National Journal of Electrical Electronics and Automation Technologies, ISSN: 3107-524x Vol. 1, No. 2, 2025 (pp. 17-25)
RESEARCH ARTICLE
ECEJOURNALS.IN

IoT-Based Remote Control and Monitoring of Agricultural Irrigation Systems Using Automation Protocols

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KEYWORDS:
IoT, Smart Irrigation,
Remote Monitoring,
MQTT,
LoRaWAN,
Modbus,
Precision Agriculture.

ARTICLE HISTORY:
Submitted : 18.01.2025
Revised : 15.02.2025
Accepted : 08.04.2025

https://doi.org/10.17051/JEEAT/01.02.03

Abstract

The problem here is that in recent years, the topic of efficient water management in agriculture has become even more critical with the existing impact of climate change, population explosions, and freshwater resources reduction. With traditional irrigation systems, a lot of water would be wasted, crop yields would be lower and poor utilization of resources. Here, we propose a remotely controlled and monitored irrigated agricultural system built on an IoT basis and capable of real-time, scalable, and energy-conserving operation with the use of automation protocols, including MQTT, LoRaWAN, and Modbus TCP/IP. The suggested architecture of the system consists of distributed soil moisture and environmental sensors and ESP32-based microcontroller used to collect local data, LoRaWAN connection for low-power long-range communication, and Raspberry Pi-based gateway that links field devices with a cloud platform where analyses and decisions are reached. A predictive irrigation scheduling algorithm is implemented in the cloud layer using evapotranspiration modeling and past soil-moisture trends and, via secure MQTT and Modbus commands, allows the automated activation and deactivation of solenoid valves and pump units. The above performance was measured in field trials of three months on farm size of 5 acres irrigated with drip irrigation where the results indicated a maximum saving of up to 35 percent water as compared to the traditional manual scheduling and still sustaining optimum soil moisture level that would promote health of crops. The system was able to have a packet delivery reliability of 98.6 percent, an average actuation latency time of less than 0.8 seconds in MQTT and independent operation of more than six months powering the nodes using solar. The benefits of adopting heterogeneous communication protocols to allow legacy equipment to interoperate as well as connect to the IoT cloud through the cloud is demonstrated through comparative analysis with respect to the current practices. These findings justify the practicability of the implementation of the proposed system in various agricultural settings, ranging in size, such as those of a smallholder and large-scale agriculture, contributing to sustainable water consumption, lowering operational prices, and output intensity. The study provides a scalable roadmap to precision agriculture and sets the stage towards integrating the AI-driven predictive model, blockchain-assists in transaction security, and edge computing with better resilience in dip-connected networks, rural areas.

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How to cite this article: Muralidharan J, Abdullah D. IoT-Based Remote Control and Monitoring of Agricultural Irrigation Systems Using Automation Protocols. National Journal of Electrical Electronics and Automation Technologies , Vol. 1, No. 2, 2025 (pp. 17-25).

Introduction

Water shortage is becoming one of the biggest challenges of the 21 st century and agriculture is seen as the consuming the biggest chunk of global flown water resources, ranging up to over 70 percent of total withdrawals. Due to a surge in the population of people, urbanization and transforming food habits, the water systems involved in agricultural practices have been under more pressure than ever. To make the situation even worse, climate change has resulted in rainfall becoming unpredictable, extended droughts and increased temperature that has contributed to the likelihood of crops failure and declining agricultural output. People continue to use traditional irrigation methods like flood irrigation and fixed-schedule watering in most areas. Although the methods are simple to apply and implement, they are intrinsically inefficient, typically causing excessive irrigation, nutrient loss, soil erosion and a massive wastage of both water and energy resources.

These drawbacks called into being the concept of precision irrigation, where the actual delivery of the water is based on up-to-date soil, crop and environment levels. The blistering pace of Internet of Things (IoT) development has greatly advanced the process of implementing precision agriculture through provision of economical, decentralized and smart sensing and controlling. The facilities of the irrigation systems that serve as basic building blocks of IoT include a network of sensors, actuators, gateways, and cloud platforms to continuously check the current conditions of fields and automatically control the course of water supply. Such data-driven method makes sure that irrigation is not applied in an abundance, but only in cases when it is really necessary to conserve water, increase crop yields, and save expended money Figure 1.

