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RESEARCH ARTICLE

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DESIGN AND IMPLEMENTATION OF A SCALABLE LORA-BASED IOT IRRIGATION SYSTEM WITH DUAL CONTROL MECHANISMS

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ABSTRACT

Efficient water management is a critical challenge in large-scale agriculture, especially in remote areas where manual monitoring and control of irrigation systems are impractical. This paper presents the design and implementation of a scalable, LoRa-based Internet of Things irrigation system with dual control mechanisms, offering both local and remote control of irrigation processes. The system comprises field sensor nodes that transmit environmental data—such as soil moisture, temperature, and pump status—to both a local control node and a cloud gateway. Users can manage irrigation remotely via a cloud-based dashboard, while local control is achieved through manual intervention at the control node. A synchronization mechanism ensures that changes in actuator states are reflected across the system, regardless of where the control originates. By employing Long Range technology for extended communication distances and MQTT (Message Queuing Telemetry Transport) for efficient cloud connectivity, the system supports reliable, low-power operation over distances of up to 5.76 kilometers. Field tests validate its effectiveness, showcasing its potential to enhance water use efficiency in agriculture and reduce the need for constant human oversight in irrigation management. The scalable design ensures the system can adapt to various agricultural field sizes, making it practical for wide-area irrigation management.

I. INTRODUCTION

Efficient water management in agriculture is increasingly critical due to growing water scarcity and the need for sustainable practices. Agriculture accounts for approximately 70% of global freshwater withdrawals, emphasizing the importance of optimizing irrigation systems [1]. Traditional irrigation methods often require significant human intervention and are inefficient, leading to water wastage and suboptimal crop yields [2]. These challenges are exacerbated in remote or large-scale agricultural settings where manual monitoring and control are impractical. The Internet of Things (IoT) offers transformative solutions by enabling automation and optimization of irrigation processes through interconnected, low-power devices that communicate wirelessly [3]. IoT-based systems facilitate real-time monitoring and control, allowing for precision agriculture where inputs like water are applied only when and where needed, enhancing sustainability and productivity [4]. Scalability is a crucial aspect of these systems, designed to accommodate the expansive and varying sizes of agricultural fields [5].

One primary challenge in deploying IoT for agriculture is maintaining wide-area coverage while keeping energy consumption low. Traditional wireless technologies like Wi-Fi are limited in range and consume significant power, making them unsuitable for large-scale agricultural applications [6]. Technologies like Zigbee and Bluetooth are more energy-efficient but are not optimized for long-range communication, which is often necessary in rural environments [7]. Low-Power Wide-Area Networks (LPWAN) have emerged as a solution for IoT applications requiring extended communication range and low energy consumption [8]. Among LPWAN technologies, LoRa stands out due to its ability to provide reliable data transmission over many kilometers while operating on minimal power [9]. LoRa employs chirp spread spectrum modulation, which is robust against interference and can achieve long-range communication with low power consumption [10]. This makes it ideal for large agricultural areas with complex terrains, where maintaining connectivity is challenging. LoRa's scalability features are particularly advantageous for accommodating a growing number of devices in expansive fields [11].

Previous studies shows that precise control over irrigation can significantly reduce water consumption while maintaining crop health [12]. An IoT-based smart irrigation system was proposed by H. Zhang et al. [13] utilizing wireless sensor networks to monitor soil moisture and environmental conditions in real time, reducing the need for manual intervention and improving water use efficiency. A. Kumar and B. Singh [14] emphasized the importance of designing scalable IoT solutions that can expand to accommodate varying field sizes, ensuring that the benefits of IoT technologies are accessible to farms of all scales. M. Ali, S. Khan, and L. Wang [15] designed and implemented an IoT-based smart irrigation system using LoRaWAN technology, demonstrating enhanced energy efficiency and reliable data transmission over long distances suitable for large agricultural fields. Additionally, integrating advanced data analytics into IoT-based irrigation systems has shown promise in optimizing irrigation scheduling. M. Patel and D. Roy [16] demonstrated how predictive analysis using historical and real-time data can improve water use efficiency and crop yield. While previous studies have made significant strides in developing IoT-based irrigation systems, several challenges remain unaddressed, particularly concerning energy efficiency, the integration of local and remote-control mechanisms, and the seamless scalability of such systems in remote or large-scale agricultural settings. Existing solutions often focus primarily on either local control or cloud-based management but rarely provide a unified approach that combines both effectively.

This paper presents the design and implementation of a scalable, LoRa-based IoT agricultural irrigation system that integrates both local and cloud-based control mechanisms. The system's dual approach adds robustness and flexibility. The local control node provides real-time, on-site decision-making and allows manual intervention when needed, crucial in environments where internet access is intermittent or unavailable. Simultaneously, cloud integration enables users to monitor and control irrigation remotely, providing a broader scope for managing the system from any location. The modular and scalable design allows for easy addition of field sensor nodes, ensuring the system can expand to cover larger agricultural areas.

By incorporating these features, the system is well-suited for large-scale agricultural applications, addressing challenges related to water management, energy efficiency, and the need for automation. The scalable architecture ensures that the system can adapt to various field sizes and complexities, making it a practical cost-effective solution for wide-area irrigation management.

II. SYSTEM ARCHITECTURE

The system architecture includes three core components: a field sensor node, a local control node, and a gateway node connected to a cloud platform. The field node collects real-time environmental data such as soil moisture, temperature, and humidity. This data is transmitted to both the control node and the gateway node using a point-to-multipoint communication scheme. The control node enables local decision-making, and the gateway facilitates remote monitoring via a cloud-based control and monitoring platform. The platform, named Kolibrio, has been developed for the purpose of this application.

