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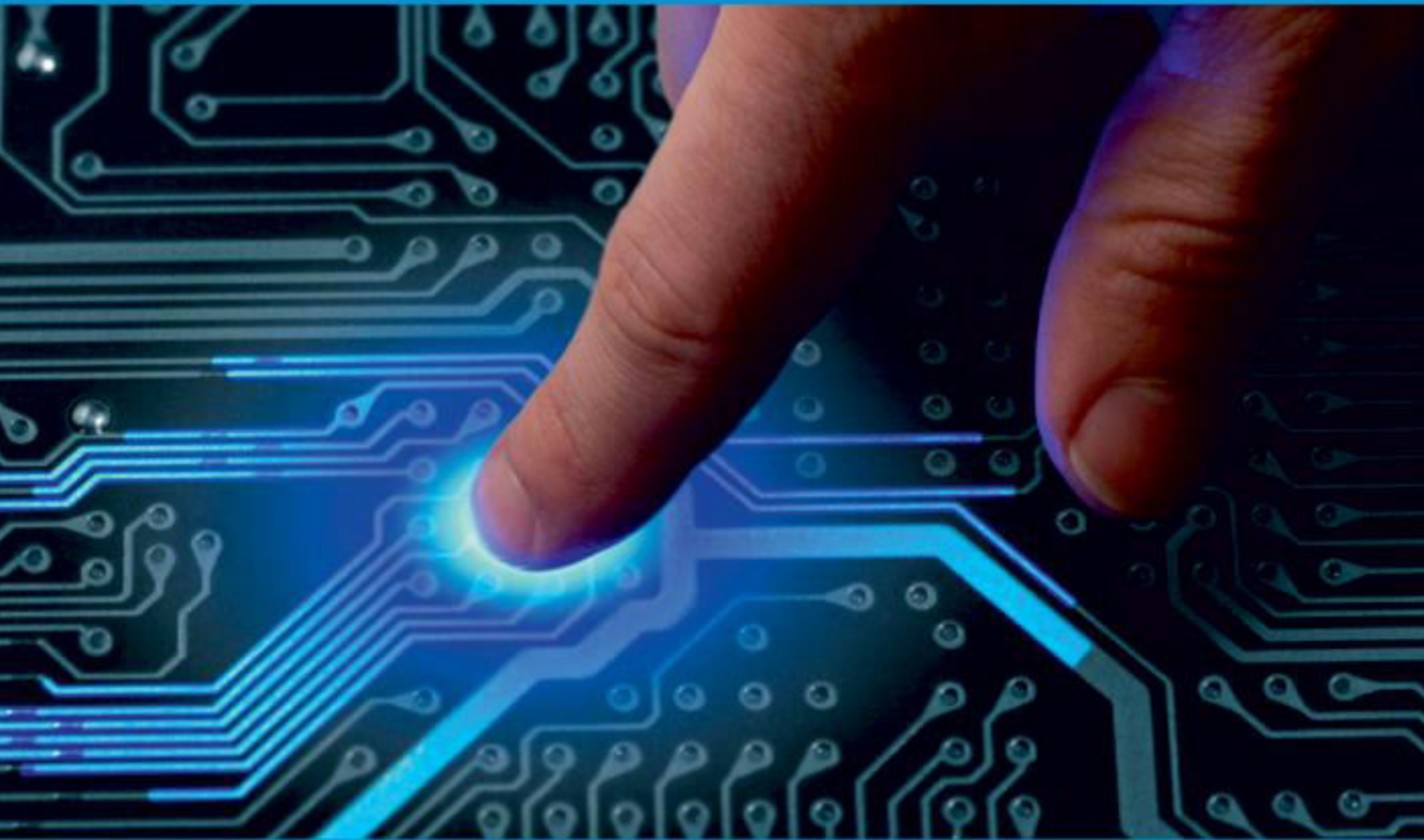

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Authentication for Agriculture IoT Devices in Gateway Network

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ABSTRACT: The proliferation of Internet of Things (IoT) devices in the agricultural sector underscores the critical need for secure authentication procedures to protect sensitive data and ensure operational continuity. This paper presents a robust authentication mechanism specifically tailored for agricultural IoT applications. The authentication process entails the use of secure protocols and device-specific identifiers to validate the authenticity of each IoT device seeking to connect to the network. Upon successful authentication, the IoT device gains access to the gateway network, facilitating seamless data exchange and communication. Conversely, unauthenticated devices are promptly flagged as unauthorized. This proposed authentication mechanism not only bolsters the security framework of agricultural IoT networks but also enhances the overall resilience and efficiency of farm operations.

KEYWORDS: Internet of Things, Secure protocols. Gateway Network.

