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Enhancing Agricultural Practices through IoT: A Dual-Modality Approach for Network Resilience and User Engagement

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***Abstract*— In the realm of smart agriculture, integrating Internet of Things (IoT) technologies promises to revolutionize traditional farming practices. However, challenges such as network unreliability in remote agricultural settings and the need for user-friendly, real-time monitoring and control systems persist. This paper presents an innovative IoT-based system that addresses these issues through a dual-modality approach: integrating edge-level decision-making for continuous operation during network disruptions and cloud-based monitoring and control via user-friendly desktop and mobile applications. Employing LoRa and LoRaWAN for efficient long-range communication, the system showcases resilience in challenging network environments, ensuring uninterrupted agricultural management. The implementation includes sophisticated sensors for accurate data collection and integrates with the Loriot platform for seamless data management. Results from controlled testing environments confirm the system's reliability in sensor accuracy, communication efficiency, and seamless transition between cloud and edge computing. The development of intuitive applications further enhances the system's practicality, offering farmers enhanced control and real-time insights into soil conditions. This research contributes significantly to the advancement of smart agriculture, demonstrating a comprehensive, adaptable, and user-friendly solution for modern farming challenges.**

Keywords—IoT, Edge and Cloud Computing, LoRa and LoRaWAN, Sensor Technology.

I. INTRODUCTION

Agriculture is undergoing a significant transformation, driven by the pressing *challenges* of climate change, water scarcity [1], and the increasing need for sustainable practices. In this context, smart agriculture, leveraging Internet of Things (IoT) technologies, emerges as a pivotal solution. However, effective deployment of IoT systems in agriculture faces two primary challenges: network unreliability in remote areas and the need for efficient, user-friendly monitoring and control systems.

Recent studies in the field have proposed various IoT-based solutions. Nageswara Rao and B. Sridhar [2] proposed a three-layer IoT architecture using soil moisture and temperature sensors, with data sent to a cloud platform via Raspberry Pi for irrigation decisions. This system's reliance on constant cloud connectivity could limit its application in areas with unstable network connections. Similarly, Krishna Singh, Samyak Jain, Varun Andhra, and Shilpi Sharma [3] introduced an automated irrigation system using IoT and data science, emphasizing real-time analytics. However, its dependency on Wi-Fi for data transmission may hinder its effectiveness in expansive agricultural settings. P. Rajalakshmi and S. Devi Mahalakshmi [4] developed an IoT system with a four-layer architecture, incorporating various sensors and wireless modules for data transmission. Like the previous studies, its functionality heavily depends on uninterrupted network availability. A. Vij, S. Vijendra, A. Jain, S. Bajaj, A. Bassi, and A. Sharma [5] explored the automation of farm irrigation systems using IoT and machine learning approaches, focusing on the advantages of automation. While these studies highlight the growing trend of employing IoT for agricultural efficiency, they also reveal a common limitation: the dependency on stable network connections for cloud-based decision-making and data transmission, which is impractical in remote agricultural areas with intermittent connectivity.

This paper addresses these limitations by proposing a dual-modality IoT system that operates both at the cloud and edge levels. Initially, the system utilizes cloud-level decision-making for routine operations. However, it uniquely transitions to edge-level autonomy during network disruptions, ensuring continuous, reliable operation. Additionally, integrating user-friendly desktop and mobile applications provides farmers with real-time monitoring capabilities and manual control options, further enhancing the system's utility and adaptability.

This paper is structured as follows: The Methodology section details the design and development of the dual-modality IoT system, emphasizing its innovative features. In the results and discussions section, findings demonstrating the system's capabilities in both cloud-based and edge-level operations, supported by real-world data, are presented. The Discussion section analyzes the implications of these results for smart agriculture, particularly focusing on the system's resilience and adaptability. Finally, the Conclusion summarizes the key contributions of our work and suggests avenues for future research in this area.