The system is designed with scalability at its core. The modular architecture allows for the easy addition of field sensor nodes and actuators without significant reconfiguration.

The MQTT protocol plays a key role in enabling efficient communication between the gateway node and the Kolibrio dashboard, ensuring lightweight, reliable data transmission for remote management [17]. The use of MQTT protocols supports scalability by efficiently managing increased data traffic from additional nodes. By employing LoRa technology for long-range, low-power communication, the system can cover extensive agricultural areas in an energy efficient manner.

II.1 LORA MODULE CONFIGURATION

The E32-433T20DC LoRa module is pivotal in enabling long-range communication in an energy-efficient manner. Firmware was created to manage the configuration of parameters such as frequency, spreading factor, bandwidth, and power output, ensuring optimal performance in long-range, low-power data transmission [18], [19]. In all nodes, communication between the microcontroller and the LoRa module is established through the UART interface, using the E32LoRa open-source library [20]. This library simplifies data encapsulation for transmission and handles the module’s operation modes, including Normal, Wake-up, Power-Saving, and Sleep, to optimize energy efficiency in wide-area deployment.

As detailed in our previous study [21] and shown in Figure (1), the power consumption pattern of the E32-433T20DC was analyzed to understand its impact on battery life. While in sleep mode, the module consumes only 4.6 µA, before transitioning to a wake-up phase where it draws 15.4 mA for approximately 410 ms. During transmission, the current spikes to 102 mA for 820 ms as it sends a 58-byte packet at 2.4 Kbps. This analysis informs the current system's design, ensuring efficient operation within the constraints of battery powered IoT deployments.

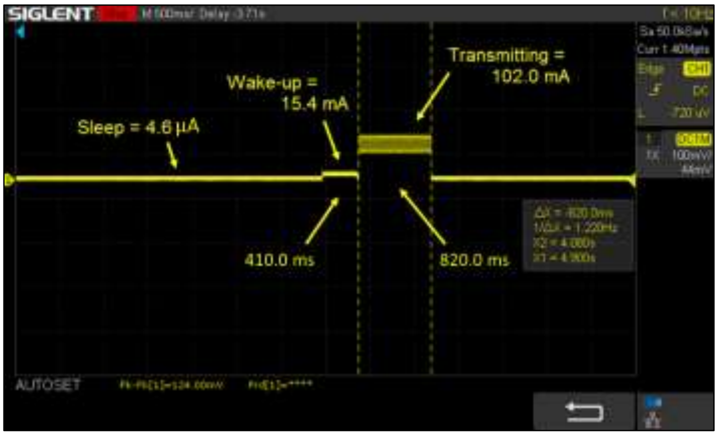

Figure 1: Signal of transmitted data while in the Sleep mode. Source: [21].

II.2 SENSORS AND ACTUATORS

The system integrates two primary environmental sensors: the DHT11 for temperature and humidity monitoring [22] and a soil moisture sensor to measure soil water content [23], [24]. The firmware initializes these sensors and processes the data collected, ensuring reliable transmission of environmental data to both local and cloud systems.

- DHT11 Sensor: Provides 40-bit humiture data via a digital signal, measuring temperature and humidity.

- Soil Moisture Sensor: Outputs analog signals corresponding to soil moisture levels.

The system controls a low-cost submersible water pump using a relay, which is activated based on sensor data and user commands. The pump's operation is crucial for automating irrigation based on environmental analysis, and the relay ensures efficient, reliable activation/deactivation of the pump [25].

II.3 FIRMWARE AND MICROCONTROLLER OPERATIONS

The system's functionality is driven by firmware that handles interactions among sensors, actuators, microcontrollers, and communication modules. The Arduino platform is utilized due to its versatility and ease of use for rapid prototyping [26]. Firmware was developed for both the Arduino Nano and the NodeMCU v3 boards, each selected for its suitability in specific parts of the system.

The Arduino Nano microcontroller specifically handles the field sensors and actuators. It processes sensor readings and communicates with the LoRa module for transmitting data to both the local control node and the gateway, allowing real-time decision-making at the local level [26]. Communication between the Arduino Nano and the OLED display occurs via the I2C interface, providing real-time feedback on sensor readings, actuator status, and system conditions. The NodeMCU v3 board [27], acts as the gateway, connecting to the Kolibrio dashboard via Wi-Fi. It manages data exchange between the field sensor and the cloud platform, allowing for remote monitoring and control through the Kolibrio platform. The microcontroller firmware is designed to support scalability by allowing easy integration of additional sensors or nodes, as illustrated in Section III, which describes the nodes.

II.4 COMMUNICATION MANAGEMENT

The communication architecture integrates both local and cloud-based systems using LoRa and Wi-Fi. The communication protocols and network topology are designed to support scalability, efficiently managing increased data traffic as more nodes are added.

• **Field Node Communication:** The field node transmits environmental data and actuator status in a point-to-multipoint configuration. Data is broadcasted to all addresses within a specific channel, allowing simultaneous data exchange. See Figure (2) [18]. Both the control node and the gateway, identified by their common channel, can receive the data. The field node sends the status of the actuator with every transmission, ensuring synchronization between local and remote controllers.