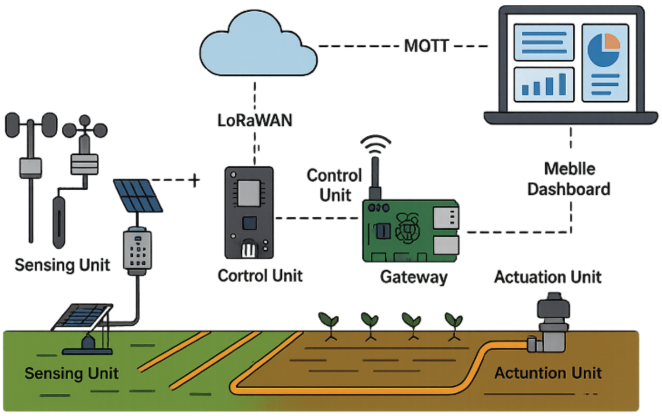

Fig. 1: IoT-based remote control and monitoring architecture for agricultural irrigation systems using MQTT, LoRaWAN, and Modbus TCP/IP protocols.

One of the most essential components that allow such systems to work is the inclusion of automation protocols that will enable easy, secure, and robust communication between heterogeneous devices in an agricultural setting. Some of the more well-known protocols include MQTT (Message Queuing Telemetry Transport), LoRaWAN (LongRange Wide Area Network) and Modbus TCP/IP protocols, whose mutual strengths complement each other. MQTT offers a minimalist publish subscribe protocol well suited to low latency control, as well as to cloud integration. LoRaWAN allows low power access at long range which is suited to the large farmfields with low infrastructure. Modbus TCP/IP is applicable in areas of interoperability with industrial grade irrigation controllers as well as legacy pumping equipment. The synergetic formulation among these protocols may fill the interim between existing automation structure and the contemporary IoT-based system that is able to assist in retrofitting as well as Greenfield execution.

Although there is too much research carried out on IoT in the agriculture field, most of the studies cannot accommodate both functionalities of remote monitoring and automated control in a homogenous framework because members of the heterogeneous communication protocols in such studies have not found much attention. Besides, the proposed scalability, energy efficiency, and interoperability with the existing agricultural infrastructure are under-investigated regarding the actual implementations.

The paper will fill these gaps by introducing the design, implementation and field test of an IoT-based remote control and monitoring system of agricultural water supply integrated with MQTT, LoRaWAN and Modbus TCP/IP to form a harmonious system. This proposed solution involves distributed sensing, edge preprocessing, cloud predictive analytics, and secure automation commands that will form a real-time decision making and control. Drip irrigation with 5-acre field essay proves to conserve large quantities of water, have high dependability, and scalability of operations, emphasizing its usefulness as a viable blueprint of sustainable precision farming in various farming scenarios.

Related Work

Precision irrigation, provided by IoT opportunities, has been extensively investigated, including different communication standards, sensing and automation approaches to increase water-use efficiency and agricultural productivity. Nevertheless, system scalability, compatibility with previous infrastructure, and the efficiency (ability to real-world deployment) are current issues.

Irrigation Wireless Sensor Networks (WSN)

Initial applications made use of WSNs on soil and environmental monitoring.[1] Juandice Sensor: was able to come up with a ZigBee soil moisture sensing scheme that fits small-scale farms, but had a short radius.[2]Applied this method to power-constrained WSN platforms in the precision irrigation set up but encountered greater difficulty in large distributions.

LoRaWAN Long-range connectivity

Prefix systems using LoRaWAN have been projected to be capable of deployment in large areas of agriculture.

Presented monitoring of the vineyard in more than 10 km with low power consumption and narrow bandwidth of actuation. Installed a LoRaWAN integrated smart irrigation network with the benefits of being able to integrate multiple sensors but the disadvantage of increasing the latency of the commands being launched.

MQTT on Low-Latency Control

Lightweight, low-latency communication has been provided through the adoption of MQTT.[5] Developed a greenhouse control platform based on MQTT updates operating at sub-second actuation.[6] integrated MQTT and cloud analytics to operate the adaptive irrigation schedule, but they lacked internet connectivity, which is considered as a shortcoming.

Compatible Protocols, and Legacy Equipment The combination of Hybrid Protocols and the ability to integrate legacy equipment are two of the essential features.