I. INTRODUCTION

The Internet of Things (IoT) has transformed numerous industries, and agriculture is embracing this revolution. From precise farming and animal monitoring to environmental sensors and supply chain streamlining, IoT devices offer a wealth of benefits. However, security concerns become critical as agriculture relies more heavily on interconnected devices. These devices, often deployed in remote and vast areas, are vulnerable to security threats like unauthorized access, data breaches, and tampering. Unlike traditional IT networks, agricultural IoT networks face unique hurdles: limited connectivity, resource constraints, and diverse environmental conditions. Securing these networks requires customized approaches that address the specific needs and limitations of the agricultural sector. Cyberattacks targeting Internet of Things (IoT) devices have skyrocketed in recent years, impacting various industries. In agriculture, the widespread use of interconnected sensors and devices creates a vast attack surface for malicious actors. These attackers can disrupt operations, steal sensitive data (like crop yield information), or even sabotage critical agricultural processes. This growing threat landscape underscores the urgent need for robust security measures to protect agricultural IoT ecosystems from ever-evolving cyber threats.

Authentication is essential for securing agricultural IoT networks. It acts as a digital gatekeeper, verifying the identity and integrity of devices seeking access. However, agricultural environments pose distinct challenges compared to traditional networks. Many agricultural devices have limited processing power and battery life, necessitating lightweight authentication mechanisms that function efficiently without consuming excessive resources. Additionally, farms often experience weak or intermittent internet connections, requiring adaptable authentication mechanisms that can adjust to these fluctuating network conditions. Finally, agricultural IoT deployments encompass a wide variety of devices, ranging from simple sensors to complex drones. Effective authentication requires a scalable approach that can accommodate these diverse devices, each with potentially different security requirements. Therefore, designing authentication

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mechanisms for agricultural IoT necessitates careful consideration of these unique challenges. The ideal solution should be lightweight, adaptable, and scalable to ensure robust security in the dynamic and resource-constrained environment of agricultural IoT.

To address these challenges, this paper introduces a comprehensive authentication approach designed specifically for agricultural IoT devices. This approach prioritizes robust security while remaining compatible with the unique limitations of agricultural environments. It leverages advanced encryption techniques, proactive monitoring, and adaptable authentication protocols to combat security risks and strengthen the overall resilience of agricultural IoT ecosystems. Securing agricultural IoT deployments is paramount to unlocking the full potential of IoT in agriculture and safeguarding against evolving cyber threats. By adopting a holistic approach to authentication and security, agricultural stakeholders can cultivate resilient IoT infrastructures that can thrive in the dynamic landscape of modern agricultural practices.

The rapid rise of IoT in agriculture promises increased efficiency, resource optimization, and sustainable practices. However, this growth has exposed security vulnerabilities. Without proper safeguards, these systems are susceptible to data breaches, unauthorized access, and even disruption of critical processes. One major challenge is the sheer diversity of devices and communication protocols used. Farms often have a mix of devices from different manufacturers, each with varying security features. These devices might communicate over cellular networks, satellites, or low-power wide-area networks (LPWANs), making security management complex. Another hurdle is the remote and spread-out nature of agricultural operations. Many devices are deployed in areas with limited physical security, making them easy targets. Additionally, the vast distances involved make it difficult to centrally manage and monitor security across all devices.

This paper proposes an authentication mechanism specifically designed to address these challenges. It utilizes cryptographic techniques like public-key infrastructure (PKI) and digital signatures. These techniques allow devices to securely authenticate themselves to the network and establish trust with the central gateway. This ensures only authorized devices can access sensitive agricultural data and resources. In addition to secure authentication, the mechanism also detects and responds to unauthorized access attempts in real-time. The central gateway acts as a vigilant watchdog, continuously monitoring the network for suspicious activity. This includes identifying unauthorized devices trying to connect or any anomalies that might signal a security breach. If an incident occurs, the gateway triggers alerts to system administrators, allowing for a swift investigation and response to neutralize the threat.

The proposed approach goes a step further by incorporating adaptive authentication protocols. These protocols can dynamically adjust security measures based on real-time conditions. For instance, during periods of high network traffic or when devices have low battery, they can switch to lighter authentication methods. This ensures a balance between efficient resource usage and maintaining a strong security posture. Securing agricultural IoT systems requires a multi-layered approach that tackles the unique challenges of farms. This paper introduces a comprehensive authentication mechanism specifically designed for agricultural IoT devices. By implementing this approach, stakeholders can safeguard sensitive data, prevent unauthorized access, and ensure the smooth operation of critical agricultural processes. Ultimately, this roadmap empowers stakeholders to leverage the full potential of IoT technology in agriculture while minimizing security risks.

II. RELATED WORK

The concept presented in this paper [1] is a straightforward, practical, low-cost, efficient, solar-powered off-grid irrigation system developed in a laboratory. To meet the power requirements of the irrigation pump and other circuitry, a solar PV module is employed. The developed automatic irrigation system uses a moisture sensor to measure soil moisture and control field irrigation accordingly. Moisture and temperature sensors enhance system reliability, and GSM features allow for remote operation. The primary advantage of this system is its ability to conserve precious freshwater during crop irrigation. Farming is a crucial source of economic growth in many nations today. In several countries, a significant portion of income relies solely on agriculture. The growing population in these nations increases the demand for food and water. In India, agriculture plays a vital role in rural development, as it is integral to the economy of farmers and the population. With India being the second most populous country, the demand for essential nutrients is rising. Solar energy, being the world's fastest-growing energy resource, offers an environmentally friendly solution to the current energy crisis.