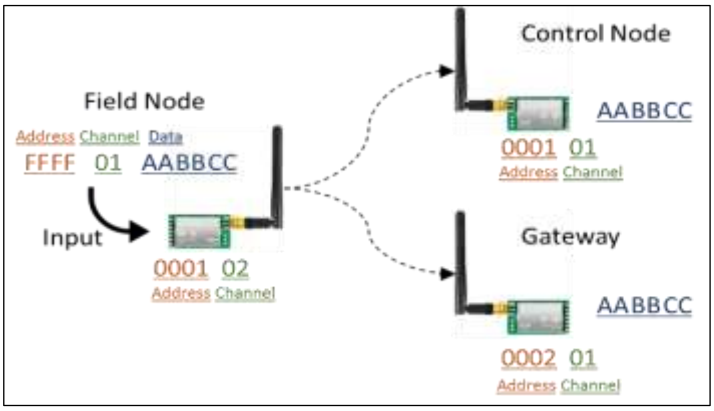

Figure 2: Transmission of field data.
Source: Authors, (2025).

• **Control Node and Gateway Communication:** Both the control node and gateway node communicate with the field node in a point-to-point manner using specific address and channel configurations. See figure (3) [18].

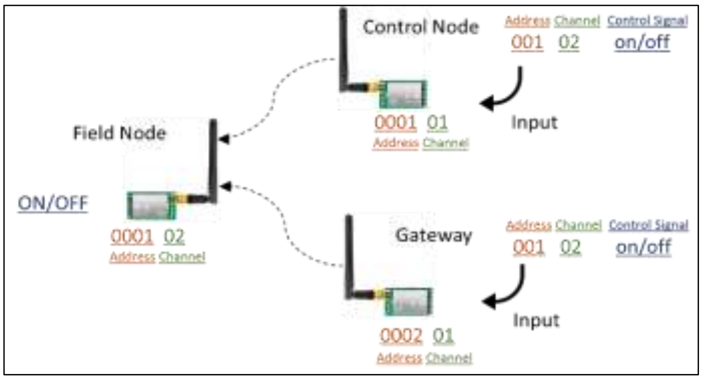

Figure 3: Transmission of control commands.
Source: Authors, (2025).

• **MQTT Protocol for Cloud Integration:** The NodeMCU board, serving as the gateway, communicates with the Kolibrio platform based on a publish-subscribe model using the MQTT protocol [17]. Figure (4) illustrates the communication architecture using the MQTT protocol.

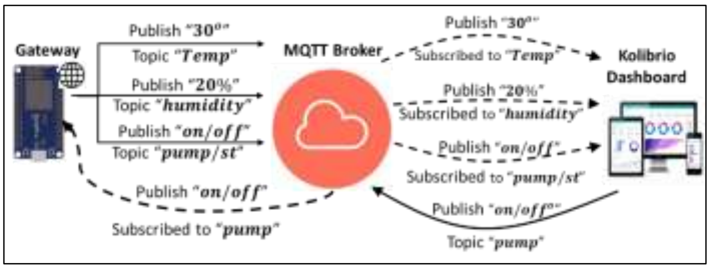

Figure 4: Communication architecture using the MQTT protocol.
Source: Authors, (2025).

The gateway connects to the local Wi-Fi network and acts as the intermediary between the field sensors and the cloud dashboard. It gathers sensor readings and publishes this data to specific MQTT topics: `/FieldNode1/temperature`, `/FieldNode1/humidity`, and `/FieldNode1/soil_moist`. This data is serialized into JSON format using the ArduinoJson library before being sent via the `mqtt_client.publish()` function [28]. The Kolibrio dashboard, subscribed to these MQTT topics, visualizes the sensor data, allowing the user to monitor environmental conditions in real time. The dashboard also provides a control interface, enabling users to turn the pump on or off remotely by publishing to the `/FieldNode1/pump` topic. The NodeMCU, subscribed to these control topics, listens for incoming commands, and forwards them to the field node using LoRa.

The system's bidirectional communication is robust; the NodeMCU sends updates about the actuator status back to the Kolibrio dashboard by publishing actuator states to the `/FieldNode1/pump_st` topic. This ensures the cloud platform is always synchronized with the local system, regardless of where the control action originates. Additionally, the system publish-subscribe model as well as the two-level MQTT topic design ensures flexibility and scalability for larger agricultural deployments. For instance, the addition of a field node would only require the addition of a topic such as `/FieldNode2/temperature`, and

`/FieldNode3/temperature` and so on. The gateway matches the first level to the appropriate field node address, and the second level to the sensor data.

III. SYSTEM COMPONENTS

The system is a robust energy-efficient IoT-based LoRa irrigation solution with cloud integration, designed for both local and remote control in large-scale agricultural irrigation.

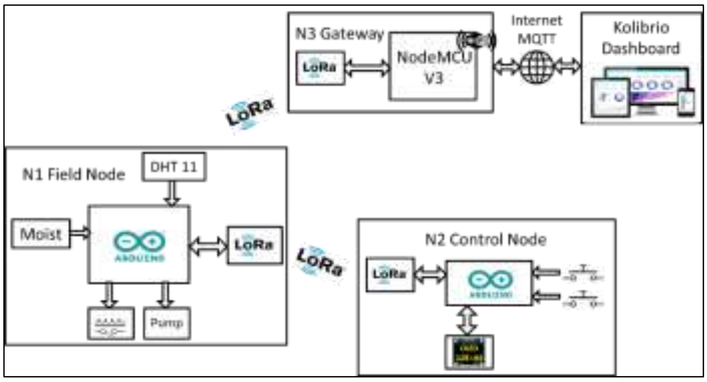

Figure 5: System diagram.
Source: Authors, (2025).