II. DEVELOPMENT OF THE IOT-BASED AGRICULTURAL SYSTEM

The development of the IoT-based agricultural system was driven by the need to tackle two primary challenges: network unreliability and the requirement for user-friendly monitoring and control. The system integrates advanced IoT technologies, including LoRa and LoRaWAN for long-range communication, along with sophisticated sensors for real-time environmental data collection, as illustrated in Fig. 1. Key stages in the design process included:

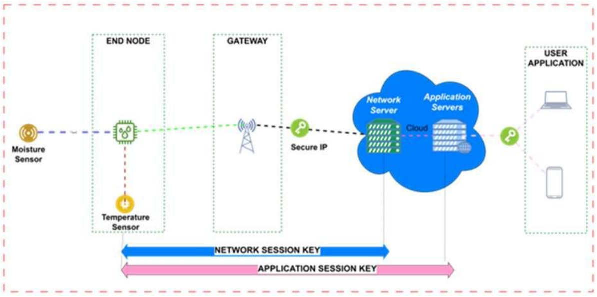

Fig. 1. System Development Architecture

A. Sensor Integration and Data Collection

The development of the IoT-based agricultural system centered around the deployment of various environmental sensors is crucial for smart agriculture. These sensors, integral to data collection, include devices for measuring soil moisture, temperature, humidity, and light intensity, each categorized based on the physical properties they measure.

Among soil moisture sensors, the types commonly used are resistance, capacitance, time-domain reflectometry (TDR), and neutron probes. However, for IoT-based soil moisture monitoring systems, capacitive and resistive sensors are often preferred [6]. This preference stems from their affordability and ease of integration, making them particularly suitable for IoT applications where cost-effectiveness and simplicity in connectivity are paramount. Capacitive sensors, chosen for their accuracy in measuring soil moisture levels alongside temperature sensors, formed the core of the data collection framework in this system. Their low cost and ease of integration are advantageous, especially for large-scale deployments or projects with budget constraints. These sensors offer analog or digital output signals, facilitating seamless integration with microcontrollers or IoT platforms, essential for efficient data collection and analysis.

B. LoRa and LoRaWAN for Communication

The system utilised LoRa technology and the LoRaWAN protocol, which are essential for ensuring long-range and low-power communication in remote agricultural settings. LoRa's capability to support spreading factors ranging from 7 to 12 allows a balance between data rate, range, and power consumption. Higher spreading factors(SF) enhance robustness against interference and improve sensitivity, beneficial for long-range applications [7], though at the cost of lower data rates due to longer symbol durations.

The symbol duration (Ts) is determined by the SF and the bandwidth (BW) as decided by (1):

$$Ts = \frac{2^{SF}}{BW} \qquad (1)$$

Furthermore, the symbol duration of a given SF, denoted as $Ts(_{SFn})$is precisely double that of the previous SF level, $Ts(_{SF(n-1)})$, as described by (2).

$$Ts(_{SFn}) = 2 * Ts(_{SF(n-1)}) \qquad (2)$$

This relationship illustrates the exponential growth in symbol duration with each increment in SF, which can be clearly visualised in the tabular format, as shown in TABLE *I*TABLE *I*.

TABLE 1. Transmission Time Symbols for BW125

Spreading Factor	Ts
SF7	1.024ms
SF8	2.048 ms
SF9	4.096 ms
SF10	8.192 ms
SF11	16.384 ms
SF12	32.768 ms

The bit rate (Rb) of LoRa transmission, which is subject to variation based on SF and BW settings, can be expressed as using (3):

$$Rb = SF * \frac{BW}{2^{SF}} \qquad (3)$$

However, LoRa also utilises a coding rate (CR) for error detection and correction, which is factored into the nominal bit rate calculation, resulting in the modified (4)[7]:

$$Rb = \left(SF * \frac{BW}{2^{SF}}\right) * \left(\frac{4}{4+CR}\right) \qquad (4)$$

Where CR varies from 1 to 4, denoting the level of error correction applied. Higher CR values ensure more robust error correction, enhancing transmission resilience but at the same time extending transmission times.

End nodes in a LoRaWAN network can be activated using either Over-The-Air Activation (OTAA) or Activation By Personalization (ABP). These methods establish critical session keys for secure data transmission. OTAA is preferred for enhanced security, as it dynamically generates keys during the join process [8]. It requires end-nodes to be pre-configured with a DevEUI (a globally unique identifier), an AppEUI (application identifier), and an AppKey [9]. Conversely, ABP involves pre-loading keys during the manufacturing of the end device. Key management involving DevAddr for device identification, NwkSKey for authentication, and AppSKey for encryption is fundamental for secure and authorised access to the network.