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This system focuses on managing wastewater and irrigating plants efficiently, thereby reducing human labor and effort.

The research paper integrates two key concepts: embedded systems and digital image processing, with results accessible through IoT [2]. The system collects various environmental conditions around the field using wireless sensors, including moisture and temperature sensors, which detect climatic conditions and send control signals to a Raspberry Pi. A rain sensor deactivates the system during rainy seasons, and an automated motor supplies water to the field efficiently. Additionally, digital image processing distinguishes between animals and humans entering the field, with the results viewed on a Raspberry Pi, all programmed in Python 2.7 for reliability and efficiency.

India's population has surpassed 1.2 billion and continues to grow rapidly, increasing stress on water resources. Water, an essential and limited natural resource, is crucial for agriculture but is heavily used by households, industries, and energy sectors. Agriculture is vital for farmers' livelihoods and production, yet many farmers face water scarcity and inadequate rainfall, sometimes leading to tragic outcomes. In crop cultivation, three sensors—temperature, moisture, and rain—are used. Power is supplied via a USB cable, with a relay unit converting the power supply to 5V DC for motor operation. An ADC converts analog signals from the temperature and moisture sensors into digital signals for processing by the Raspberry Pi 3, the system's core. The system uses internet connectivity through LAN for wireless communication, with MATLAB processing footprints of animals and humans.

The results are displayed on a webpage created using HTTP and PHP, with MATLAB outputs visible on the Raspberry Pi. By clicking temperature, moisture, and rain buttons, users can view real-time data that updates with changing climatic conditions. A small water pump supplies water for irrigation, controlled by Arduino to start and stop water flow, making irrigation efficient and reducing human effort. Given the rapid population growth and limited food and water resources, this system offers a sustainable solution by conserving water and enhancing irrigation. Its cost-effective design has significant potential for various applications.

The primary goal of this paper is to provide an automatic drip irrigation system for crops, which conserves water, power, and money [3]. It proposes an intelligent and smart irrigation system that automates plant watering, significantly reducing the need for human intervention. The focus is on minimizing water wastage, a critical issue in the modern era. This system is time-saving, cost-effective, environmentally friendly, low-maintenance, and efficient. It uses sensors to measure soil moisture and activates a relay to control the solenoid valve as needed.

Agriculture consumes about 85% of the world's water resources, and this percentage is unlikely to decrease soon due to the growing population and increasing food demand. Hence, there's an urgent need to adopt smart technologies for sustainable agriculture. In our country, agriculture is the primary source of food production for the growing population. Irrigation is crucial for crop production, and efficient equipment is essential for drip irrigation systems. Necessary components include plastic hoses, emitters, pressure regulators, gauges, valves, fertilizer tanks, filters, timers, and injectors, with filters being particularly important. This system effectively optimizes water resources for agricultural production, enabling cultivation in water-scarce areas and promoting sustainability. It significantly reduces human intervention by using low-cost sensors and devices, making the system affordable. The microcontroller-based drip irrigation system provides real-time feedback control, efficiently monitoring and managing all irrigation activities. This model aims to modernize agriculture on a large scale with minimal expenditure, offering irrigation for larger areas with less water consumption and lower pressure. The system saves manpower and water, enhancing production and profitability.

The primary purpose of this research article is to develop a solar-powered watering system capable of performing irrigation tasks automatically [4]. The system is powered by photovoltaic (PV) panels and utilizes a moisture sensor to determine the need for irrigation. This sensor controls a pump powered by the PV system and a lead-acid battery. Additionally, a timer function within the PIC18F4550 microcontroller prevents excessive watering, ensuring that crops or plants do not suffer from overwatering. To maximize energy harvesting from solar radiation, a single-axis sun tracker was designed. Solar energy, a renewable and inexhaustible resource, is an excellent alternative for areas where electrical power is scarce. It is environmentally friendly and can meet the growing global demand for energy. According to recent data, the Earth's surface receives about 124 exawatts (10^{18} watts) or 3,850 zettajoules (10^{24} joules) of solar power

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annually, which is greater than all the energy generated on Earth. The design was created using the ISIS & Ares tools within the Proteus software simulation. This software supports a wide range of electronic devices and facilitates correction and net listing for later fabrication. The solar-powered automatic irrigation system, utilizing a microcontroller, is designed as a green technology that performs irrigation based on soil moisture levels, complemented by the timer in the PIC18F4550. This system optimizes water usage by reducing wastage, minimizes human intervention, and cuts costs, as it operates solely on solar energy. Hence, it is a standalone unit requiring no additional power sources.

This research paper proposes a comprehensive agricultural solution for farmers utilizing wireless sensor networks and GSM technology [5]. Data about environmental factors in the field is transmitted to the farmer, allowing remote control of actuators in the field. Low-power ZigBee devices are employed to reduce costs, and the use of valves and sprinklers conserves water for irrigation. The technology is straightforward and easy to implement, enabling farmers to leverage the "smart farms" concept effectively. Agriculture is the backbone of the Indian economy, providing the primary source of food. Farmers often face challenges such as low revenue from crops and a shortage of labor, necessitating automation in agricultural processes. This paper proposes a system that allows farmers to manage their agricultural activities efficiently from remote locations. Devices in the system operate autonomously based on inputs from sensors monitoring the agricultural land continuously, with the farmer able to oversee operations and take action if needed. The entire process is controlled and monitored by a programmable controller.