The architecture integrates a field node, a control node for local decision-making, and a gateway node for cloud-based management through the Kolibrio platform. Each component is designed with scalability in mind, ensuring the system can grow without significant reconfiguration. Figure (5) illustrates the system and corresponding components of the nodes. The system can be scaled with minimal intervention to incorporate additional field nodes. Sensors and actuators can also be easily integrated into the respective nodes, as illustrated in the schematics and flowcharts below, where a redundant actuator is incorporated in the form of a relay to demonstrate the scalability of the system.

III.1 FIELD NODE

The field node is responsible for gathering real-time environmental data and executing actuator control. Equipped with the DHT11 sensor for temperature and humidity measurement and a soil moisture sensor, it monitors key environmental parameters.

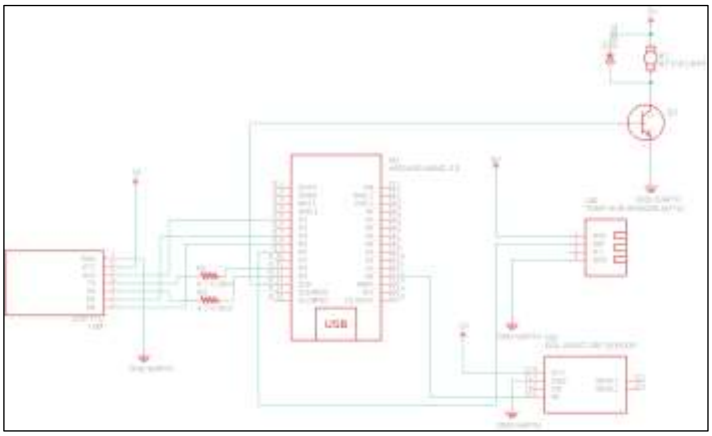

Figure 6: Schematic diagram of Field Node (N1).
Source: Authors, (2025).

Figure (6) shows the schematic of the field node, including sensor connections and communication pathways. The node incorporates the E32-433T20DC LoRa module, which facilitates long-range communication between the field node, control node, and gateway. Data collected by the sensors is transmitted to both the local control node and the cloud gateway. Field node is designed for easy replication and deployment, allowing the system to scale by adding more nodes to cover larger agricultural areas. Simply adding a replica having a distinct address and channel configurations, configured to transmit data to the same gateway channel.

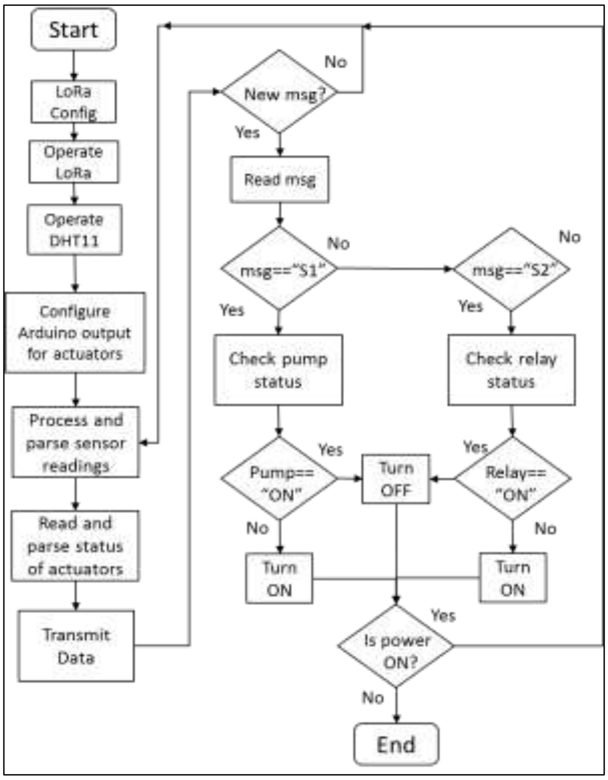

Figure 7: Flowchart of Field Node (N1).
Source: Authors, (2025).

Figure (7) illustrates the flowchart of how the node processes sensor readings and determines whether to activate the water pump, relaying the pump's status to both the control node and the cloud. The figures demonstrate how additional actuators (or sensors), such as a redundant relay, can be incorporated to enhance functionality and scalability.

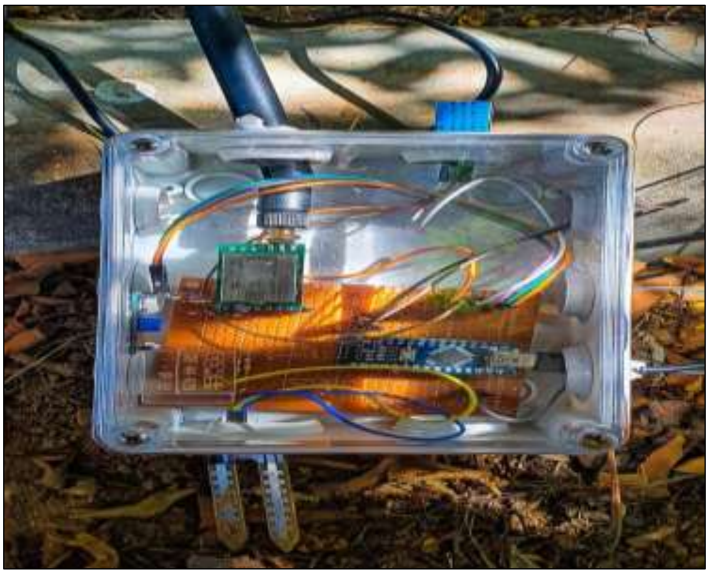

Figure 8: actual deployment of the field node.
Source: Authors, (2025).

