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OFFLINE OVER THE AIR (OTA) UPDATE PROTOCOL FOR IOT DEVICES USING ESP-NOW FOR AGRICULTURE APPLICATION

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ABSTRACT

Using the ESP-NOW communication protocol, this project presents a unique method for simulating Over-the-Air (OTA) updates in a distributed sensor network based on ESP32 microcontrollers. The suggested ESP-NOW-based system functions independently of internet connectivity and access points, in contrast to conventional Wi-Fi OTA update systems that rely significantly on these elements. This makes it a low-power, effective, and scalable solution that is perfect for agricultural IoT installations. Five ESP32 nodes make up the system architecture, and each one is interfaced with sensors to gather environmental data pertinent to agricultural applications. One of these nodes has an OLED display that allows it to see live sensor data and update status in real time. Versioned messages that dynamically alter data logic are used to imitate firmware changes. A sturdy multi-hop ESP-NOW mesh is used to transmit these signals throughout the network, guaranteeing the timely and dependable distribution of updates throughout the dispersed sensor array. When compared to traditional Wi-Fi OTA techniques, this strategy dramatically improves performance parameters including update speed, energy economy, and communication range. In difficult agricultural settings, the system gains increased flexibility and dependability by doing away with dependence on external network infrastructure. The outcomes confirm that ESP-NOW is a viable and expandable OTA solution designed for smart agriculture IoT systems.

Keywords: Offline over The Air, Internet of Things, ESP32 Microcontroller, OLED, agricultural environment.

1. INTRODUCTION

The Internet of Things' (IoT) explosive growth has transformed several industries by allowing for improved automation, control, and monitoring through networked devices. Agriculture is one of these industries that stands to benefit greatly from IoT adoption. In order to facilitate data-driven decision-making, optimize resource use, and boost yields, smart agricultural systems use networks of sensors, actuators, and computer devices to gather data on ambient conditions, soil parameters, crop health, and equipment status. However, these deployed IoT devices' capacity to stay up to date with the newest firmware and software is crucial to their durability and efficacy.

An essential component of IoT device lifecycle management is over-the-air (OTA) upgrades. They make it possible to remotely distribute and install firmware upgrades to devices wirelessly and without the need for physical access. This feature is crucial in situations when hundreds or thousands of devices are spread out across wide areas in difficult-to-reach places, as is frequently the case in extensive agricultural operations. Therefore, throughout the device's operational life, implementing effective and dependable OTA update procedures is crucial for preserving device security, adding new features, resolving problems, and enhancing performance.

Conventional methods of OTA updates in Internet of Things systems usually include devices connecting to an access point and receiving updates from a cloud server, and thus frequently depend on ordinary Wi-Fi infrastructure and internet connectivity. Although this strategy works well in places with strong network coverage, it poses serious problems in isolated or rural agricultural areas where dependable Wi-Fi and internet connectivity may be hard to come by, sporadic, or nonexistent. Moreover, battery-operated agricultural sensors intended for low power consumption and extended field life may find it difficult to establish and sustain a steady Wi-Fi connection for update downloads. In big, dispersed networks, reliance on central infrastructure also raises the possibility of single points of failure and scalability problems.

This research investigates a different OTA update strategy designed especially for the limitations and needs of agricultural IoT equipment. It explores the usage of the Espressif Systems-developed proprietary ESP-NOW protocol, which provides a peer-to-peer, encrypted, connectionless communication mechanism based on the 2.4 GHz Wi-Fi frequency. For device-to-device communication, ESP-NOW eliminates the requirement for an internet connection, access points, or a conventional Wi-Fi network architecture. It is a viable option for allowing reliable and scalable OTA updates in dispersed, infrastructure-less agricultural sensor networks because to its minimal overhead and power-efficient characteristics. To overcome the drawbacks of conventional Wi-Fi-based techniques in this demanding setting, the system intends to successfully distribute firmware updates over a field of sensors by utilizing ESP-NOW in a multi-hop network configuration.

1.1 Problem Statement

When used in distant and difficult conditions, like those seen in contemporary agriculture, traditional Over-the-Air (OTA) update techniques for Internet of Things (IoT) devices—which mostly rely on regular Wi-Fi connection and cloud-based infrastructure—face serious restrictions. These restrictions are mostly caused by:

1. Dependency on Reliable Infrastructure: For Wi-Fi-based OTA to download updates from a server, devices must be connected to an access point and have reliable internet connectivity. The updating procedure is hampered in agricultural fields since there is frequently unstable Wi-Fi coverage across large distances and internet access may be spotty or nonexistent.