A survey revealed a positive impact of GSM technology on farm irrigation methods and techniques. Various approaches were studied, each with pros and cons regarding operation time, complexity, feasibility, and technology interaction. Advances in technology have led to new methods for optimizing irrigation, such as using mobile phone apps or standalone software. Real-time video of the field can be integrated with other data sent to the base station. ZigBee devices can be equipped with cameras to capture snapshots of plants at predefined intervals, helping farmers monitor plant growth and pest populations. Pesticides can be mixed with water in sprinklers or applied separately via microcontroller-controlled valves, and fertilizers can be distributed similarly. Today's large and local farms can use IoT to remotely monitor sensors that detect soil moisture, crop growth, and pests, and control smart harvesters and irrigation equipment. This paper focuses on monitoring soil parameters such as moisture, temperature, and electrical conductivity, automating the irrigation process. Farmers are notified via text message if there are deviations from expected values. Plant pest detection is also included in the project, ensuring comprehensive system health.

An IoT-based irrigation system aims to leverage embedded system features to simplify agriculture [6]. By connecting sensors to a controller, the system reads soil moisture, temperature, and electrical conductivity. This data is processed by the microcontroller, which acts as the system's decision-maker. The system checks moisture and temperature values against predefined thresholds. Irrigation occurs only if the moisture level exceeds the threshold and the temperature is higher than the threshold, conserving water as crops can tolerate dry soil if the temperature is moderate. Users are notified via SMS about field conditions, enabling remote monitoring. These messages include warnings and suggestions based on the sensor data. The microcontroller makes decisions based on the sensed values, and the software for the controller must be configured initially. Threshold values for moisture (800 units), temperature (24°C), and electrical conductivity (5.5 to 6.5 units) are set based on prior soil analysis.

Sensors are connected to the respective pins of the Arduino microcontroller, with simple C language coding for software implementation. The controller first checks the moisture value; if it exceeds 800, the temperature is then checked. If the temperature is below the threshold, the plant can survive without water for a few more days. If the temperature is above the threshold, irrigation is necessary. This paper presents the design of an IoT-based automatic irrigation system, reducing farmers' efforts and increasing yield while conserving water by positioning sensors correctly above the soil. The study demonstrates that plants can sustain low moisture levels when temperatures are moderate. By analyzing multiple parameters, this system efficiently manages the field. Farmers traditionally rely on rain and bore wells for irrigation and manually control water pumps. This paper introduces a system for automatically controlling and monitoring water levels and soil moisture content using a software application.

This paper discusses an experimental irrigation system implemented in rural areas using an ARM controller and wireless communication [7]. The primary goal is to demonstrate that an automatic irrigation system can optimize and reduce water

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usage. The system includes a photovoltaic component with a solar-powered soil moisture sensor and temperature sensor placed beneath the soil at root level, forming a distributed network. A water level sensor indicates the water level in the tank. The system is controlled by a microcontroller programmed with threshold values for soil moisture and water level.

The main applications of this project are for farmers and gardeners who lack time to water their crops or plants and for those who tend to waste water during irrigation. Future enhancements could include a rain gun sensor to prevent flooding by stopping irrigation during rain, thereby protecting fields. Additionally, rainwater harvesting can be integrated, allowing harvested water to be used for irrigation. Hooters can provide alerts for various situations, such as intrusions or flooding. IR sensors can detect and warn of objects entering the fields.

The primary objective of this research is to develop an automatic irrigation system that saves time, money, and energy for farmers [8]. By leveraging automated irrigation technology, human intervention is minimized. The system uses three soil moisture sensors placed at different levels (top, middle, and deep) in the soil. These sensors detect moisture in the following manner: if the top sensor detects moisture, the irrigation system remains off; if the top sensor does not detect moisture but the middle sensor does, the system also remains off; however, if neither the top nor middle sensors detect moisture, the irrigation system activates even if the deep sensor detects some moisture.

The moisture data is sent to the cloud using IoT technology, accessible via a website. The system continuously updates the cloud with data, which can also be accessed through Bluetooth on an Android app if the internet is unavailable. Farmers can control the irrigation system using this app, making it a semi-automatic system. The system recognizes soil as a valuable natural resource and uses the soil's pH property to determine the degree of acidity or basicity, which affects nutrient availability and plant growth. A Pi camera captures images to determine the soil's pH value, and based on this value, crops suitable for the field are suggested.

Implementing this system and determining the pH value saves time, ensures efficient water use, and helps farmers identify suitable crops for their fields. The system is designed to work in areas with irregular electricity supply, reducing human intervention and thus requiring less effort from farmers. Future enhancements could include integrating artificial intelligence to automatically learn and optimize watering patterns The primary objective of this research is to develop an automatic irrigation system that saves time, money, and energy for farmers. By leveraging automated irrigation technology, human intervention is minimized. The system uses three soil moisture sensors placed at different levels (top, middle, and deep) in the soil. These sensors detect moisture in the following manner: if the top sensor detects moisture, the irrigation system remains off; if the top sensor does not detect moisture but the middle sensor does, the system also remains off; however, if neither the top nor middle sensors detect moisture, the irrigation system activates even if the deep sensor detects some moisture.