Figure (8) shows the actual deployment of the field node, demonstrating the connected sensors, LoRa module, and actuator control setup. The picture provides a visual representation of how the components are laid out in the field, ensuring the reader has a practical understanding of the system’s physical layout.

III.2 CONTROL NODE

The control node provides localized decision-making capabilities, enabling manual intervention when necessary. It is equipped with an OLED screen displaying real-time environmental data and pump status, allowing on-site monitoring without relying on cloud access.

The control node, as described in section II, sends specific commands to the field node via a point-to-point link such as activating or deactivating the irrigation pump. It also listens for broadcasted data from the field node, including sensor readings (e.g., soil moisture, temperature) and pump status. Users can manually control the irrigation pump through the control node using push buttons that issue commands to the field node. With minor adjustments, the node can manage data from multiple field sensor nodes and control multiple actuators, ensuring seamless scalability as the number of nodes increases.

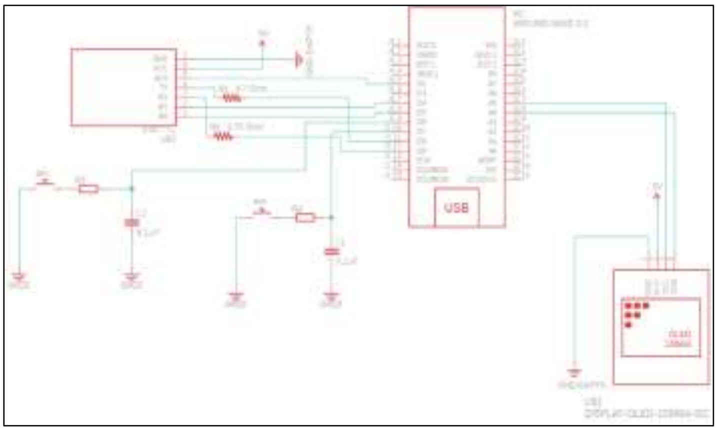

Figure 9: Schematic diagram of control node (N2).
Source: Authors, (2025).

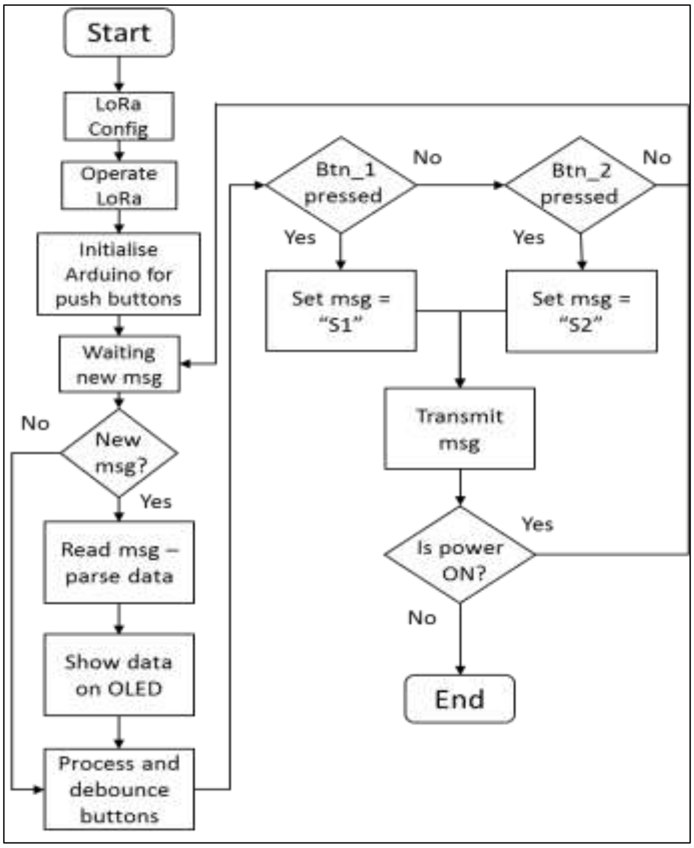

Figure 10: Flowchart of Control Node (N2).
Source: Authors, (2025).

Figure (9) details the schematic of the control node, highlighting the OLED display, buttons, and LoRa communication module. Figure (10) explains the flowchart of how the control node processes incoming data and allows for manual override.

As illustrated, the system is scalable to control multiple actuators by merely increasing the physical number of push buttons and minimal modification to the firmware. The addition of a redundant actuator in the form of a relay is illustrated in both figures below. Different buttons can be dedicated to specific field nodes; hence, the control of actuators in different field nodes can be easily enabled, scaling the system to incorporate several field nodes.Figure (11) shows a picture of the control node setup featuring an OLED screen displaying live environmental data and buttons used for manual control of actuators.

