Collection System Overview

The SCARECRO remote sensing system is composed of sensors, aggregators, gateways (hardware components), a middle agent, a database, a dashboard, and artificial intelligence models (software components), illustrated in Figure 1 (Everett, M., G. Wells, and J. Shovic). The gateway is a Raspberry Pi computer that handles compiling all sensor data before sending it to the middle agent, an AWS (Amazon Web Services) cloud computer which sends all system data to a cloud-hosted database, via an internet connection. This database is accessed by an external AI (artificial intelligence) system and a visualization dashboard, both of which operate outside the on-farm data collection system. The weredog's purpose is to take over as a new middle agent if the original middle agent goes down for any reason. However, due to the reliability of AWS, this component was not needed and thus was not implemented.

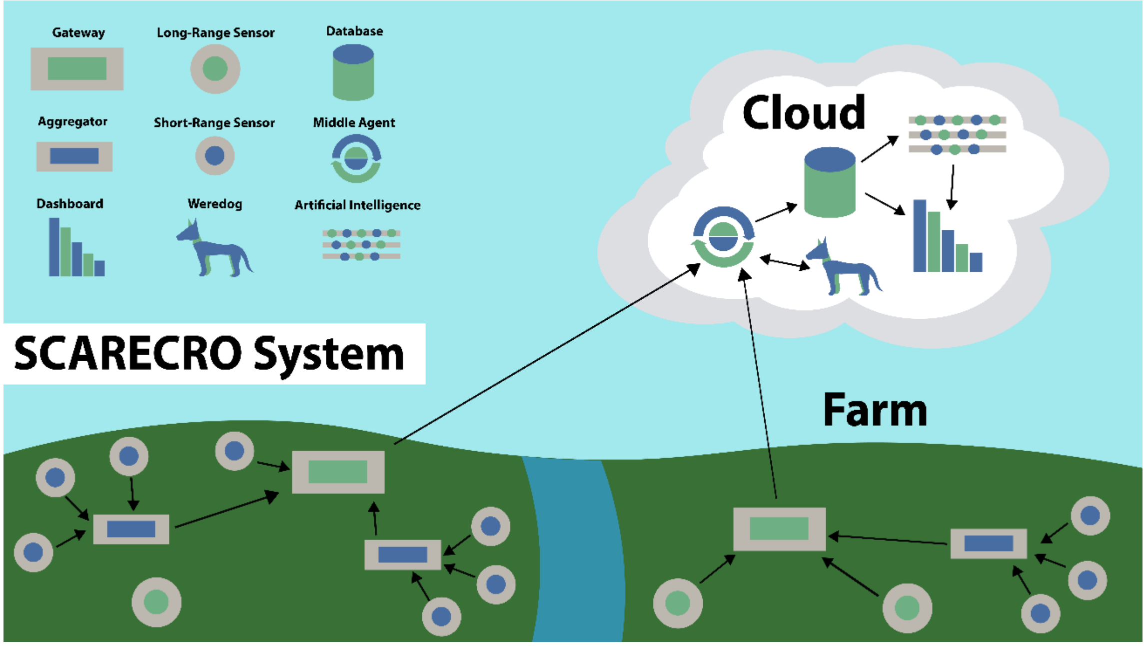

Fig 1. Block diagram of the SCARECRO communication structure.

All hardware components comprising of one Gateway, one middle agent, one database, and a combination of long-range, short-range, and wired sensors were installed at the Sandpoint Organic Agriculture Center (SOAC) in Sandpoint, Idaho. Specifically, a Bmp280 short-range sensor, directly connected to the Gateway, alongside two WeatherRack2 long-range sensors transmitting data via 433 MHz radio, were employed to report weather data to the Gateway at five-minute intervals. A Renogy solar controller acted as another short-range sensor, transmitting data via a Bluetooth connection. Additionally, Gateway statistics, which are self-reported and inherent to the gateway, were collected. All collected data is stored in a local database in the gateway before being transmitted over WiFi using MQTT to the middle agent. However, due to various factors, MQTT communication intermittently failed, resulting in dead periods during which no data was transmitted to the middle agent until connectivity was restored. The deployment of SCARECRO in SOAC was initiated in June of 2023, and over a four-month period spanning from July 1st, 2023, to October 12th, 2023, the occurrences of dead periods and the effectiveness of the recovery mechanism were documented and analyzed.

Installation

Fig 2. Map of SCARECRO sensor placement at SOAC.

Figure 2 shows the sensor configuration at SOAC with approximate distances. The WeatherRack2 sensors are approximately 160 feet north and south of the gateway, respectively. The main building, denoted by the red arrow, houses the main WiFi modem which is slightly less than 500 feet from the gateway's antenna. The gateway collects data from each sensor in five-minute intervals, storing a local copy, before attempting to pass this data to the middle agent and then a cloud-hosted database. This step in the communication procedure is where, if network connection is interrupted, outages occur.