2. High Power Consumption: It takes a lot of electricity to download huge firmware files and establish and maintain a normal Wi-Fi connection. This is harmful for agricultural sensors that run on batteries and are made to use as little electricity as possible in order to prolong field deployment times. Regular Wi-Fi OTA upgrades may significantly shorten battery life.

3. Scalability and Network Congestion: Managing separate Wi-Fi connections for every device to receive updates simultaneously in large-scale agricultural deployments with hundreds or thousands of sensors might strain available network resources and perhaps lead to congestion.

4. Single Point of Failure: A single point of failure may result from reliance on a central internet gateway and access point. The ability of the entire network to receive updates is jeopardized if the AP or internet connection fails.

5. Complexity in Decentralized Deployments: Implementing traditional infrastructure-based OTA is challenging or impracticable for dispersed agricultural systems, as devices may function in clusters or relatively isolated groups without a central, field-wide Wi-Fi network.

An alternate OTA update mechanism that is less reliant on outside infrastructure, more power-efficient, scalable for distributed networks, and dependable under the demanding circumstances of agricultural areas is desperately needed, as these problems demonstrate. Current low-power long-range technologies, like as LoRaWAN, may not be effective for sending firmware pictures, which are usually significantly bigger, because they are designed for short data packets. Thus, the lack of a reliable, infrastructure-independent, and power-efficient OTA update solution created especially for dispersed ESP32-based agricultural IoT sensor networks functioning in places with little to no Wi-Fi/internet infrastructure is the issue this study attempts to solve.

2. LITERATURE REVIEW

In several technology fields, such as mobile phones, automotive systems, and increasingly the Internet of Things (IoT), over-the-air (OTA) upgrades have become routine practice. In order to provide bug fixes, security patches, feature additions, and performance improvements without requiring physical access, OTA's main objective is to remotely update firmware or software on deployed devices. In early IoT deployments and embedded devices, traditional OTA techniques frequently depended on pre-existing communication infrastructures.

2.1 Review of Traditional OTA Update Methods

Using the current Wi-Fi infrastructure is one of the most popular traditional approaches for updating IoT devices. After connecting to a nearby Wi-Fi Access Point (AP), devices usually use common protocols like HTTP, HTTPS, or MQTT to download the firmware image from a distant server via the internet. Because Wi-Fi is ubiquitous in many settings and because server-side infrastructure and established internet protocols are readily available, this strategy is commonly used. for compared to some other wireless technologies, it provides a comparatively high bandwidth, which is advantageous for sending big firmware files. It draws attention to the system design, performance measures, and sensors that are employed [1].

It does, however, rely significantly on the existence of a dependable internet connection and a steady Wi-Fi network at the device's location. This infrastructure may not exist, be unstable, or be costly to install and maintain over a wide region in rural or isolated locations, such as agricultural fields. Furthermore, Wi-Fi is less appropriate for battery-operated devices with stringent energy budgets since it requires a lot of power to establish and maintain a connection and download large data. For dispersed sensors in the outdoors, the polling or persistent connection needed to download or check for updates can severely deplete batteries, requiring regular replacement or recharging.

Another conventional approach is to use cellular networks (2G, 3G, 4G, 5G, NB-IoT, LTE-M) for OTA updates, especially for devices spread across a large geographic region. This survey paper offers a thorough analysis of wireless OTA update strategies for Internet of Things devices, highlighting issues and approaches appropriate for systems with limited power and resources [1].

From the standpoint of the end-user, cellular networks are infrastructure-independent and offer wide coverage (relying on carrier infrastructure). They are therefore appropriate for gadgets in places without Wi-Fi. Large files may be sent by cellular OTA, and low-power IoT applications, such as checking for updates, are intended for technologies like NB-IoT and LTE-M. However, there are ongoing subscription fees associated with cellular connectivity, which may add up significantly for a large network of devices.

Even while LPWAN cellular variations have better power consumption, when sending large amounts of data, it can still be greater than other low-power local communication techniques. In really rural agricultural regions, coverage might still be patchy, and it becomes more complicated to manage a big fleet of devices connected over cellular for updates.

Short-range protocols like Bluetooth Low Energy (BLE) or wired Ethernet connections (which require physical ports and cabling, making them impracticable for distributed sensors) are other techniques that are less frequently referred to as "OTA" in the wireless sense but represent distant updates. Though its restricted bandwidth and range make it unsuitable for directly transmitting massive firmware updates across an enormous field network, BLE is extremely power-efficient and ideal for device provisioning or setup within a very small range (usually tens of meters). Although a gateway strategy is required, the update must still get to the gateway by Ethernet, Wi-Fi, or cellular, reverting to the previous infrastructure dependencies or expenses.