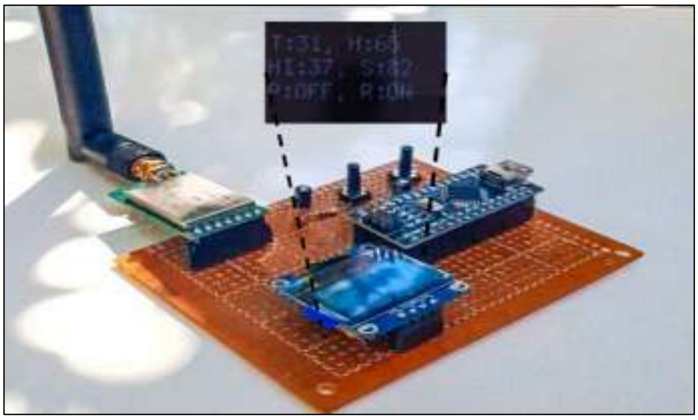

Figure 11: Control node.
Source: Authors, (2025).

III.3 GATEWAY

The gateway node bridges the local irrigation system and the cloud-based Kolibrio platform. Built on the NodeMCU v3 board with an integrated ESP8266 Wi-Fi module, it collects data from the field node and sends it to the cloud. It is designed to handle communication with multiple field nodes, supporting network expansion. This is realized by transparently relaying any received message regardless of the transmitter and publishing it based on the first level of the MQTT topic, as discussed in Section II. The gateway is also responsible for relaying control commands from the Kolibrio platform and transmits them back to the appropriate field node depending on the first level of the MQTT topic.

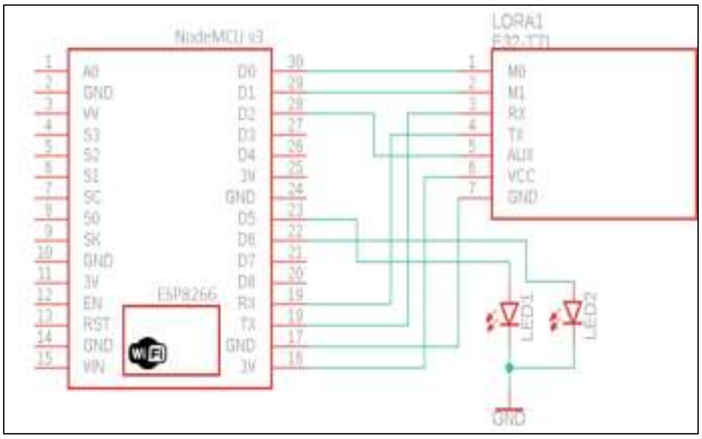

Figure 12: Schematic circuit diagram of gateway.
Source: Authors, (2025).

Figure (12) demonstrates the schematic of the gateway node, showing its connections.

Figure (13) explains the communication flow between the gateway and the cloud, including data transmission and processing of control commands. Figure (14) illustrates an image of the gateway node in operation.

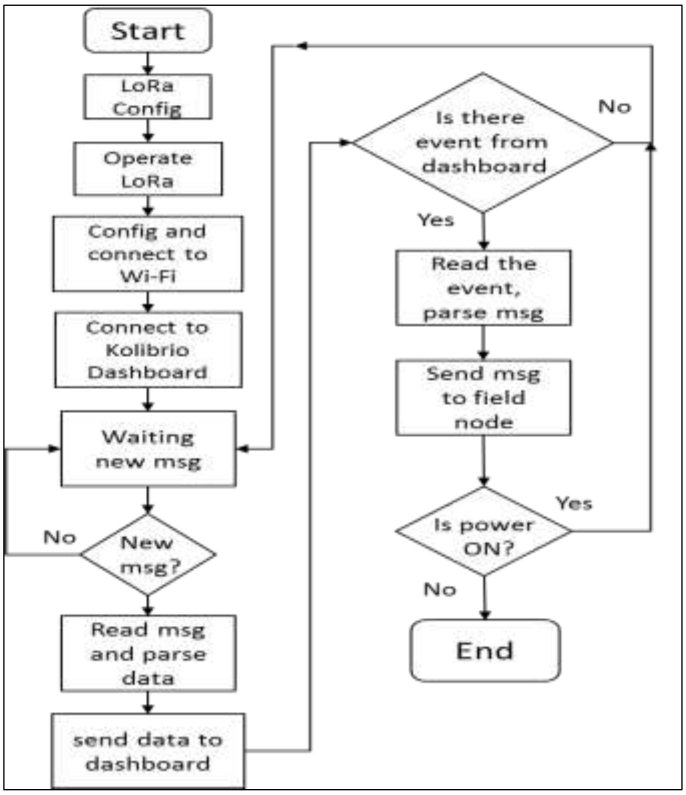

Figure 13: Flowchart of the gateway.
Source: Authors, (2025).

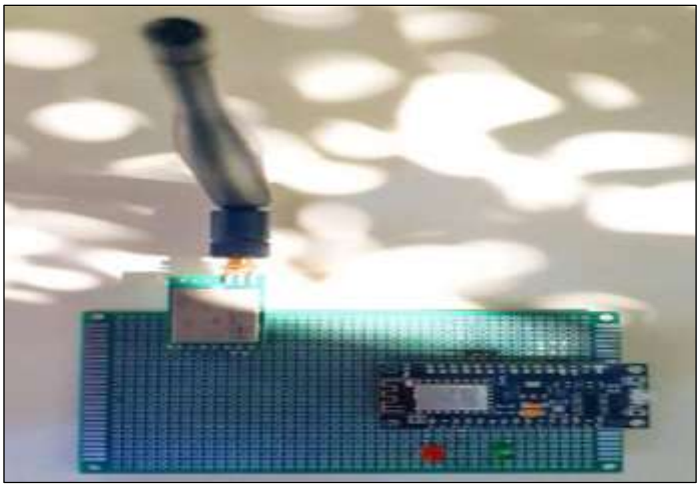

Figure 14: Gateway node.
Source: Authors, (2025).