Class A devices within the LoRaWAN network were utilised in this project due to their significant battery efficiency. Moreover, OTAA was chosen over ABP because of its superior security features, which allows for key replacement and configuration optimization. This strategic selection aimed to optimize the performance and security of the LoRaWAN network for agricultural IoT applications, ensuring reliable communication over the extensive distances typical in farming areas.

C. Cloud and Edge-Level Decision Making

The system was engineered to operate primarily at the cloud level, leveraging the cloud's computational power for routine data processing and decision-making. In instances of network instability, the system was designed to autonomously switch to edge-level processing, thereby maintaining continuous operation without relying on cloud connectivity.

D. LoRiot Platform Integration

A critical component of the system was its integration with the Loriot IoT platform. This platform managed network communication, ensuring efficient data transmission between the sensors and the cloud. It also provided robust data storage solutions, making real-time and historical sensor data accessible to the user applications. This integration was pivotal in achieving reliable data availability and management across the system.

E. Development of Desktop and Mobile Applications

The user interface aspect involved creating intuitive desktop and mobile applications. These applications provided farmers with real-time data visualization, historical data access, and manual control over the irrigation system, enhancing user engagement and decision-making capabilities.

F. Implementation and Testing

Implementation of the system occurred in a controlled agricultural environment to facilitate testing. The focus was on assessing sensor accuracy, communication reliability, and the seamless transition between cloud and edge-level operations. The user applications were evaluated for responsiveness and ease of use, ensuring that data presentation and control mechanisms were intuitive and effective.

This integration resulted in a comprehensive IoT system capable of autonomous irrigation management and providing real-time insights to farmers, maintaining functionality even in unstable network conditions.

III. Results And Discussions

The implemented IoT system underwent extensive testing in a controlled agricultural environment to assess its performance and reliability. The following are the key findings:

A. Sensor Accuracy and Reliability

The capacitance sensors effectively measured soil moisture levels, providing accurate data essential for irrigation decisions. The temperature sensor also showed high reliability in environmental monitoring. Fig. 2 illustrates a scenario in which the soil was extremely dry, leading to the activation of the irrigation system, as evidenced by the activation of a yellow LED on the graphical user interface (GUI).

Fig. 2. Soil Very Dry

B. Communication Efficiency

Leveraging LoRa and LoRaWAN, the system maintained consistent long-range communication, crucial in remote areas. Data transmission to both cloud and edge devices was seamless, with minimal latency. Fig. 3 illustrates the communication efficiency.

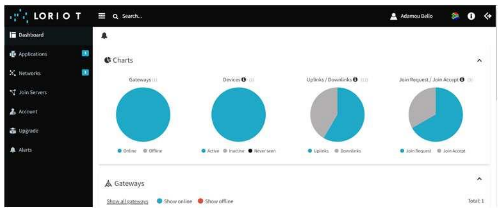

Fig. 3. System in Running Mode

C. Application Functionality

The desktop and mobile applications provided real-time data visualization and manual control options. Users could easily switch between automated and manual irrigation modes. The interface was intuitive, allowing for easy navigation and interaction, as shown in Fig. 2.

D. Cloud Platform Integration

Effective data synchronization with the Loriot platform was observed, ensuring data availability for real-time and historical analysis. Fig. 4 shows the cloud platform integration. Data were consistently transmitted to the user application.

FCntUp	Time	Port	Data
10	7 days ago	2	00 0e 1f 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
9	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
8	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
7	7 days ago	2	00 0e 1d 18 01 f4 fe 3e 09 0d 05 03 ab 00 00
6	7 days ago	2	00 0e 1f 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
5	7 days ago	2	00 0e 21 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
4	7 days ago	2	00 0e 1c 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
3	7 days ago	2	00 0e 1d 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
2	7 days ago	2	00 0e 1d 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
1	7 days ago	2	00 0e 1c 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
11	7 days ago	2	00 0e 1e 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
10	7 days ago	2	00 0e 1a 19 01 f4 fe 3e 09 0d 05 03 ab 00 00
9	7 days ago	2	00 0e 21 19 01 f4 fe 3e 09 0d 05 03 ab 00 00

Fig. 4. Received Frame Data

Where 'FCntUp' refers to the LoRaWAN frame counter for uplink messages, which tracks the number of frames sent. The 'Time' value indicates the duration for which the Gateway registered the message's arrival. 'Port' denotes the LoRaWAN frame port number (FPort) utilised by the End Node to send this uplink message, and 'Data' represents the hexadecimal format of the End Node's uplink payload.