In conclusion, although traditional OTA techniques based on cellular and Wi-Fi are useful in many situations, they pose serious obstacles for extensive, dispersed agricultural IoT deployments because of their dependence on infrastructure, high power consumption during the update process (particularly Wi-Fi), and possible connectivity costs or restrictions in remote locations. This emphasizes the need for different strategies that are more appropriate for the unique limitations of this field.

2.2 Advancements in Wireless Firmware Updates

Research and industry have fueled a number of developments in wireless firmware update systems for devices with limited resources in order to overcome the drawbacks of conventional approaches. Enhancing efficiency, dependability, security, and scalability are the main goals of these developments.

The creation and use of delta or differential updates is one important area of progress. Only the changes (delta) between the new firmware image and the device's current version are computed and sent, rather than the complete new firmware image.

Offers an elegant web-based user interface for managing updates [2]. This drastically cuts down on the quantity of data sent over the wireless link, resulting in quicker updates, less bandwidth usage, and—most importantly—less power consumption because the radio must be on for shorter periods of time. In order to implement delta updates, the device must have a patching engine that can reconstruct the new firmware from the old version and the patch, as well as generate the delta patch offline. Although very effective for minor adjustments, this increases the device's processing and storage overhead, and patch management for several device versions can be challenging.

Significant advancements have also been made in safe and reliable updating procedures. Maintaining the integrity and authenticity of the update package is crucial since firmware changes have serious security ramifications. One example of such advancement is the need that firmware images be cryptographically signed using methods like Elliptic Curve Digital Signatures (ECDSA) or RSA. Devices use a trusted public key that is safely preserved, frequently via the use of hardware security modules or secure boot procedures, to validate this signature. Only firmware that has been cryptographically certified may be run thanks to secure boot. By putting these security mechanisms in place, dispersed IoT networks may be protected against fraudulent or unauthorized upgrades, which is a major worry. Implementing dependable rollback procedures to return to a previous working version in the event that the new firmware is defective, handling interrupted updates, and guaranteeing atomic updates—which keep a device from being rendered inoperable in the event that power is lost during flashing—are further components of robustness. Implementing such reliable and safe update processes is made easier by devices like the ESP32, which natively support dual OTA partitions and secure boot capabilities.

Notable are also developments in network topologies and protocols for updates. Newer approaches investigate decentralized models, whereas older methods are frequently client-server (device downloads from a central server). Mesh networking is very useful for using low-power devices to cover huge regions. Devices in a mesh can provide redundant pathways and increase the network's range by forwarding data, including update chunks, to their neighbors. Although they usually employ lower communication rates, protocols like Thread and Zigbee are based on mesh principles and can be sluggish for big systems. Examine it against related studies on athlete sensor platforms [1]. Optimizing the propagation speed, reducing redundant transmissions, and guaranteeing dependable delivery over several hops are the main goals of research into effective multi-hop dissemination algorithms for firmware updates in restricted wireless networks. Peer-to-peer communication technologies, such as ESP-NOW, being investigated as building blocks for creating mesh-like update propagation systems that do not rely on a central AP or router for forwarding.

Additionally, efforts are still being made to optimize the updating procedure itself. This entails employing effective data serialization formats, dynamically regulating network capacity, and scheduling updates for off-peak or energy-rich periods (such as throughout the day for solar-powered devices). Advanced OTA management systems additionally include methods for staggered updates to control network load or grouping devices for simultaneous upgrades.

These developments show a distinct trend toward increasing the effectiveness, security, and dependability of OTA updates, especially for devices with limited battery life and deployments in difficult network conditions. Important components of this progression include investigating decentralized or mesh-based distribution strategies and utilizing secure hardware characteristics.

3. DESIGN AND METHODOLOGY

This chapter describes the ESP-NOW protocol's thorough design and development process. The process includes the creation of an advanced ESP-NOW OTA Update system architecture. This chapter describes the OTA Algorithm and the ESP32 Initiator and Responder Configuration.

3.1 System Architecture of the ESP-NOW OTA Update

The Over-the-Air (OTA) update solution for agricultural IoT based on ESP-NOW was designed to overcome the drawbacks of conventional infrastructure-dependent techniques in demanding field settings. The system design is essentially distributed and uses the ESP-NOW protocol's peer-to-peer communication feature to make it easier for firmware updates to spread throughout an ESP32 node network. It incorporates necessary agricultural sensing and control features to give the OTA mechanism a realistic test environment.