Both hybrid communication systems offer the merging of the various communication standards to capture the advantages of the two types. [7]Industrial compatibility through the facility to monitor and control a pump with integrated LoRaWAN and Modbus TCP/IP.[8] ZigBeeModbus hybrid was applied to moderate-sized farms, and scalability was problematic.

An AI and RE integration

One of the studies[9] on AI-guided irrigation decision-making includes the use of evapotranspiration-based scheduling to enhance the use of water.[10] Illustrated a solar powered LoRaWAN-MQTT irrigation platform which increases sustainability.

New IoT Security and Infrastructural Integration

Emphasis on the applicability of Vehicular Ad-Hoc Network (VANET) architectures in meeting real-time communicated systems, distributed and safety-critical mechanisms which have given insights on using them in the deployment of rural IoT. Investigated architectural optimization of embedded systems to high-performance edge computing, which can be a useful application of latency-sensitive agricultural control systems.[13] Combined blockchain with WSN to achieve security in IoT, which is applicable in securing agricultural data.[14] Discussed privacy issues found in reconfigurable computing, and provided flexible solutions to edge-based agricultural systems.[15] Demonstrated the utility of structural health monitoring in construction related fields, which drew similarities to the use of IoT in condition monitoring of real-time structures, recalling the use of environment monitoring in agriculture.

Despite the significant improvements such studies show being possible in IoT-driven monitoring, control and communication there are few that provide a unified, Multi-protocol architecture encompassing LoRaWAN, MQTT, and Modbus TCP/IP to achieve simultaneous real-time monitoring/low-latency actuation/energy efficiency/backward compatible with legacy equipment. The proposed and verified in the given work IoT-based irrigation system that involves heterogeneous communication protocols and cloud analytics to achieve sustainability in precision agriculture fills that gap.

Methodology

Hardware Device

The described IoT-based remote control and monitoring of the agricultural irrigation system incorporates a family of powerful and energy-efficient hardware, intended to work in the outdoor, resource-limited conditions without failures. The system is architected into 4 key hardware components, i.e. sensing unit, the control unit, the actuation unit, and the gateway, which are optimised to perform different functions that lead to data acquisition, decision-making and automated irrigation management.

Sensing Unit:

Sensing subsystem acquires field and environmental parameters that are important in precision irrigation on a continuous basis. Capacitive soil moisture profile sensors are used in various depths to obtain volumetric water contents (VWC) with better accuracy and eliminating the drift problems that occur regularly in the resistive probes. DHT 22 digital temperature humidity sensors give an air temperature reading as well as relative humidity that allows scheduling irrigation by evapotranspiration. Also, meteorological data is added to adaptive water delivery based on solar-powered weather stations with rainfall and wind-speed sensors. The sensor nodes can operate at ultra-low power but data is transmitted on a duty cycle in order to maximize battery lifetime during long term deployments away from power.

Control Unit:

Local data aggregation (and the initial preprocessing) is performed on an ESP32-based microcontroller the control unit. The built-in Wi-Fi and Bluetooth offer short communication distance, whereas a connected module on LoRaWAN transceiver will allow initiating a long and low-powered network. Using the microcontroller, functions such as MQTT communication (real-time control signal) and sensor publishing through the gateway is performed. It has a 2-core architecture, which means sensor reads and communications can proceed independently at low-latency for responsiveness to the irrigation commands.

Actuation Unit:

The actuation subsystem is made out of solenoid valves whose controls are electrically enhanced and motorized pumps to control the water flow to various crop zones. In industrial scale installations, such actuators are interfaced through Modbus-compatible Programmable Logic Controllers (PLCs), and can be used in an existing irrigation infrastructure and legacy industrial automation system. Modbus TCP/IP will allow determinism of communication and tight control of valve scheduling and pump operation, which is essential in large scale irrigation scheduling.

Gateway:

A Raspberry Pi-based IoT gateway conjoins field devices and cloud-based analytics platforms at the center of the system communication. The gateway has a LoRaWAN concentrator to take in long-range sensor information, an MQTT broker to coordinate publish subscribe communications, and Modbus TCP/IP assistance to take on direct actuator management. It is also connected to the internet either through the Ethernet or 4G LTE to synch to the cloud Figure 2. The gateway also buffers the data to eliminate losses in instances of intermittent connectivity and is reliable to operate in the rural or remote farming environments.