III.4 KOLIBRIO DASHBOARD

The Kolibrio dashboard, developed specifically for this application, serves as the cloud-based user interface for the irrigation system. It is an open-source platform providing customizable dashboards to monitor sensor data and control actuators remotely. Features include:

- Real-Time Visualization: Live sensor readings such as soil moisture, temperature, and humidity.
- Historical Data Analysis: Graphs displaying historical data trends, allowing users to identify patterns and optimize irrigation schedules.
- Remote Control: Toggle switches to control actuators like the irrigation pump.
- Accessibility: Accessible from any internet-connected device, including computers, smartphones, and tablets.
- Scalability Support: The dashboard can handle data from multiple field sensor nodes, making it suitable for larger deployments.

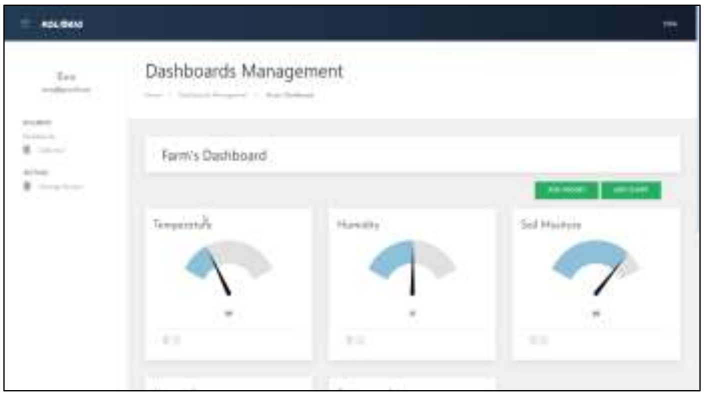

Figure 15: Example of the Kolibrio dashboard.
Source: Authors, (2025).

Communication between the gateway and Kolibrio is handled using the MQTT protocol, as discussed in section II, ensuring reliable and efficient data transmission. The dashboard is customizable, allowing users to create multiple dashboards with widgets tailored to their needs. As the number of field nodes increases, the dashboard can be easily configured to include additional data streams and control elements. An example of the Kolibrio dashboard is illustrated in figure (15).

IV. RESULTS AND DISCUSSIONS

IV.1 RANGE MEASUREMENTS

The range performance of the E32-433T20DC LoRa module was tested to assess its capability in long-range data transmission under various configurations.

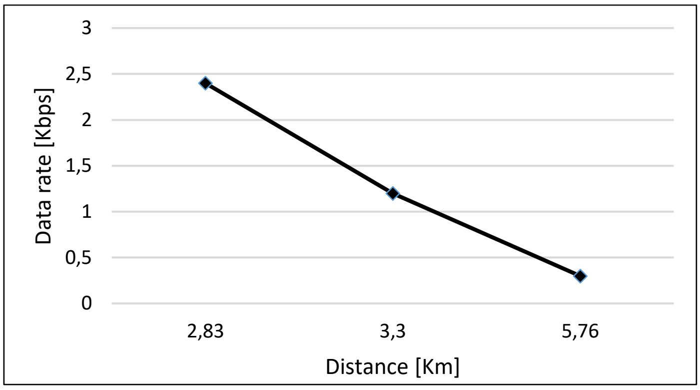

Figure 16: Data Rate vs. Communication Range.
Source: Authors, (2025).

As shown in Figure (16), LoRa technology, renowned for its extended range, confirms that the module can transmit data up to 5.76 kilometers at a data rate of 0.3 Kbps under ideal line-of-sight conditions. As the data rate increases, the effective communication range decreases; however, reliable transmission was sustained over several kilometers even at higher rates. This confirms the system's suitability for large-scale agricultural fields, ensuring reliable monitoring over extensive areas, which is ideal for spatially distributed farms and environmental monitoring in remote locations (see Table 1). The long-range capability reduces the need for additional infrastructure, supporting scalability by allowing more nodes to connect over wide areas without significant network changes.

Table 1: coverage areas for various air data rates.

Air Data Rate [Kbps]	Communicaition Distance [km]	Range Area [Hectares]
0.3	5.76	10,418
1.2	3.30	3,420
2.4	2.83	2,516

Source: Authors, (2025).

IV.2 SYSTEM FUNCTIONALITY

The IoT-based irrigation system effectively manages and monitors environmental conditions in real time. The system employs point-to-multipoint communication from the field sensor node to both the gateway and the local control node. Meanwhile, point-to-point communication between the gateway and control node ensures bidirectional control and feedback.

Data Flow and System Responsiveness

Field nodes, equipped with moisture and temperature sensors, gather critical environmental data, and transmit these values to both the local control node and the gateway. The data is visualized in real time via the Kolibrio cloud dashboard on any connected device (laptop, mobile, etc.). This facilitates remote management and analysis of environmental conditions and system statuses, such as pump operation. The cloud integration ensures real-time synchronization between the local control node and the cloud, allowing for seamless irrigation management regardless of network availability.