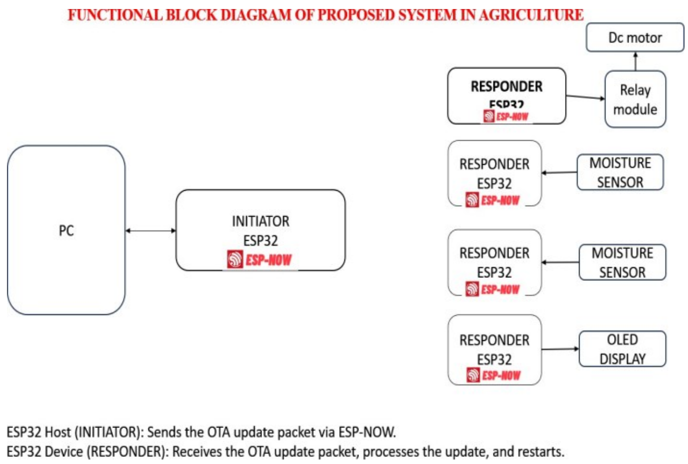


Fig 3.1(a): Functional Block Diagram of proposed system in Agriculture

4. Components description

- **Moisture Sensor:** An Analog-to-Digital Converter (ADC) enabled GPIO pin on the ESP32 (such as GPIO34 or GPIO35, which are usually ADC1 capable) is linked to the analog output pin of the soil moisture sensor. To guarantee that the sensor's output voltage range is compatible with the ESP32's ADC input voltage range (usually 0-3.3V for ADC1), proper voltage division or sensor type selection is required.

- **Relay Module:** A digital output GPIO pin on the ESP32 (such as GPIO16 or GPIO17) is linked to the relay module's control pin. The relay coil needs a certain voltage (for example, 5V or 12V, depending on the module) and current, which are normally supplied by an external transistor or driver integrated circuit that is managed by the 3.3V logic output of the ESP32. The DC motor's power source is switched by the relay connections.
- **DC Motor:** The relay module's connections are used to connect the DC motor to an external power source. To prevent voltage spikes when the motor is turned off, a flyback diode is connected in parallel with the motor to safeguard the relay and ESP32.
- **OLED Display (on one designated responder):** The I2C pins of the ESP32 (usually GPIO21 for SDA and GPIO22 for SCL) are linked to an I2C-based OLED display (such as the SSD1306 128x64).

5. Flow chart

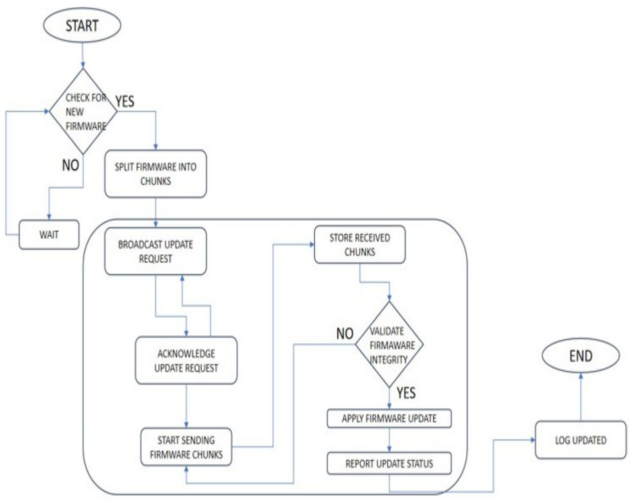
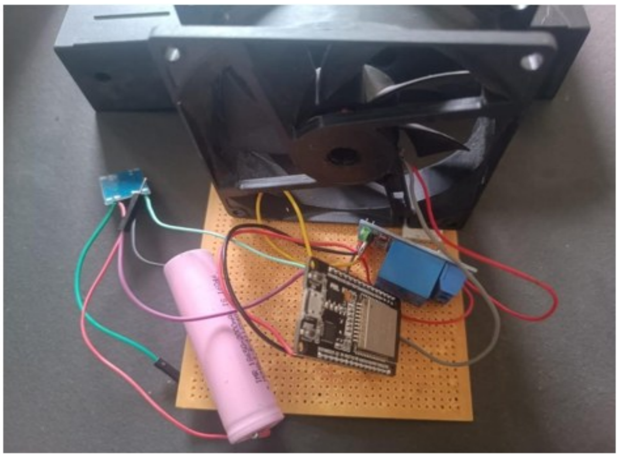


Fig.5.1 project of the flow chart

6. OUTPUT RESULTS



Fi. 6.1 Showing on final output results

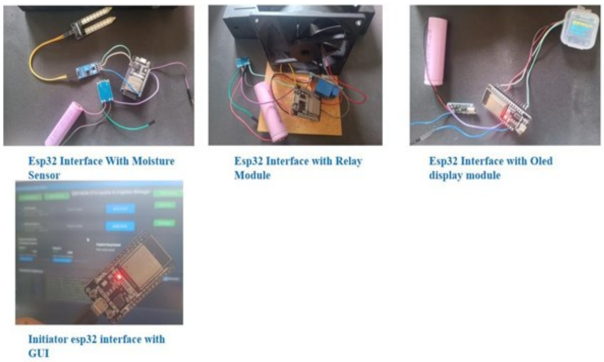


Fig. 6.2 showing the individual components one by one.