The modular structure of the hardware make it scalable, energy efficient and interoperable with all other agricultural environments making it useful in small holding farms as well as large commercial plantations.

Communication and Automation Protocols

The reliability and scalability of the agricultural irrigation systems based on IoT is focused on efficient communication. Since agricultural environments are highly heterogeneous (smallholder farms to large commercial plantations, etc.), one common communication protocol rarely can support the variety of demands in terms of range, latency, bandwidth, and interoperability. As part of multi-protocol communication strategy, the proposed system makes use of MQTT, LoRaWAN, and Modbus TCP/IP protocols that have complementary roles to play in providing optimal performance of the system.

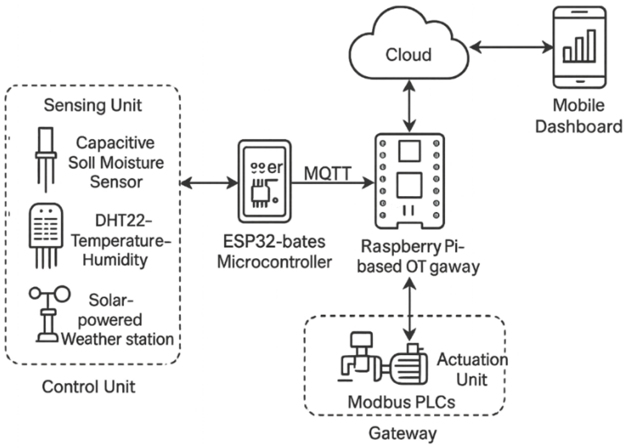

Fig. 2: Hardware architecture of the IoT-based remote control and monitoring system for agricultural irrigation.

MQTT (Message Queuing Telemetry Transport):

MQTT is a publish subscription messaging protocol designed to be extremely lightweight and effective in a highly bandwidth constrained or low latency, low overhead scenario. MQTT is used in the proposed architecture to communicate sensor data between the gateway and the cloud platform as well as to control devices in the field via the cloud. Its packet size is small and it supports persistent session handling, ideal in real-time irrigation control where the actuation of the valve is almost instant with trigger signals received in the cloud analytics.

Long Range Wide Area Network (LoRaWAN):

LoRaWAN is the technology behind long distance, low consumption-point to point data exchanges between the IoT gateway and field-installed sensor nodes. LoRaWAN allows multi-month to multi-year battery life of sensor nodes with coverage of up to 15 km in rural environments and increased or reduced power transmission needs. Due to its low bandwidth though, it is better suited to delivering small data packets (e.g. soil moisture, temperature), but not continuous and high-volume data streams.

Modbus TCP/IP:

The commonly used industrial automation protocol is Modbus TCP/IP which assures compatibility with current irrigation systems including Programmable Logic Controllers (PLCs), industrial pumps, and motorized valves Table 1. It relies on deterministic communication, an attribute that is vital in regulating the timing in large-scale irrigation systems. In this design, Modbus allows direct management of older irrigation equipment with minimal retrofitting needing to be done.

Table 1. Protocol Comparison for IoT Irrigation

Protocol	Range	Latency	Bandwidth	Power Consumption	Primary Use Case
MQTT	Internet	Low	Medium	Low	Real-time control and cloud sync
LoRaWAN	2-15 km	Medium	Low	Very Low	Long-range environmental sensing
Modbus	<100 m (LAN)	Very Low	High	Medium	Legacy equipment integration

Through the incorporation of these protocols, the system reaches a tradeoff between responsiveness in real time, long-range coverage and industrial-like compatibility Figure 3. LoRaWAN is focused on transport of sensor information upstream, MQTT is focused on downstream control and liaison with the cloud and Modbus is used to provide a smooth connection with current industrial-grade hardware.