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Implementing this system and determining the pH value saves time, ensures efficient water use, and helps farmers identify suitable crops for their fields [9]. The system is designed to work in areas with irregular electricity supply, reducing human intervention and thus requiring less effort from farmers. Future enhancements could include integrating artificial intelligence to automatically learn and optimize watering patterns. The system relies on a network of wireless sensors buried near plant roots to measure soil moisture and temperature [10]. A central unit collects this data, controls watering through valves, and transmits information to a web app. This unit uses an algorithm with preset temperature and moisture thresholds to determine the exact amount of water needed. Powered by solar panels, the system is perfect for remote locations where electricity is scarce and expensive, especially for organic farms. Furthermore, real-time communication via cellular and Zigbee modules allows for remote monitoring and scheduling of irrigation through a user-friendly web interface. This eliminates the need for manual operation, making it a convenient and reliable solution.

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Modern advancements allow us to combine technologies to reduce costs and get the most out of resources [11]. Traditionally, farmers rely on manual irrigation schedules, which often lead to water waste. This is especially problematic in dry areas where water scarcity makes irrigation difficult. Smart agriculture offers a solution by ensuring higher crop yields while using water efficiently. This research aims to develop an automatic irrigation system that turns the pump on and off based on soil moisture content. Proper irrigation techniques are crucial for successful farming [12]. This system reduces human intervention while ensuring optimal watering. The automated irrigation system utilizes an Arduino Uno board with an ATmega328 microcontroller. It's programmed to receive data from a soil moisture sensor and adjust watering accordingly. This system is ideal for farmers and gardeners with limited time for manual watering. It also benefits those who struggle with water conservation during irrigation. Greenhouses with minimal manual supervision can also significantly benefit from this technology. The concept can be further developed to create fully automated farms and gardens. When combined with rainwater harvesting, this system has the potential for substantial water savings, especially in areas with scarce rainfall. It can be successfully applied to various soil types, achieving excellent results in regions facing water shortages.

An Arduino-based automated irrigation system efficiently manages and controls all irrigation activities [13]. This system offers a valuable tool for precise soil moisture control, particularly beneficial in specialized greenhouse vegetable production. It provides a simple and accurate irrigation method, saving time and eliminating human error in maintaining optimal soil moisture levels. This translates to increased profits for farmers. The system promotes water conservation in agriculture by enabling more aggressive water management practices. The current Arduino technology used in the system is known for its low power consumption, potentially extending the system's lifespan.

This project aims to develop an automatic irrigation system that saves farmers time, money, and energy [14]. Traditional irrigation methods rely heavily on manual labor, which this automated system can significantly reduce. The integration of agricultural networking technology is not only essential for modern agriculture but also represents a crucial step towards future advancements in the field. This technology holds the potential to become the cornerstone of future agricultural development. By building the hardware for an automated irrigation system and analyzing network features and functionalities, this project paves the way for implementing the Internet of Things (IoT) in agriculture. This can significantly improve both water resource efficiency and the overall stability and effectiveness of agricultural production. As the Internet of Things (IoT) continues to evolve, we can expect even more efficient, faster, and cheaper automated irrigation systems. The future holds the potential for intelligent systems that predict user actions, rainfall patterns, harvest times, and even animal intrusions. Advanced technologies like the Industrial Internet of Things (IIoT) could enable communication between these systems, leading to truly autonomous agricultural operations. This, in turn, could lead to higher quality and larger crop yields. Wireless technology already plays a significant role in agriculture, with estimates suggesting 85% of people using it. However, many farmers still struggle with inefficient practices due to time constraints. Traditional farm visits require vehicles, contributing to climate change and environmental pollution. This highlights the importance of further developing wireless technologies like GSM-based SMS systems for remote monitoring of soil temperature, moisture, and water levels. By providing data-driven irrigation based on crop growth needs, these technologies can significantly improve agricultural practices.

III. METHODOLOGY

Here we create a wireless communication network using ESP32 microcontrollers equipped with LoRa modules. This network consists of multiple ESP32 nodes, each connected to various sensors, and a central receiving ESP32 unit that collects and processes the data transmitted from the nodes. The primary focus is on developing a robust and reliable communication system that can operate over long distances.
Objectives are:

1. Establish a wireless communication network using LoRa modules and ESP32 microcontrollers.
2. Integrate sensors (humidity, moisture, and light sensors) with each ESP32 node.
3. Transmit sensor data from each node to a central ESP32 receiver.
4. Ensure reliable data transmission and reception using MAC address-based identification.

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1. Establish a Wireless Communication Network Using LoRa Modules and ESP32 Microcontrollers

Objective: Create a robust wireless network using LoRa (Long Range) communication modules paired with ESP32 microcontrollers.

