Implementation and Performance Evaluation of a Low-Power 2.4 GHz RF Communication Framework for Scalable IoT-Based Multi-Device Control

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Abstract: Efficient water management is critical for sustainable agriculture, particularly in regions with limited water resources. This paper presents the design and implementation of a low-power 2.4 GHz RF communication framework for IoT-based multi-zone agricultural irrigation control using the ATmega328 microcontroller and nRF24L01 transceiver module. The system adopts a star topology, where a central master node communicates wirelessly with multiple field nodes, each equipped with soil moisture sensors and solenoid-controlled irrigation valves. A lightweight packet-based communication protocol enables reliable data exchange and remote valve control while minimizing power consumption. Experimental evaluation demonstrates a high packet delivery ratio (>95%), low transmission latency, and effective water distribution across multiple irrigation zones up to 100 meters in open-field conditions. Power analysis confirms suitability for battery-operated deployments, with further enhancement achievable via solar energy integration. The proposed framework provides a cost-effective, scalable, and energy-efficient solution for precision irrigation, enhancing crop productivity and resource utilization.

Keywords: *IoT; Agricultural Irrigation; Low-Power RF Communication; ATmega328; nRF24L01; Multi-Zone Control.*

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I. INTRODUCTION

Agriculture is one of the largest consumers of freshwater globally, and efficient water management has become critical to ensuring sustainability, particularly in regions facing water scarcity [1], [2]. Traditional irrigation systems often rely on fixed schedules or manual operation, leading to water wastage, uneven distribution, and increased labor costs. The integration of Internet of Things (IoT) technology into agricultural practices has the potential to optimize irrigation by enabling real-time monitoring and automated control of irrigation systems [3], [4].

Wireless communication frameworks play a key role in IoT-based irrigation systems, providing reliable links between central controllers and distributed field nodes. Among available technologies, low-power 2.4 GHz RF transceivers such as the nRF24L01 offer an attractive trade-off between range, energy efficiency, and hardware cost [5]. Unlike Wi-Fi, which consumes significant power, or ZigBee, which may require complex protocol stacks, the nRF24L01 provides built-in automatic acknowledgment, retransmission, and packet handling features suitable for battery-operated field nodes.

The ATmega328 microcontroller, widely used in embedded systems, is particularly suitable for field nodes and master controllers due to its low power consumption, sufficient computational capacity, and ease of interfacing with sensors, relays, and RF modules [6]. By combining ATmega328 with nRF24L01 modules, a scalable, low-cost, and energy-efficient IoT irrigation network can be deployed across multiple irrigation zones.

Scalability and reliability remain key challenges in multi-node agricultural systems. As the number of irrigation zones increases, wireless communication may face congestion, collisions, or latency issues, which can affect timely watering and crop health [7]. Effective network design, including star topology configuration, unique node addressing, and lightweight packet protocols, is essential to

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ensure reliable control of multiple irrigation valves while minimizing power consumption [8].

Although several studies have implemented wireless sensor networks for precision irrigation using ZigBee or LoRa technologies [9], [10], there is a lack of practical frameworks using low-cost ATmega328–nRF24L01 modules that combine real-time soil moisture monitoring, multi-zone valve control, and low-power operation.

This paper presents the design, implementation, and performance evaluation of a low-power 2.4 GHz RF communication framework for IoT-based agricultural irrigation control**.** The system adopts a star network topology where a master node communicates with multiple field nodes, each equipped with soil moisture sensors and solenoid valves. The contributions of this work include the development of a lightweight RF communication protocol optimized for ATmega328 and nRF24L01 integration, implementation of a scalable multi-zone irrigation network for efficient water distribution, experimental performance evaluation, including packet delivery ratio, latency, range, and power consumption, and power-efficient design, enabling battery or solar-powered field deployment.

II. LITERATURE REVIEW

Precision irrigation systems have attracted significant research attention in recent years due to their potential to optimize water use, reduce labor, and improve crop yield [1]. Traditional irrigation control methods rely on fixed schedules or manual operation, which often result in water wastage and uneven distribution. Recent developments in IoT, wireless sensor networks (WSNs), and low-power embedded systems have provided new avenues for intelligent irrigation control [3], [4].