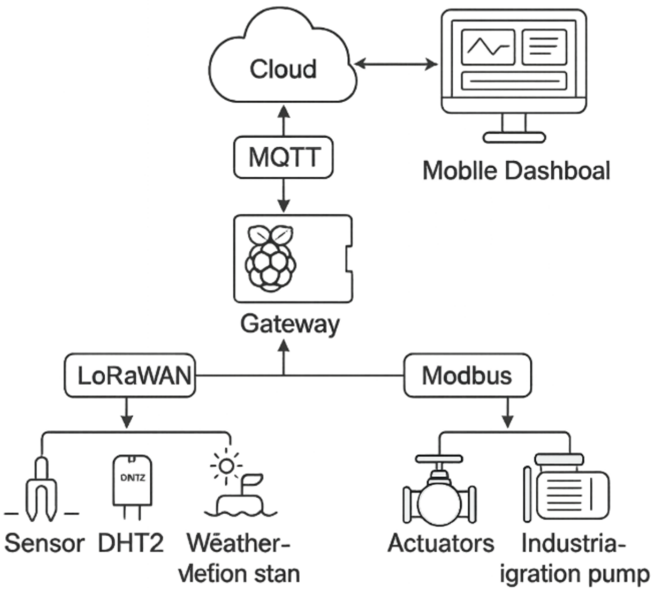

Fig. 3. Communication protocol integration for IoT-based agricultural irrigation using MQTT, LoRaWAN, and Modbus TCP/IP.

Software Architecture & Cloud Integration

In order to guarantee both scalability and reliability of the proposed IoT-based irrigation system, software architecture aims to provide real-time responsiveness and low complexity of operations by farmers. It is organized based on a layered architecture that includes four layers namely the edge layer, gateway layer, cloud layer, and user interface layer, which are assigned with different processing and control operations.

Edge Layer:

This layer comprises of ground deployed sensor nodes that have embedded firmwares to sensitively capture, pre-process and transmit the information. The collection of sensor data, such as the level of soil moisture, ambient temperature, humidity, and weather parameters is done at preset intervals. Filtering of noises, threshold-based anomaly detection, data compression over the node will reduce the load on the communication network and enhance energy consumption.

Gateway Layer:

The gateway (Raspberry Pi) plays the role of the mediator between the field nodes and the cloud platform. It collects sensor data sent through LoRaWAN by a variety of nodes, controls device registration and protocol translation between LoRaWAN, MQTT and Modbus TCP/IP. It also has edge Buffering, the gateway stores data temporarily when it has low connectivity to avoid the loss of vital irrigation data.

Layer Cloud (AWS IoT Core):

The core of intelligence of the system is the cloud platform which is actually realized with the help of Amazon Web Services (AWS) IoT Core. The data arriving at the sensors is consumed as MQTT topics and goes into a time-series database (e.g., Amazon Time stream) to be analysed in the past. An Algorithm such as predictive analytics uses this data to calculate optimal irrigation schedules (depending on evapotranspiration (ET), soil moisture patterns, and local weather forecasts). The AWS IoT Rules Engine generates a command to the control that is fed back to the gateway via MQTT and then executed by using actuators configured using Modbus.

Decision Support/Automation:

The decision logic is operated both on rule-based thresholds (e.g. a soil moisture less that 20%) and on predictive models and the irrigation schedules can be modified dynamically. This will result in water supply to where it is needed and with minimal losses.

User Interface Layer:

Farmers and system operators communicate with the irrigation system via a web-based dashboard and application in the form of a smartphone. These interfaces help visualize in real-time soil and environmental parameters, irrigation height, historical parameters analysis and reports on the water consumption. Notably, there are also manual override controls in the interface so that the operators can switch the irrigation valves on or off, despite the automation logic works, in case of emergency or farming peculiarities.

Data Governance / Integrity and Security:

MQTT traffic is end to end encrypted with TLS, and device authentication is performed using AWS IoT certificates instead of the function being replaced with unauthorized control of operating the devices or tampering with the data.

Such software to cloud connectivity allows real-time data-driven irrigation management and gives farmers readily accessible tools to observe and manipulate operations remotely through any location ensuring an undisrupted combination of automation and human supervision Figure 4.