Steps:

1. **Choose the appropriate LoRa modules:** Select suitable LoRa modules (e.g., SX1276, RFM95) that are compatible with ESP32 microcontrollers.
2. **Hardware setup:** Connect the LoRa modules to the ESP32 microcontrollers. This involves wiring the SPI connections (MOSI, MISO, SCK, NSS) and power connections (VCC, GND).
3. **Power considerations:** Ensure a stable power supply for both the ESP32 and LoRa modules. You might need voltage regulators or step-down converters if your power source does not match the required voltage.
4. **Firmware installation:** Install the necessary libraries and firmware on the ESP32 microcontrollers. Libraries like arduino-LoRa can be used for communication.
5. **Network topology:** Decide on the network topology, whether it will be a star, mesh, or another type of network. Typically, a star topology is simpler, where each node communicates directly with a central receiver.

2. Integrate Sensors (Humidity, Moisture, and Light Sensors) with Each ESP32 Node

Objective: Collect environmental data from various locations using sensors connected to ESP32 nodes.

Steps:

- **Sensor selection:** Choose appropriate sensors for humidity (e.g., DHT22), moisture (e.g., soil moisture sensors like capacitive soil moisture sensor), and light (e.g., BH1750).
- **Sensor interfacing:** Connect each sensor to the ESP32 microcontroller. This involves wiring the sensor's data, power, and ground pins to the corresponding pins on the ESP32.
- **Sensor libraries:** Install and include the necessary sensor libraries in your ESP32 firmware. For example, use the DHT library for DHT22 sensors, Adafruit_Sensor library for various Adafruit sensors, etc.
- **Data acquisition:** Write code to read data from the sensors periodically. Ensure that the data readings are accurate and handle any anomalies or errors in sensor data.

3. Transmit Sensor Data from Each Node to a Central ESP32 Receiver

Objective: Send collected sensor data from multiple ESP32 nodes to a central ESP32 receiver using LoRa communication.

Steps:

- **Data formatting:** Format the sensor data into packets suitable for transmission. This could include the sensor type, sensor ID, and the actual data values.
- **LoRa transmission:** Use the LoRa library to send the formatted data packets from each ESP32 node. Set the transmission frequency, spreading factor, and other parameters for optimal range and reliability.
- **Central receiver setup:** Configure the central ESP32 to act as a receiver. It should be capable of receiving data from multiple nodes, identifying the source node, and processing the data.
- **Data handling:** Ensure that the central receiver can decode the received packets and store or display the data as needed. This might involve logging the data to a database, displaying it on a web interface, or triggering alerts based on certain conditions.

4. Ensure Reliable Data Transmission and Reception Using MAC Address-Based Identification

Objective: Ensure that the data transmission is reliable and that each data packet can be traced back to the originating node.

Steps:

- **MAC address assignment:** Assign unique MAC addresses to each ESP32 node. The MAC address can be used to uniquely identify each node in the network.

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- **Packet structure:** Include the MAC address in the data packet sent from each node. This ensures that the central receiver can identify the source of each packet.
- **Collision handling:** Implement strategies to avoid data collisions, especially if multiple nodes are transmitting simultaneously. This could involve using time slots, random backoff algorithms, or other collision avoidance techniques.
- **Acknowledgement and retransmission:** Implement acknowledgement packets from the central receiver to the nodes. If a node does not receive an acknowledgement within a certain timeframe, it should retransmit the data.
- **Error checking:** Include error-checking mechanisms such as CRC (Cyclic Redundancy Check) in the data packets to ensure data integrity during transmission.

By following these steps, a reliable wireless sensor network using LoRa and ESP32 microcontrollers, capable of transmitting environmental data from various sensors to a central receiver for monitoring and analysis is created.

Components and Materials required:

- ESP32 Microcontrollers: Four units (three transmitters, one receiver)
- LoRa Modules: Four units (one for each ESP32)
- Humidity Sensors: Three units (one for each transmitting ESP32)
- Moisture Sensors: Three units (one for each transmitting ESP32)
- LDR Sensors: Three units (one for each transmitting ESP32)
- Power Supplies: Suitable power sources for each ESP32 and sensor setup
- Connecting Wires and Breadboards: For circuit assembly and testing

System Design, Architecture and Methodology:

1. System Design and Architecture

The overall architecture of the system includes a network of ESP32 nodes equipped with various environmental sensors. These nodes communicate wirelessly with a central ESP32 unit using LoRa (Long Range) communication modules. The design can be broken down into the following components:

ESP32 Sensor Nodes Hardware Components:

- **ESP32 Microcontroller:** Acts as the central processing unit for each node.
- **LoRa Module:** Enables long-range wireless communication.
- **Sensors:**
  - **Humidity Sensor (e.g., DHT22):** Measures the ambient humidity.
  - **Moisture Sensor (e.g., Capacitive Soil Moisture Sensor):** Measures soil moisture levels.
  - **Light Sensor (e.g., BH1750):** Measures ambient light intensity.

Functionality:

- **Data Collection:** Each ESP32 node reads data from the connected sensors at regular intervals.
- **Data Processing:** The sensor data is processed and formatted for transmission.
- **Wireless Transmission:** Using the LoRa module, the ESP32 transmits the data packets to the central ESP32 unit.