The SOAC implementation of SCARECRO uses a directional antenna (pictured in Figure 3) to connect to the network which is again located roughly 500 feet from the module itself. This antenna was mounted using bamboo poles, which provide enough flexibility to avoid breakage but also make the system's connection unreliable due to shifts in the antenna's position in the wind.

Fig 3. SOAC gateway installation.

In addition to physical antenna instabilities, connection issues were also observed due to the network used at SOAC. This site utilized a network belonging to the University of Idaho, which presented challenges not encountered at other SCARECRO installation sites. Specifically, unique credentials were needed to connect to this network, and login timeouts caused several unexpected system outages, particularly early in the observation period. The gateway, shown in Figure 3, also functions as a hotspot for the aggregator (which was ultimately not used in this study). Managing connections to both the main network and the hotspot through two different antennas was a significant part of the network research. Following initial system installation, after the gateway rebooted following a loss of connection, the networks would not boot up correctly, requiring manual reconnection. This issue has since been resolved, so manual reconnections are no longer necessary.

Recovery Mechanism Overview

With the specific installation and outage details addressed, attention can now turn to the recovery mechanism that was implemented. This mechanism detects dead periods and recovers data collected during that time, ensuring that no data is lost despite temporary network issues. A block diagram of this process is depicted in Figure 4.

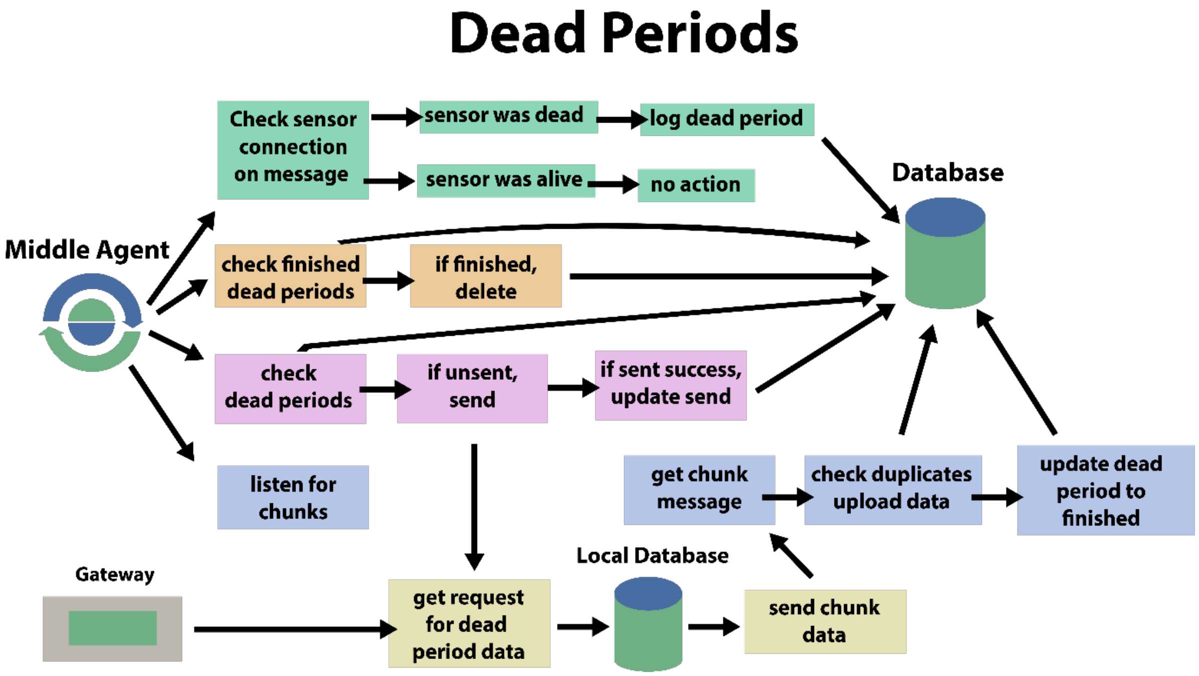

Fig 4. Dead period detection and data recovery mechanism overview.

Each time the middle agent receives collected data from the gateway, it logs a message for each connected sensor, including the current time. It then compares this time with the last time a message was logged for that sensor. If the difference exceeds a set tolerance period, the middle agent assumes the connection is dead and logs a dead period request in the database. This log includes information on which sensor is down and the time since it was last seen.

At set intervals, the middle agent retrieves all dead period logs from the database and sends them to the gateway. The gateway then pulls all local data matching the specified time and sensor(s) and sends it to the middle agent in chunks for processing and uploading to the database. Upon receiving the first chunk of data from the gateway, the middle agent marks the dead period as finished by adding the sensor reconnection time to the original dead period log. The middle agent deletes all finished dead period logs daily.