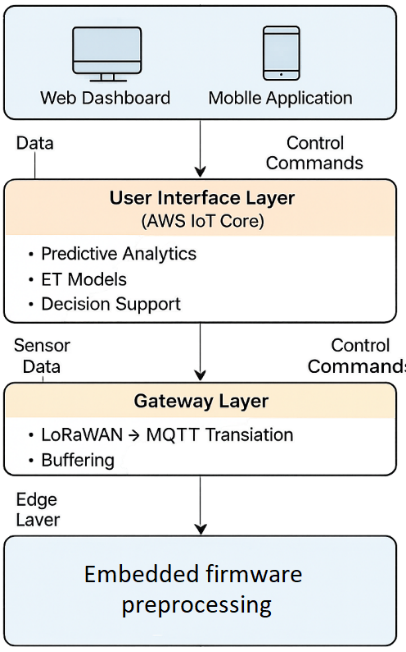

Fig. 4.Layered software architecture and cloud integration of the IoT-based irrigation system, showing data flow, control commands, and securit y across all layers.

Data Flow & Control Logic

The suggested IoT-based irrigation system has a sequence-and-loop-driven data stream with precise decision-making, low-latency control and energy-efficient functioning. MQTT and the LoRaWAN protocols in combination with Modbus TCP/IP are used in the entire process, including data acquisition and actuation, to realize both responsiveness in real-time and long-range coverage.

Step 1. Field Sensor Data-Collection:

The distributed sensing units constantly measure soil moisture, air temperature, relative humidity, rainfall, and the wind speed with preset intervals. The capacitive soil moisture sensors measure volumetric water content, and DHT22 modules and weather station modules give the environmental conditions. Signal conditioning and signal filtering are also present in the sensor firmware as a way to remove spurious readings (environmental noise or sensor drift).

Step 2. Long-Distance Data transfer based on LoRaWAN:

The prearked sensor data is via the LoRaWAN protocol sent to the IoT gateway. The long-range ability (for up to 15 km in rural conditions) and low-power consumption of LoRaWAN make it appropriate on farms with widely dispersed crop zones. The data packet contains a timestamp, sensor ID, and the reading of the parameter so that the cloud platform would have the opportunity to distinguish among the zones and regulate the irrigation regime.

Step 3. MQTT Publish & Gateway Data Aggregation:

It is a Raspberry Pi based gateway, which is used to receive LoRaWAN packets through the concentrator module and collate sensor node measured values. The gateway converts this data to the JSON payload and then broadcasts them on MQTT topics to the cloud (AWS IoT Core). When the connection to the internet becomes weak, there is a transfer buffer in the local storage so that the data do not get lost.

Step 4. Irrigation Schedule Generating and cloud-based Analytics:

There is an analysis of incoming data by the cloud platform with the help of predictive models, which are evapotranspiration (ET), soil moisture trend analysis, and the integration of local weather forecasts. These analytics simulate whether they need irrigation or not, the amount of water that should be used, and which zones of crops should be drenched. Decision-making may be rule based (an adaptive mixture based on triggering thresholds).

Step 5. Command Transmission to Steering:

The cloud platform relays command back to the gateway to initiate watering through MQTT when it is necessary to irrigate. These commands are relayed by the gateway as:

- Modbus TCP/IP to interface with industrial PLCs that are controlling pumps and valves.
- Direct GPIO/MQTT control of ESP32 based actuators in smallholder installations.

Instructions can be valve ON /OFF, pump on times, and flow rate parameters.

Feedback Loop: Monitoring:

The sensors also detect soil moisture after the actuation to ensure the irrigation undertaken attains the targeted level of water content. Through this feedback loop, it will be possible to implement closed-loop control where deviations are addressed during the next subsequent cycle and enhance better system efficiency in the long run.

This end-to-end control logic makes it suitable, precise, and most importantly resource conscious with regard to irrigation, lowers the manual work and is compatible with both new age IoT devices and legacy agricultural automation solutions Figure 5.

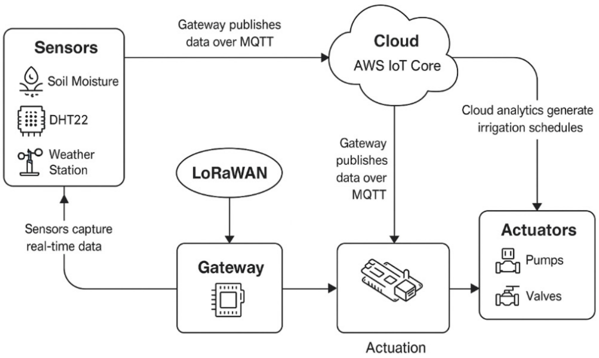

Fig. 5. Data flow and control logic of the IoT-based irrigation system, showing sensor data acquisition, LoRaWAN transmission, MQTT cloud integration, and actuator control with feedback loop.