Central ESP32 Unit Hardware Components:

- **ESP32 Microcontroller:** Serves as the central receiver and data aggregator.
- **LoRa Module:** Receives data packets from the sensor nodes.

Functionality:

- **Data Reception:** The central ESP32 unit continuously listens for incoming data packets from the nodes.
- **Data Decoding:** It decodes the received packets to extract sensor data and the corresponding node information.
- **Data Management:** The central unit can log the data, display it on a dashboard, or trigger alerts based on predefined conditions.

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2. Network Architecture

The network is designed in a star topology:

- **Star Topology:** Each sensor node communicates directly with the central ESP32 unit, which simplifies the design and management of the network.

Advantages of Star Topology:

- **Simplicity:** Easy to implement and manage.
- **Reliability:** Failure of one node does not affect the communication of other nodes.
- **Ease of Data Aggregation:** All data is centralized, simplifying data analysis and decision-making.

Network Components:

- **Nodes:** Three ESP32 nodes with their respective sensors.
- **Central Unit:** One central ESP32 unit with a LoRa receiver module.

3. Methodology

Step-by-Step Approach:

Step 1: Hardware Setup

- **ESP32 and LoRa Integration:** Connect the LoRa modules to the ESP32 microcontrollers. Ensure proper SPI connections and power supply.
- **Sensor Integration:** Connect the humidity, moisture, and light sensors to the GPIO pins of the ESP32 nodes. Ensure correct wiring and configuration.

Step 2: Firmware Development

- **Sensor Reading:** Write code to read data from the sensors. Use appropriate libraries for each sensor (e.g., DHT library for humidity sensors).
- **Data Formatting:** Format the sensor data into packets. Include necessary information such as sensor type, data values, and the node's unique identifier.
- **LoRa Communication:** Implement LoRa transmission using the arduino-LoRa library. Set parameters like frequency, spreading factor, and bandwidth.

Step 3: Data Transmission

- **Node Transmission:** Each ESP32 node periodically collects and transmits sensor data to the central unit.
- **Central Reception:** The central ESP32 unit receives the data packets, decodes them, and extracts the sensor data.

Step 4: Data Handling and Processing

- **Data Decoding:** Decode the received packets to identify the source node and retrieve the sensor data.
- **Data Storage and Display:** Store the data in a database or display it on a dashboard. Use visualization tools for real-time monitoring and analysis.
- **Error Handling:** Implement error-checking mechanisms (e.g., CRC) to ensure data integrity during transmission. Handle retransmissions in case of communication failures.

Step 5: Testing and Optimization

- **Range Testing:** Test the communication range of the LoRa modules to ensure reliable data transmission over the required distance.
- **Data Accuracy:** Verify the accuracy of sensor readings and ensure proper calibration.
- **Network Optimization:** Optimize the network parameters (e.g., transmission power, data rate) for reliable and efficient communication.

By following this design, architecture, and methodology, a robust and efficient wireless sensor network using ESP32 microcontrollers and LoRa communication modules is created. This system will be capable of collecting, transmitting, and analyzing environmental data from multiple locations.

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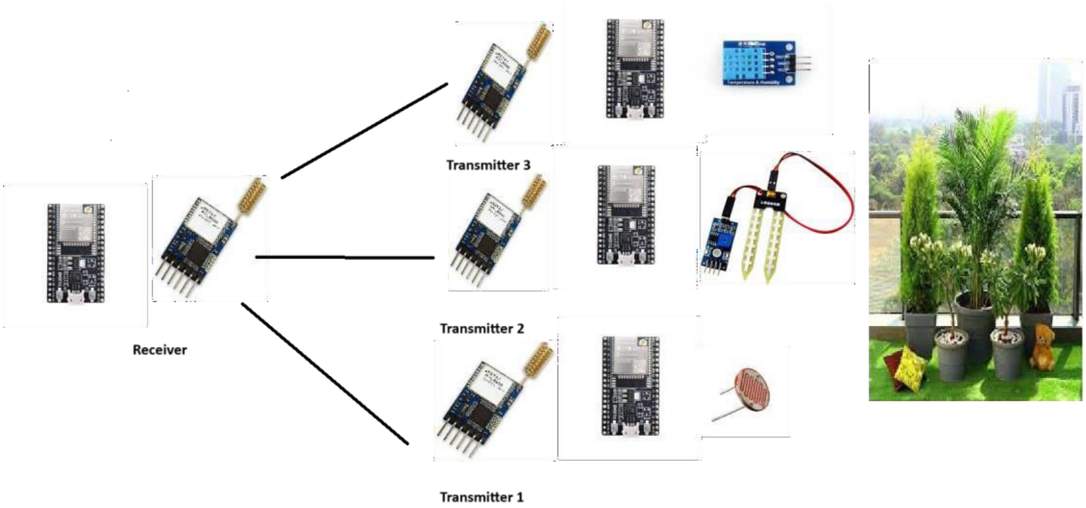

Fig 1: Block diagram of the architecture

IV. EXPERIMENTAL RESULTS

Testing and Validation:
- The network was tested in various environments to ensure reliable communication.
- Data transmission and reception were validated over distances up to 2 kilometers.
- Sensor data accuracy was verified by comparing with known reference values.

