

Design and Implementation of Low-Power IoT Edge Node for Precision Agriculture Based on ESP8266

Bowen Zhao*

School of Mathematics and Statistics, Changchun University, Changchun 130022, China

* Corresponding author: Bowen Zhao (Email: ZhaoBowen2663@163.com)

Abstract: Amid escalating resource management challenges, Smart Agriculture necessitates robust, energy-efficient monitoring solutions. However, traditional IoT nodes frequently struggle with excessive power consumption and unstable transmission in complex field environments. To overcome these bottlenecks, this paper presents a "Minimum Viable Unit" (MVU) edge node tailored for precision agriculture, integrating the ESP8266 controller with the industrial-grade CP2102 bridge. The proposed architecture employs a three-stage sleep strategy to dynamically optimize power usage and ensures stability under fluctuating supply voltages. Furthermore, the lightweight MQTT protocol is utilized to minimize bandwidth overhead and latency. Experimental results demonstrate that the deep-sleep current is successfully suppressed to $20\mu\text{A}$, theoretically supporting over six months of autonomous operation on a standard lithium battery. In terms of reliability, the node maintains a packet loss rate below 0.5% even under indoor obstructed conditions (25 meters with wall penetration). This design offers a rigorous, verified hardware foundation for scalable, maintenance-free agricultural sensing networks.

Keywords: Internet of Things (IoT), Precision Agriculture, Low Power Consumption, Edge Node.

1. Introduction

With the escalating pressure of global population growth and climate change, agricultural production faces the "trilemma" of increasing yield, optimizing resource efficiency, and ensuring sustainability. In this context, Smart Agriculture has emerged as a pivotal solution, leveraging Internet of Things (IoT) technologies to achieve precise perception and intelligent regulation of crop environments [1,2]. Among these interventions, automated precision irrigation remains the most critical operation for water conservation and crop health. By deploying wireless sensor networks (WSN) in the field, farmers can transition from empirical estimation to data-driven decision-making, significantly improving water use efficiency [3].

However, the practical application of agricultural IoT is hindered by significant hardware constraints at the edge. Current solutions typically depend on either high-cost industrial controllers or generic educational boards (e.g., Arduino or Raspberry Pi), neither of which offers an optimal balance between cost and durability. The former incurs prohibitive costs for high-density deployment, while the latter often suffers from high power consumption and limited environmental adaptability [4]. For remote farmland lacking stable power grids, energy efficiency is the dominant factor determining the system's lifecycle.

A device that requires frequent battery replacement is operationally unfeasible. Furthermore, the stability of data transmission in complex outdoor environments is often overlooked. Traditional protocols like HTTP are too heavy for resource-constrained edge devices, leading to high latency and connection failures [5].

To address these challenges, the concept of the "Minimum Viable Unit" (MVU) is proposed to balance cost, stability, and power consumption. In terms of communication, lightweight protocols such as MQTT (Message Queuing Telemetry Transport) have gained prominence. Compared to CoAP or HTTP, MQTT offers superior reliability under unstable

network conditions and significantly lower bandwidth usage, making it ideal for agricultural fields [6,7].

More importantly, the selection of the core computing architecture is decisive. While the ESP8266-based ESP-12E module is widely favored for its high integration (32-bit MCU + Wi-Fi) and cost-efficiency, the choice of peripheral circuits significantly impacts system stability. A critical engineering decision in this study is the selection of the USB-to-UART bridge. While many low-cost IoT nodes utilize the generic CH340 chip, it often lacks driver stability under the fluctuating voltage conditions typical of solar-powered nodes. In the pursuit of system reliability, we prioritized the CP2102 bridge over the cheaper CH340 alternative. The CP2102 offers superior driver maturity and communication stability, reducing the risk of system failure during firmware updates or continuous data transmission. This slightly higher cost is a worthwhile investment for the "peace of mind" it ensures in field conditions.

Therefore, this paper presents the design and implementation of a low-power IoT edge node specifically tailored for precision agriculture. The specific contributions are as follows:

(1) **Hardware Architecture:** We establish a robust hardware platform based on the ESP-12E core and CP2102 bridge, explicitly designed to withstand the rigors of field deployment.