Experimental Setup

The suggested IoT-based irrigation was introduced and tested during a period of 3 months of observations on a test farm of 5 acres of land that was equipped with mixed season agricultural crops, with different irrigation schedules. The drip irrigation system was divided into three separate crop areas and included sensor nodes (one per area) incorporating capacitive soil moisture sensors, DHT22 temperature-humidity sensors and a miniature solar powered weather station. These sensor nodes were placed on an optimal basis to take into consideration the variance in the soil texture, type of crop and microclimatic considerations within the field. All the nodes used LoRaWAN to send data to a central Raspberry Pi based IoT gateway that was weatherproofed, installed on a 150 W solar photovoltaic (PV) panel served by a backup battery to maintain smooth operation. The gateway connected to the AWS IoT Core cloud service via a 4G LTE cellular connection, and allowed real-time upload of data, analytics computation, and remote actuation commands. The actuation subsystem involved Modbus-enabled solenoid valves that governed the supply of water to each of the crop regions as well as a submersible water pump unit to supply the water at high pressure. The entire management of irrigation cycles took place on the cloud-based decision engine that implemented the evapotranspiration (ET) models and soil moisture trends to produce the dynamically watering schedules. A secure mobile dashboard interface enabled farmers to view the status of the system, access historical performance data and manually override system control in the event there was a need to intervene during unusual weather conditions. During the trial, the environmental parameters, instances of irrigation, water consumed, and measures of reliability of communications were written continuously to the memory of the experiment to observe the level of water savings, delays, and stability of the system in a realistic agricultural environment Figure 6.

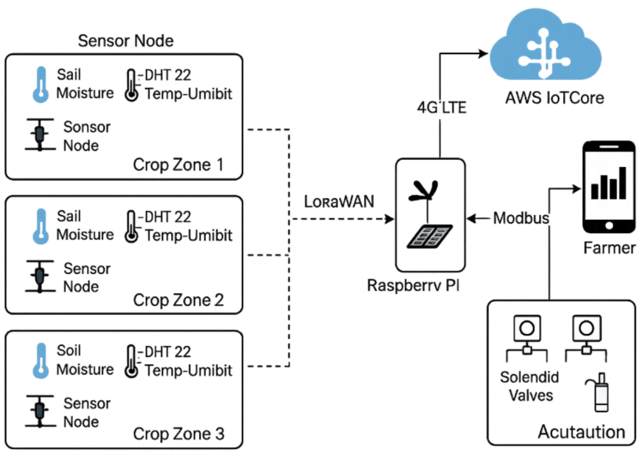

Fig. 6. Experimental setup of the IoT-based irrigation system showing sensor node deployment in three crop zones, LoRaWAN communication to the Raspberry Pi gateway, AWS IoT Core cloud integration, and Modbus-controlled actuation system.

Results and Discussion

The proposed IoT based framework of irrigation control and monitoring was found to save a great deal of water by comparing it to the traditional manual scheduling of the irrigation control. With the three-month observation time, the system was saving 35% of water on average, which was explained by the real-time limits and predictive SO moisture use and evapotranspiration schedule use. This meant that water could only be applied when moisture content of the soil is reduced to the optimum level relevant to the type of crop under cultivation and it avoided over- watering and also reduced wastage of water as a result of surface runoff, and deep percolation. Moreover, the zoning-based control also enabled the possibility of precise irrigation of selected spots other than blanket watering thus enhancing the effectiveness of water utilisation. When compared to manually programmed irrigation schedules, it was found that the proposed system kept crops healthy and yield befitting yet decreasing the total amount of water used, an aspect that makes its use practical in the sustainable use of water in farm environments with limited water resources.

Moreover, the system displayed an extremely high energy efficiency besides being a water conservation system; this was because the solar-powered sensing nodes and gateway units were implemented. Photovoltaic power backed with battery also allowed the continuous operation subject to up to six months without maintenance intervention even when there was fluctuating weather. The independence that comes with this is especially useful to remote farms that do not have consistent access to the grid. In addition, the choice of low-power communication, LoRaWAN as a data acquisition protocol and the lightweight MQTT over cloud interactions reduced the overall energy footprint of the system Figure 7. The autonomous nature of such nodes also leads to a decrease in the total operational costs besides being compatible with the goal of the world towards greener IoT deployments wherein energy harvesting is becoming more favoured to promote environmental sustainability.