E. Edge-Level Decision Making

During periods of network disruption, the system successfully switched to edge-level operation. This transition was smooth, ensuring uninterrupted irrigation control based on the pre-set thresholds and real-time sensor data.

These results demonstrate the system's capability to provide continuous and efficient agricultural monitoring and irrigation control, even in challenging network conditions. The dual-modality approach, combining cloud and edge computing, proved to be effective in ensuring both autonomous operation and user engagement.

The results obtained from the implementation of the IoT-based agricultural system offer several key insights and contributions to the field of smart agriculture:

F. Resilience in Unreliable Network Conditions

The system's ability to switch seamlessly between cloud and edge-level decision making in response to network availability underscores its resilience. This feature is particularly crucial in remote agricultural areas where network instability is common. The successful edge-level operation ensures continuous monitoring and control, a significant advancement in IoT applications for agriculture.

G. Enhanced User Interaction and Control

The development of intuitive desktop and mobile applications enhances user engagement. These applications not only provide real-time data visualization but also allow for manual control over irrigation processes. This dual capability ensures that the system caters to both automated efficiency and user discretion, bridging a gap often found in automated agricultural systems.

H. Efficient Use of Technologies

The implementation of LoRa and LoRaWAN technologies demonstrates an efficient use of IoT for long-range communication with low power consumption. This aspect of the system design is particularly relevant for large-scale agricultural settings, where traditional Wi-Fi or cellular networks may not be feasible.

I. Data Management and Accessibility

The integration with the Loriot platform has shown that effective data management and accessibility are possible, even in complex IoT systems. This ensures that farmers have access to critical data for making informed decisions about their crops and irrigation practices.

J. Future Applications and Reaserch

The findings from this study open avenues for further research, particularly in exploring other areas of agriculture where edge-level decision making can be beneficial. Additionally, the scalability of the system to include more diverse sensors or integrate with other agricultural technologies presents an exciting area for future development.

Overall, the research contributes significantly to the advancement of smart agriculture technologies. By addressing critical challenges such as network reliability and user engagement, the developed IoT system demonstrates a comprehensive approach to modern agricultural challenges, setting a benchmark for future IoT applications in the field.

IV. CONCLUSION

This paper presented a comprehensive IoT-based system designed to address critical challenges in smart agriculture, particularly focusing on resilience in unreliable network environments and enhancing user interaction and control. The key contributions of this research are the successful integration of edge-level decision making with cloud-based monitoring and control, and the development of user-friendly desktop and mobile applications for real-time agricultural management. The implementation of LoRa and LoRaWAN technologies for long-range, low-power communication proved highly effective in remote agricultural settings, demonstrating the system's scalability and efficiency. The seamless transition between cloud and edge-level operations ensured uninterrupted functionality, a significant advancement in overcoming network unreliability issues prevalent in rural farming areas. Moreover, the intuitive design of the desktop and mobile applications empowers farmers with real-time insights and manual control over irrigation processes, bridging the gap between automated systems and human decision-making. This dual capability marks a substantial improvement in user engagement and operational flexibility in agricultural IoT systems. The integration with the Loriot platform showcased effective data management, enhancing the system's reliability and usability. These advancements collectively contribute to smarter, more sustainable agricultural practices, aligning with global efforts to combat challenges such as water scarcity and climate change.

While this study provided valuable insights into the integration of IoT technologies in smart agriculture, it also highlighted areas requiring further exploration. The implementation tested was limited by its scale and the uniformity of the agricultural environments in which it was deployed. Expanding the scope to include additional sensor types and diversifying data analytics capabilities could further enhance system performance. Investigating the scalability of the system for larger-scale deployments and its adaptability to diverse agricultural environments remains an exciting area for continued development. Additionally, integrating machine learning algorithms for predictive analytics presents a promising direction to significantly boost the efficiency and intelligence of IoT-based systems. Future work should also address the practical challenges of deploying these technologies in varying climatic conditions and the economic feasibility of widespread adoption.

In conclusion, this research represents a significant step towards realizing the full potential of IoT in smart agriculture, offering a robust, adaptable, and user-friendly solution to contemporary farming challenges.

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