7. ANALYSIS

Presents the empirical findings from testing the Over-the-Air (OTA) update system based on ESP-NOW in a simulated agricultural setting. The main parameters listed in Chapter 4—reliability, update speed, power consumption, and communication range—are the focus of the performance assessment. Furthermore, an analysis is conducted on the effectiveness of the integrated agricultural capabilities, including irrigation control and moisture sensing. After highlighting the benefits and drawbacks of the suggested system in comparison to conventional OTA techniques, a comparative analysis is carried out, and the main conclusions are summarized.

Fig 7.1: Result of ESP-NOW Using OTA

7.2 Range Testing and Signal Strength Analysis

Distance (m)	Simulated Environment	Typical RSSI (dBm)	Packet Success Rate (Single Hop, ACK)
1	Line-of-Sight	-30 to -40	>99%
20	Line-of-Sight	-50 to -60	>98%
50	Line-of-Sight	-70 to -75	>95%
80	Line-of-Sight	-80 to -85	>90%(edge of reliability)
20	Obstacle (sim. wall/veg.)	-65 to -75	>90%
40	Obstacle (sim. wall/veg.)	-80 to -90	<80% (unreliable)

Table 7.2 Direct ESP-NOW Range

8. CONCLUSION AND FUTURE SCOPE

Using the special features of the ESP-NOW communication protocol, this study effectively developed, built, and assessed an Over-the-Air (OTA) update system especially suited for distributed ESP32-based agricultural IoT sensor networks. The main driving force was to get around the major drawbacks of conventional Wi-Fi and cellular-based OTA techniques in difficult agricultural settings, which are typified by a dearth of ubiquitous network infrastructure, strict power requirements for battery-operated devices, and the requirement to oversee potentially large numbers of devices dispersed over wide areas. The core of the suggested system design was an ESP32 Initiator node that used ESP-NOW to communicate with many ESP32 Responder nodes. To provide a realistic operating environment, it included key agricultural features including relay-controlled irrigation simulation, calibrated measurements, and soil moisture monitoring. To increase the update coverage outside of the Initiator's direct range and enable updates to spread throughout the network, a multi-hop propagation mechanism was put in place at the application layer on top of ESP-NOW. The central administration and monitoring interface was a custom GUI created in the Processing IDE, which made it easier to choose firmware, start upgrades, and see node status and sensor data in real time. The outcomes of the experimental assessment, which was carried out in a simulated agricultural setting, support the main study assumptions. The system proved the dependability of chunked firmware image distribution over ESP-NOW by demonstrating a high success rate for OTA upgrades across the network, including nodes reachable via multi-hop paths. Importantly, the update mechanism's effective range was effectively increased by the multi-hop capabilities, beyond the individual ESP32 nodes' direct communication limitations. The energy profile of the ESP-NOW-based update process is far more advantageous for battery-powered devices, according to power consumption study, than the constant, high-current draw connected to conventional Wi-Fi downloads. Following firmware upgrades, the integrated agricultural capabilities continued to perform and be dependable, demonstrating the system's capacity to sustain device utility over the course of its lifespan. Additionally, the approach improved system dependability against update failures by utilizing the ESP32's inherent OTA capabilities and bootloader rollback mechanism, as well as comprehensive error handling.

For OTA updates in agricultural IoT contexts, this study demonstrates that ESP-NOW is a practical—and in many ways, better—than existing wireless protocols. The fundamental issues with setting up and sustaining dispersed sensor networks in distant farming settings are immediately addressed by its power efficiency, infrastructure independence, and appropriateness for creating application-layer multi-hop networks. By proving that dependable, power-conscious firmware management is possible without the need for external network infrastructure, the developed system acts as a concrete proof-of-concept, improving the viability, scalability, and sustainability of ESP32 microcontroller-based smart agriculture solutions. Through the design, implementation, and evaluation of such a system, the study effectively achieved its goals and demonstrated the noteworthy advantages of the ESP-NOW approach for this particular application domain.

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