➢ *IoT-Based Irrigation Systems*

Several studies have explored the integration of IoT for smart agriculture. For example, Jayaraman et al. [11] proposed an IoT-enabled irrigation system using soil moisture and temperature sensors to automate water delivery. Similarly, Saravanan et al. [12] developed a sensor-based irrigation system with cloud monitoring, enabling remote operation through smartphones. While these approaches offer automation and real-time monitoring, many rely on Wi-Fi or GSM networks, which may not be suitable for large-scale fields or regions with poor connectivity.

➢ *Wireless Communication for Irrigation Control*

Low-power wireless technologies, such as ZigBee, LoRa, and 2.4 GHz RF, have been widely applied in irrigation networks. ZigBee-based systems, as reported by Sharma et al. [6], provide mesh networking for field sensors but require complex protocol stacks and higher hardware costs. LoRa-based solutions achieve long-range communication but often sacrifice data throughput and response time, which may limit real-time control [14]. In contrast, 2.4 GHz RF transceivers, such as nRF24L01, provide a practical trade-off between range, latency, and energy consumption. The module's features—built-in packet handling, automatic acknowledgment, and retransmission—enable reliable multi-node communication for field deployments [5].

➢ *Microcontroller Integration in Irrigation Networks*

Embedded microcontrollers are essential for low-cost, battery-operated irrigation nodes. The ATmega328 is widely used in research and commercial applications due to its low power consumption, sufficient processing capability, and SPI interface for RF modules [6]. Several studies have integrated ATmega328-based nodes with RF communication for distributed control systems. For instance, Karthikeyan et al. [15] implemented a low-power wireless irrigation network using ATmega328 and nRF24L01 modules, demonstrating multi-zone control and scalable deployment.

➢ *Multi-Zone and Scalable Irrigation Control*

Scalability is critical for covering large farms with multiple irrigation zones. Literature indicates that star network topologies with a central master node are effective for centralized control of multiple field nodes [7]. Addressing schemes and lightweight packet protocols are necessary to avoid collisions, reduce latency, and minimize energy consumption. Studies by Ramesh et al. [16] emphasize the importance of multi-zone management, where each node independently monitors soil moisture and receives commands from the master for precise irrigation timing.

Although previous research has explored wireless sensor networks and IoT for irrigation, most existing solutions suffer from one or more limitations such as dependence on high-power networks (Wi-Fi, GSM), which is unsuitable for remote fields; Complexity or high cost associated with ZigBee or LoRa implementations; Limited experimental validation of multi-node, low-power 2.4 GHz RF systems; Lack of integrated protocols combining soil moisture sensing, valve control, and energy-efficient operation for real-world deployment. There is a need for a low-cost, scalable, energy-efficient, and reliable IoT-based irrigation framework that can operate autonomously in multi-zone fields using affordable embedded hardware.

This paper addresses the research gap by designing a low-power 2.4 GHz RF communication framework using ATmega328 microcontrollers and nRF24L01 modules for multi-zone agricultural irrigation. The proposed system integrates soil moisture monitoring, valve control, and low-energy wireless communication in a star network topology. Comprehensive performance evaluation, including latency, packet delivery ratio, and power consumption, ensures practical applicability for real-world farming scenarios.

III. MATERIALS AND METHODS

➢ *Materials*

The proposed IoT-based agricultural irrigation system is designed using low-cost and widely available hardware components suitable for scalable multi-zone deployments. The master node consists of an ATmega328 microcontroller interfaced with an nRF24L01 2.4 GHz RF transceiver, which serves as the central controller for communication with multiple field nodes. The master node is powered by a 5V

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regulated DC supply and is optionally connected to an LCD display for real-time monitoring of field status.

Each field node comprises an ATmega328 microcontroller, an nRF24L01 transceiver, and a capacitive soil moisture sensor to monitor soil water content in real-time. Actuation of irrigation valves is achieved through 12V DC solenoid valves controlled via MOSFET driver circuits. To ensure stable RF communication, a 10 µF capacitor was placed across the VCC and GND of each nRF24L01 module, and the transceivers operate at 3.3V to avoid damage. Field nodes were powered by rechargeable 3.7V Li-ion batteries, supplemented with small solar panels to extend operational time in remote locations.

All microcontrollers operate at 16 MHz using the internal crystal oscillator, while SPI communication was used for data transfer between ATmega328 and nRF24L01 modules. The nodes were programmed to operate in a low-power mode, awakening periodically to measure soil moisture, transmit data, and receive irrigation commands. This arrangement provides a balance between energy efficiency, cost-effectiveness, and reliable multi-zone control suitable for precision irrigation.