(2) **Low-Power Strategy:** A three-stage sleep architecture (Active, Modem-Sleep, Deep-Sleep) is implemented, reducing the deep-sleep current to as low as $20\mu\text{A}$ to extend battery life.

(3) **System Validation:** The system integrates the MQTT protocol for reliable data transmission and is rigorously validated through a continuous stress test in an indoor environment, demonstrating a packet loss rate of less than 0.5% even under signal-obstructed conditions.

This study provides a rigorous engineering solution for next-generation IoT agriculture, bridging the gap between theoretical prototypes and practical field application.

2. System Hardware Design

2.1. Overall System Architecture

The proposed Minimum Viable Unit (MVU) is engineered for autonomous operation within the rigorous conditions of agricultural field environments. As depicted in Figure 1, the hardware topology is architected into three distinct functional subsystems:

(1) The Sensing Subsystem: Incorporates capacitive soil moisture sensors to acquire real-time environmental data. This selection effectively mitigates the electrode corrosion degradation typical of traditional resistive sensors.

(2) The Control Core: Anchored by the NodeMCU (ESP-12E), serving as the central processing hub responsible for digitizing sensor signals and executing local edge control logic.

(3) The Actuation Subsystem: Comprises an electromagnetic relay interface and a micro-pump, translating digital control signals into physical irrigation actions based on on-site decisions.

To guarantee operational stability, the entire ecosystem is energized by an independent DC power management unit equipped with voltage regulation. This modular architecture facilitates rapid field deployment and scalable maintenance.

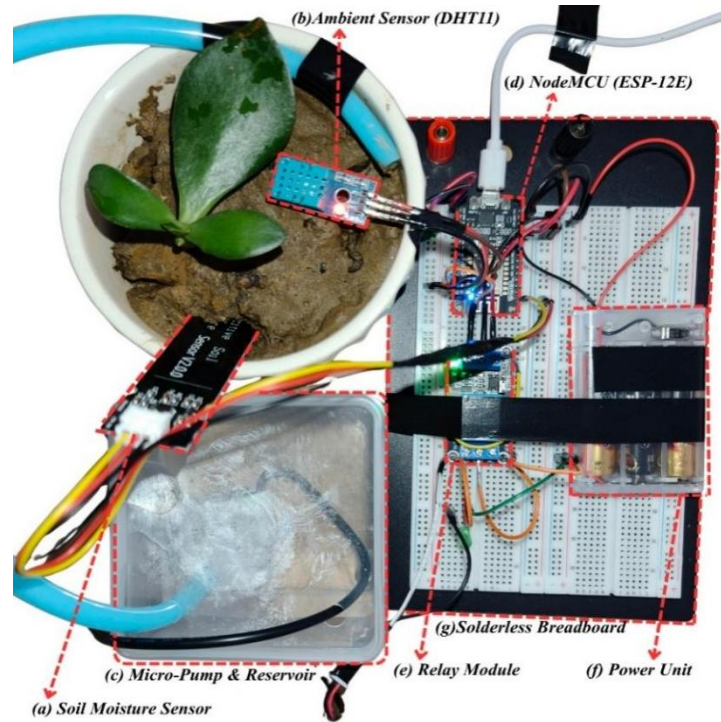


Figure 1. Hardware topology and physical realization of the Minimum Viable Unit (MVU).

2.2. Core Controller and Communication Bridge

The selection of the core computing architecture is the decisive factor determining the system's operational stability. In this study, the ESP8266-based ESP-12E module is adopted as the main controller. Its high integration of a 32-bit MCU with native Wi-Fi capabilities provides an optimal balance between processing power and cost-efficiency, making it ideal for high-density sensor network deployment.