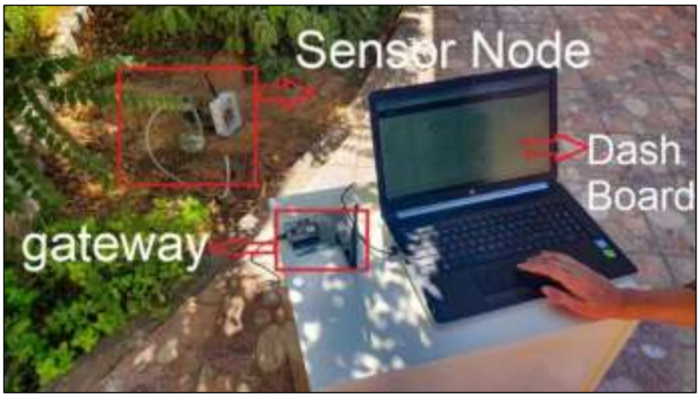

Figure 17: Real-world deployment.
Source: Authors, (2025).

Figure (17) illustrates the real-world deployment of the system, showing how the sensor nodes, control node, and gateway interact. This demonstrates the system's practical setup, emphasizing its robustness and flexibility in field operations. To clarify, the cloud-based control platform can be accessed from anywhere in the world via internet. Accessing the Kolibrio dashboard using the laptop as in figure (17) is only for demonstration purposes.

Real-Time Monitoring and Control

The Kolibrio dashboard, as shown in Figure (18), provides users with live sensor readings such as soil moisture, temperature, and humidity levels. In addition, the dashboard showcases the status of actuators, enabling remote control of the irrigation pump. Users can toggle the pump's operation through the cloud platform, which is immediately reflected on both the cloud dashboard and the OLED display of the local control node, maintaining synchronization between remote and local control.

Figure 18: Live sensor readings with control switch.
Source: Authors, (2025).

Historical Data and Analysis

The system stores historical environmental data in the cloud, accessible through the Kolibrio dashboard's graph widget as illustrated in figure (19). This feature allows for trend analysis over time, enhancing irrigation scheduling. By analyzing past sensor data, users can identify patterns in moisture levels and other parameters, enabling optimization of irrigation schedules and reduction of water consumption.

As more field sensor nodes are added, the system can handle increased data volumes. The cloud-based storage and processing capabilities ensure that historical data from additional nodes can be managed effectively, supporting scalability in data analysis. Figure (19) demonstrates the graph widget's capability to display historical data trends, empowering users to optimize long-term irrigation strategies.

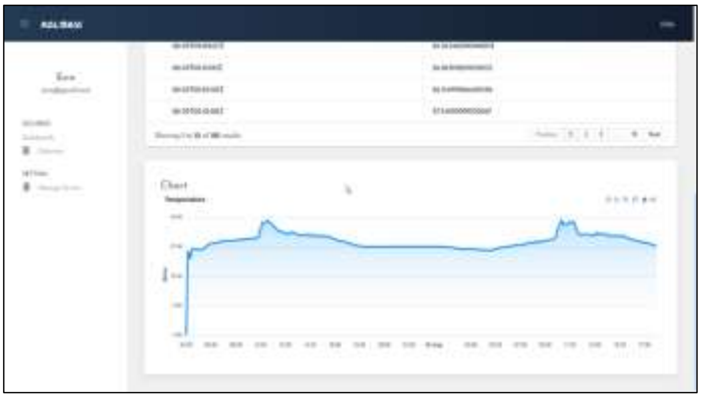

Figure 19: Graph displaying historical temperature data.
Source: Authors, (2025).

V. CONCLUSIONS

This paper presents the development and implementation of a scalable, IoT-based LoRa-Cloud Integrated irrigation system designed to address the challenges of water management in remote agricultural areas. By integrating low-power, long-range communication with cloud connectivity, the system provides a robust, energy-efficient, scalable solution for monitoring and controlling irrigation processes both locally and remotely.

The real-time data acquisition, control capabilities, and historical data analysis make it a valuable tool for optimizing water usage in agriculture. Field tests confirmed the system's ability to maintain reliable communication over distances up to 5.76 kilometers, making it suitable for large-scale agricultural deployments. The system's architecture, with dual control options, ensures continued operation even during network outages, demonstrating adaptability in both connected and disconnected environments.

The scalable design of the system ensures that it can be expanded to accommodate larger agricultural areas, making it a practical and adaptable solution for wide-area irrigation management. The modular components, efficient communication protocols, and flexible software support growth without significant reconfiguration or increased complexity.

Future research could explore enhancements such as renewable energy integration, advanced data analytics, and the implementation of adaptive transmission intervals to further improve resource efficiency. Additionally, scalability can be further tested by deploying the system in larger networks and integrating more diverse sensor types to monitor additional environmental parameters.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Salahedin Rehan, Esra Alhame, Esra Hassan.
Methodology: Salahedin Rehan, Esra Alhame, Esra Hassan.
Investigation: Salahedin Rehan, Esra Alhame, Esra Hassan.
Discussion of results: Salahedin Rehan, Esra Alhame, Esra Hassan.
Writing – Original Draft: Salahedin Rehan, Esra Alhame, Esra Hassan.
Writing – Review and Editing: Salahedin Rehan, Esra Alhame, Esra Hassan.
Resources: Salahedin Rehan, Esra Alhame, Esra Hassan.
Supervision: Salahedin Rehan, Esra Alhame, Esra Hassan.
Approval of the final text: Salahedin Rehan, Esra Alhame, Esra Hassan.

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