Results

Between July 1st, 2023, and October 12th, 2023, the four sensors deployed in SOAC reported to the gateway every five minutes. During this period, there were 67–79 logged dead periods (outages) for each sensor, adding to a total of 328.0-470.8 hours of downtime. Multiple factors contributed to these outages beyond network instability, including battery swaps and physical installation upgrades which required the gateway to be powered down temporarily. Given these contributing factors, the overall reliability of the system may be higher than the number of outages suggests. While reliability is important, in this specific case study, the somewhat unreliable connection proved beneficial as it allowed the data recovery mechanism's effectiveness to be tested in a rugged environment. Additionally, there were two WeatherRack2 sensors deployed in the orchard, so the outage information for this sensor may be inflated in both Table 1 and Table 2.

Table 1. Dead period logs.

Sensor	# Outages	Min Outage Length (Hrs)	Max Outage Length (Hrs)	Average Outage Length (sec)	Average Outage (Hrs)
WeatherRack2	79	2.058	119.056	21453.063	5.959
Renogy Solar Charger	67	1.912	158.042	37190.174	10.331
bmp280	72	1.666	18.642	16397.725	4.555
Gateway Stats	72	2.038	18.622	16442.357	4.567

A typical outage lasted a few hours, caused by various factors. However, the Renogy Solar Charger experienced extended downtime periods, primarily attributed to issues with the system's Bluetooth connectivity failing to reboot properly. Conversely, the Gateway stats and bmp280 experienced shorter downtimes, as they maintained a direct connection with the gateway, ensuring quicker recovery times. During dead periods, the gateway continued to collect data from all sensors at five-minute intervals, storing it in a local database until it could satisfy a dead period request from the middle agent. After a few hours, the gateway would detect its inability to communicate with the middle agent and attempt to reconnect by initializing a reboot. Once rebooted, the connection would automatically be re-established, and the gateway would resume normal functionality. However, during the reboot process, which usually takes less than five minutes, the gateway could not receive, store, or send data, potentially resulting in some missed records.

During the 104-day study period, a total of 149,760 records across all sensor types were expected to be collected from the gateway. Roughly 76% of this expected value ended up in the database, totaling 113,773 individual records both directly from the gateway and through the data recovery mechanism from this time. The outlined recovery mechanism successfully restored a significant portion of the missing data for each of the four sensors. Specifically, it recovered 33.63%, 28.4%, 31.99%, and 32.02% of the missing data for the WeatherRack2, Renogy Solar Charger, bmp280, and Gateway stats sensors, respectively. This recovery accounted for approximately 12.0-16.7% of the total collected data, amounting to a total of 16,815 individual records.

Table 2. Recovered and directly received data breakdown.

Sensor	Total Records	# Expected	# Missing	% Total	# Direct	# Recovery	% Direct	% Recovery
WeatherRack2	45070	59904	14834	75.2370	37554	7516	83.323719	16.676281
Renogy Solar Charger	21049	29952	8903	70.2758	17517	3532	83.220105	16.779895
bmp280	23809	29952	6143	79.4905	20919	2890	87.861733	12.138267
Gateway Stats	23845	29952	6107	79.6107	20968	2877	87.934577	12.065423

Future Directions

While leveraging SCARECRO's unreliability proved beneficial for examining the data recovery mechanism in this case study, enhancing the robustness of the system at the SOAC site is now a priority. One proposed upgrade involves installing a superior battery with an extended lifespan, particularly crucial during winter months when solar charging is less frequent, especially at night. Additionally, addressing the battery issue could entail installing an additional solar panel to augment charging capabilities.

Moreover, refactoring the SCARECRO software to support push/pull recovery would be advantageous. This would involve implementing mechanisms for detecting outages using both pull-based methods, facilitated by the middle agent, and push-based methods, directly from the gateway.

Conclusion

This case study illustrated the necessity of having a recovery mechanism for real-time systems. The range of factors contributing to system outages and dead periods simulated a rugged environment, which is a large factor contributing to communication loss in WSNs (Mafuta, et al, 2013). In a domain where data collection at consistent intervals is essential (Imam, Choudhary, and Sachan, 2015), the use of effective data recovery mechanisms is necessary.

Acknowledgments

This research benefited greatly thanks to the support of Kyle Nagy, lead horticulturist at the Sandpoint Organic Agriculture Center.

Acknowledgment is extended to Garrett Wells for his design and installation of the Datagator, which played a crucial role in SCARECRO's initial implementation.

The initial installation of the SCARECRO system was made possible with the support of Dustin and Jaclyn Mommen at Laurel Grove Wine Farm in Winchester, Virginia.

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