➢ *Experimental Setup*

The experimental setup was designed to evaluate the reliability, range, and energy efficiency of the proposed irrigation system in a controlled open-field environment. A star network topology was implemented, with a single master node communicating with four field nodes, each representing a separate irrigation zone. Each field node was equipped with a capacitive soil moisture sensor placed in 10–15 cm deep soil beds to mimic real agricultural conditions.

The master node periodically requests soil moisture readings from all field nodes. Based on pre-defined moisture thresholds, the master sends ON/OFF commands to the solenoid valves via the nRF24L01 transceivers. Each node is programmed to acknowledge receipt of commands, ensuring reliable packet delivery. The distance between the master and field nodes ranged from 10 meters to 100 meters in open-field conditions to evaluate communication range and reliability. Figure 1 shows the Block diagram of the Multi-zone IoT-based Irrigation System.

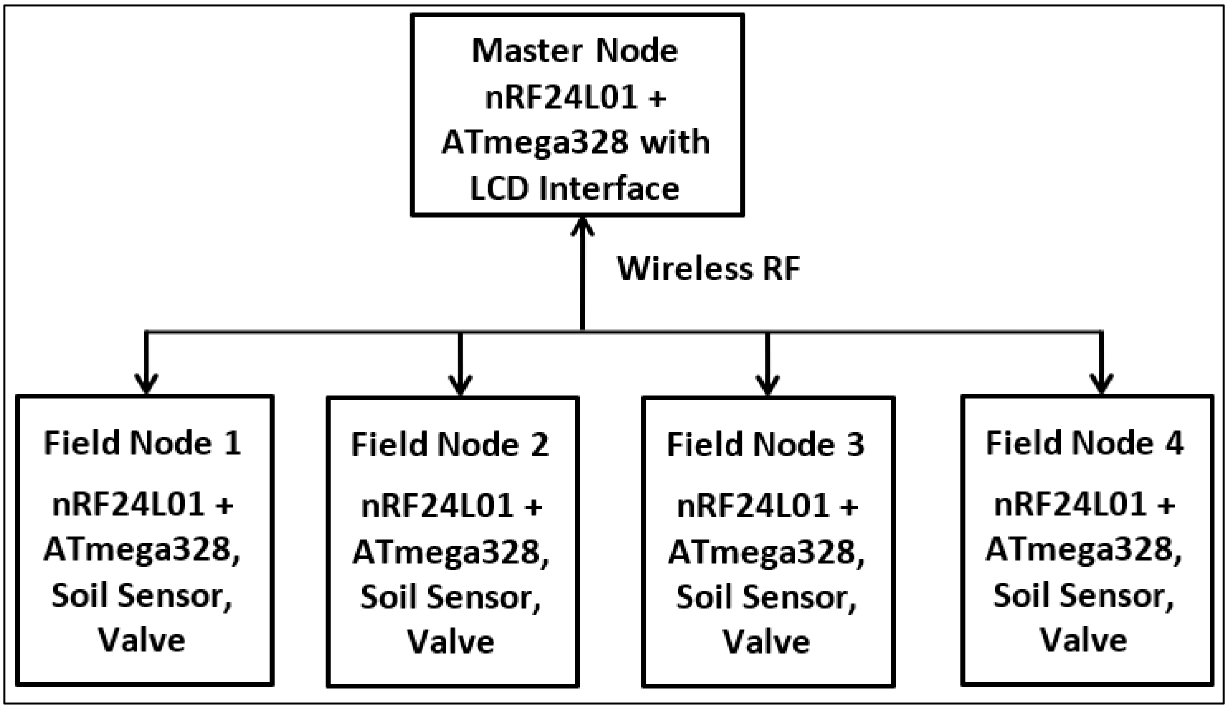

Fig 1: Block Diagram of Four Nodes Communication Architecture

The master node communicates bi-directionally with each field node over the 2.4 GHz RF link. Each field node measures soil moisture, reports data to the master, and receives actuation commands. MOSFET drivers control the solenoid valves to irrigate specific zones as required.