Considering the communication performance aspect, the system under consideration managed to perform

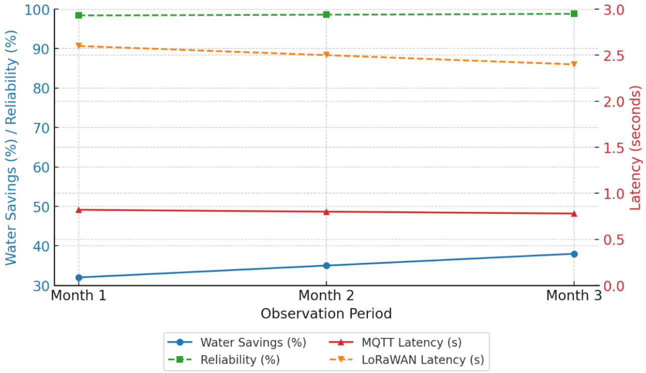

Fig. 7: Performance Metrics of the Proposed IoT-Based Irrigation System over a Three-Month Field Deployment

with low-latency and high-reliability that is essential in precision irrigation. US trials of the MQTT demonstrated an average time of execution by MQTT commands of 0.8 second duration, making the process of manual overriding or cloud-generated irrigation schedules a near real-time operating process. The data transmitting time of LoRaWAN-based sensor to the gateway is 2.5 sec on average, thus, fitting well into the scope required by an agricultural surveillance application, which does not obligate millisecond-level updates. Research on reliability demonstrated that an average packet delivery rate was 98.6% throughout the crop areas with only a few of these losses being demonstrated during transient cellular network interruptions in the gateway. Both the buffering of data processing at gateway plus LoRaWAN retry activation greatly reduced the effect of any disruption Table 2. On the whole, these findings confirm that the suggested multi-protocol IoT solution is capable of not only benefiting the functionality aspects of the smart irrigation system but also providing the efficiency, responsiveness, and robustness required to implement the solution in a real-world environment characterized by the broad diversity of agricultural use cases.

Table 2.Performance metrics of the proposed IoT-based irrigation system over a three-month field deployment.

Metric	Value	Remarks
Average Water Savings	35% reduction vs. manual scheduling	Achieved using real-time soil moisture data and evapotranspiration-based scheduling
Operational Autonomy	Up to 6 months (solar-powered nodes)	Battery + photovoltaic system enabling maintenance-free operation
MQTT Command Latency	0.8 seconds	Enables near real-time actuation of irrigation valves
LoRaWAN Data Latency	2.5 seconds	Within acceptable range for agricultural monitoring applications
Packet Delivery Reliability	98.6%	Minor losses due to transient network disruptions; mitigated with buffering and retries

Conclusion

The case study in this paper shows how an IoT-enabled agricultural Irrigation system was successfully designed, deployed and evaluated which has the ability to automate several automation protocols such as MQTT, LoRaWAN and Modbus TCP/IP to allow remote control, real-time monitoring and optimised management of water. Using long distance, low power sensing, a low latency cloud network and industrial grade actuator control the system provides several solutions to the key challenges of precision irrigation namely, resource preservation, scale of operation and adaption to legacy infrastructure. The field testing carried out through 3 months on a 5-acre farm allowed proving the system capable of reducing water use on average by 35% as compared to manual irrigation schedule without causing adverse effects on the crop growth and quality. Durability Incorporation of sensor nodes with solar power and gateway device enabled sustainable use (low maintenance) with no effect to the environment over a long period of time adding on to cost-effectiveness. The substantial packet delivery reliability (98.6 percent) and command execution time (below one second) under the MQTT protocol confirmed the quality and quickness of the communication framework to be used in the real environment. These findings underscore the fact that due to the modular nature of the system, it can be adopted in different agriculture settings including in smallholdings and large-scale farm practices. Subsequent improvements will be made to address the integration of predictive irrigation models powered by AI in an adaptive decision-making framework, blockchain-powered transaction logging that will digitally guarantee secure and transparent operation, and edge AI to allow autonomous operation in places with intermittent or no internet connection prolonging the applicability and robustness of the proposed solution.

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