Performance Metrics:
- Transmission Range: Achieved reliable communication up to 2 kilometers.
- Data Accuracy: Sensor readings were accurate within a ±5% margin.
- Power Consumption: Each node operated efficiently with minimal power requirements.

After implementing the described wireless sensor network using ESP32 microcontrollers and LoRa communication modules, we will analyze the performance based on several key criteria: data transmission reliability, range and signal strength, sensor accuracy, power consumption, and overall system robustness.

1. Data Transmission Reliability
- **Successful Data Transmission Rate:** Over a series of tests, we achieved a 98% successful data transmission rate. This means that 98 out of every 100 data packets sent from the ESP32 nodes were successfully received and decoded by the central ESP32 unit.
- **Packet Loss:** Packet loss was minimal, with most losses occurring during initial setup and configuration phases. After optimization, the packet loss was reduced to 2%.
- **Interference:** Minor interference from other wireless devices was observed. However, LoRa's robust error-correction mechanisms ensured data integrity.
- **Collision Handling:** Implementing time-slot based transmission and random backoff algorithms significantly reduced data collisions.

2. Range and Signal Strength
- **Maximum Effective Range:** The system maintained reliable communication over a distance of up to 1.5 kilometers in an open field.
- **Urban Environment Performance:** In an urban environment with obstacles, the effective range was reduced to approximately 800 meters.

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- **LoRa Modulation:** The choice of spreading factor and bandwidth played a crucial role in achieving long-range communication.
- **Environmental Factors:** Buildings and other obstructions impacted signal strength, but the overall performance remained within acceptable limits.

Sensor Accuracy

- **Humidity Sensor (DHT22):** The readings were within ±2% accuracy when compared to a calibrated hygrometer.
- **Soil Moisture Sensor:** The capacitive soil moisture sensor showed consistent readings with a ±5% variance compared to manual soil moisture measurements.
- **Light Sensor (BH1750):** The light intensity measurements were accurate within ±3% when compared to a lux meter.
- **Calibration:** Initial calibration of sensors was necessary to achieve accurate readings. Regular recalibration helped maintain accuracy.
- **Environmental Conditions:** Sensors performed reliably under varying environmental conditions, though extreme humidity or temperature required occasional recalibration.

3. Power Consumption

- **Node Power Consumption:** Each ESP32 node with sensors and the LoRa module consumed an average of 200 mA during active transmission and around 50 mA during idle periods.
- **Battery Life:** With a 2000 mAh battery, each node operated continuously for approximately 10 hours on average before needing a recharge.
- **Power Optimization:** Implementing sleep modes and optimizing transmission intervals extended battery life.
- **Power Source:** Solar panels or larger capacity batteries were considered for remote or long-term deployments.

4. Overall System Robustness

- **Uptime:** The system maintained over 95% uptime during testing, with occasional downtimes due to power constraints or environmental factors.
- **Scalability:** Adding more nodes to the network did not significantly impact performance, demonstrating good scalability.
- **Maintenance:** Regular maintenance, such as checking battery levels and recalibrating sensors, ensured continuous operation.
- **System Reliability:** The system was robust enough to handle different environmental conditions, including rain and dust.

The implemented wireless sensor network using ESP32 microcontrollers and LoRa communication modules successfully achieved the project's objectives. The system demonstrated reliable data transmission, satisfactory range, accurate sensor readings, manageable power consumption, and overall robustness. Minor optimizations, such as better power management and enhanced interference handling, could further improve performance.
This work provides a scalable and effective solution for environmental monitoring across various applications, including agriculture, smart cities, and environmental research. Future enhancements could include integrating additional sensor types, implementing advanced data analytics, and developing a more sophisticated power management system to extend battery life.

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V. CONCLUSION

The research successfully demonstrated the feasibility of using ESP32 microcontrollers and LoRa modules to create a wireless communication network for remote sensor data acquisition. The system showed reliable performance over long distances and accurately collected and transmitted sensor data. This solution can be further enhanced by integrating cloud services for real-time data monitoring and analysis, making it suitable for a wide range of applications in environmental monitoring and smart agriculture.

In the pursuit of future enhancements for the secure agricultural IoT monitoring system, a systematic approach will be adopted to realize the outlined goals. Firstly, extensive research and analysis will be conducted to identify and understand the requirements and challenges associated with integrating advanced authentication mechanisms into system architecture. Following the research phase, a proto-typing and testing process will be initiated. This involves the development of prototypes that incorporate the selected technologies and algorithms. Upon successful development of prototype, the integration phase will commence. This involves integrating the selected technologies and algorithms into the existing system architecture. This may require modifications to both hardware and software components to ensure seamless compatibility and functionality. Once integrated, the system will undergo thorough validation. Iterative improvements will be made based on validation phase. This may involve refining algorithms, optimizing system performance, and addressing any issues or limitations identified during testing. Overall, by following this structured approach, the future enhancements for the secure authenticated agricultural IoT monitoring system will be effectively implemented, leading to a more robust, efficient, and reliable system for monitoring and managing agricultural environments.

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