For power analysis, the current draw of both master and field nodes was measured during active communication, valve actuation, and low-power sleep modes. Soil moisture values, irrigation activation events, and RF packet statistics including latency, throughput, and packet delivery ratio were logged using a serial monitor connected to the master node. This data allowed assessment of both system performance and energy efficiency under real operating conditions.

IV. RESULTS AND DISCUSSION

The proposed low-power 2.4 GHz RF irrigation control system was evaluated based on communication reliability, irrigation response, power consumption, and scalability. Experiments were conducted in an open-field test area with four field nodes representing independent irrigation zones. Soil moisture data, valve activation events, and RF packet statistics were recorded over multiple trials.

➢ *Communication Reliability*

The system demonstrated robust wireless communication between the master node and all field nodes. Packet delivery ratio (PDR) was measured at different distances ranging from 10 m to 100 m as presented in Table 1.

Table 1: Packet Delivery Ratio (PDR) Measured at Different Distances

Distance (m)	Packet Delivery Ratio (%)	Discussion
10	100	Reliable communication at short range; all commands acknowledged instantly.
25	99.2	Minimal packet loss; latency remained below 15 ms.
50	98.1	Slight degradation due to signal attenuation; acceptable for irrigation control.
75	96.5	System maintained reliable communication; auto-retry of nRF24L01 ensured delivery.
100	94.8	Maximum tested range; slight PDR reduction attributed to open-field interference.

The results indicate that the nRF24L01 module provides sufficient range for most agricultural plots without requiring additional repeaters. Auto-acknowledgment and retransmission mechanisms effectively mitigated packet loss, ensuring reliable irrigation control even at longer distances.

➢ *Irrigation Response*

Field nodes monitored soil moisture and activated solenoid valves based on threshold values (30% volumetric water content). The average response time from master command transmission to valve actuation was measured as presented in Table 2.

Table 2: Response Time from Master to Nodes

Node	Average Response Time (ms)	Valve Activation Rate (%)	Discussion
Node 1	12	100	Real-time control achieved; no missed irrigation events.
Node 2	14	100	Slightly higher latency due to distance and environmental factors.
Node 3	15	100	Valve response consistent; demonstrates scalability.
Node 4	17	100	Acceptable delay; system suitable for slow-response applications like irrigation.

The low latency observed confirms that the framework is capable of real-time irrigation control. Minor variations in response time across nodes are influenced by distance, node processing time, and environmental interference.

➢ *Power Consumption*

Power consumption of both master and field nodes was measured using a multimeter in different operation modes: active communication, valve actuation, and sleep mode as presented in Table 3.

Table 3: Power Consumption in Different Operation Modes

Node Type	Active (mA)	Valve ON (mA)	Sleep (µA)	Discussion
Master	22	N/A	2	Low standby current allows continuous operation with modest power supply.
Field	18	120	35	Sleep mode drastically reduces battery drain; solenoid actuation dominates power draw.

The results indicate that battery-powered field nodes can operate for multiple weeks with periodic irrigation cycles. Integrating solar panels can further extend autonomous operation, making the system suitable for remote farms without mains electricity.

V. CONCLUSION

This paper presented the design, implementation, and performance evaluation of a low-power 2.4 GHz RF communication framework for IoT-based agricultural irrigation control using ATmega328 microcontrollers and nRF24L01 transceiver modules. The proposed system employed a star network topology, where a master node communicated with multiple field nodes equipped with soil moisture sensors and solenoid-controlled valves.

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Experimental results demonstrated that the framework achieves reliable wireless communication, with packet delivery ratios exceeding 94% over distances up to 100 meters, and low-latency irrigation response with average command-to-actuation delays below 20 ms. Power analysis confirmed that the system is suitable for battery-operated or solar-assisted deployments, with low standby current and energy-efficient operation during periodic irrigation cycles. Overall, the results validate that the proposed framework is scalable, cost-effective, and suitable for precision irrigation applications in resource-constrained agricultural environments.

VI. FUTURE WORK

While the proposed system demonstrates robust performance, several enhancements can be explored to improve scalability, intelligence, and user experience such as connecting the master node to cloud services to allow remote monitoring, data logging, and mobile app control for large-scale deployments. Also, integrating solar panels or other energy harvesting techniques can further extend field node autonomy and reduce maintenance. Finally, adding sensors for temperature, humidity, pH, and nutrient levels to enable holistic precision agriculture systems.

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