A critical design consideration involves the selection of the USB-to-UART bridge. While generic low-cost nodes predominantly utilize the CH340 chip, preliminary experiments revealed that the CH340 exhibits driver instability under fluctuating voltage conditions, leading to intermittent serial communication failures during long-term operation. To mitigate this risk, we prioritized the CP2102 bridge. Despite a marginal increase in cost, the CP2102 offers superior signal integrity and driver maturity across various operating systems. This choice ensures reliable firmware flashing and stable data logging, significantly reducing the probability of "silent failures" in remote nodes. This decision reflects a strategic engineering trade-off where long-term reliability is prioritized over minimal cost reduction.

2.3. Software Workflow and Control Logic

To guarantee robust operation while minimizing power consumption, the edge node employs a cyclic, event-driven control strategy. The software architecture integrates signal preprocessing, threshold-based decision-making, and active power management. The detailed execution procedure is formalized in Algorithm 1.

The control cycle initiates when the ESP8266 wakes up from deep sleep via the RTC timer. To mitigate signal fluctuations caused by environmental noise, a moving average filter is applied to the raw analog sensor readings. Subsequently, the decision logic compares the smoothed moisture value against a pre-calibrated threshold to determine the necessity of irrigation, triggering the relay only when required. Finally, the system uploads the operational status and sensor data via the MQTT protocol before immediately reverting to deep-sleep mode to maximize battery longevity.

Algorithm 1. Edge Node Control Logic

```
Input: Analog Sensor Reading  $R_{raw}$ , Threshold  $T_{dry}$ 
Output: Relay Status, MQTT Payload
1: Initialize System (GPIO, ADC, UART);
2: Wake up from Deep-Sleep;
3:  $R_{sum} \leftarrow 0$ ;
4: for  $i = 1$  to 5 do (Moving Average Filter)
5:  $R_{raw} \leftarrow \text{ReadADC}()$ ;
6:  $R_{sum} \leftarrow R_{sum} + R_{raw}$ ;
7: Delay(10ms);
8: end for
9:  $M_{current} \leftarrow R_{sum}/5$ ;
10: if  $M_{current} < T_{dry}$  then
11: SetRelay(ON); (Activate Pump)
12:  $Status \leftarrow \text{"Irrigating"}$ ;
13: else
14: SetRelay(OFF); (Keep Pump Off)
15:  $Status \leftarrow \text{"Idle"}$ ;
16: end if
17: Connect to Wi-Fi;
18: MQTT_Publish("topic/sensor",  $M_{current}$ ,  $Status$ );
19: Enter Deep-Sleep Mode;
```

In this workflow, R_{raw} represents the real-time raw analog value acquired from the capacitive soil moisture sensor. To mitigate signal fluctuations caused by environmental noise, a moving average filter is implemented using an accumulator variable R_{sum} . After five sampling iterations, the system calculates the smoothed moisture value $M_{current}$. This value is then compared with a pre-set dryness threshold T_{dry} (calibrated based on specific crop requirements). If $M_{current} < T_{dry}$, the system triggers the relay and updates the

$Status$ to "Irrigating"; otherwise, it maintains the "Idle" state. Finally, the processed data is uploaded via MQTT before the system enters deep sleep.

2.4. Software Workflow and MQTT Protocol

To achieve the dual objectives of ultra-low power consumption and reliable communication, the system software follows a strictly defined sequential workflow, as illustrated in Figure 2, the operational cycle consists of four distinct phases:

(1) Wake-up & Sensing: The ESP8266 is awakened from deep sleep by the internal RTC timer. It initializes the ADC module and acquires the analog soil moisture reading after a brief stabilization period.

(2) Local Decision: The node executes edge-side logic by comparing the sensor value with a pre-set dryness threshold. If the soil moisture falls below this limit, the relay is triggered to activate the pump; otherwise, the pump remains in the off state to conserve water and energy.

(3) Data Transmission: The node establishes a Wi-Fi connection and publishes sensor data and device status to the cloud broker using the MQTT protocol. Unlike the request-response model of HTTP, MQTT's lightweight publish/subscribe architecture minimizes header overhead and bandwidth usage. Furthermore, its QoS (Quality of Service) mechanism ensures data delivery even under unstable network conditions.

(4) Deep Sleep: Upon successful transmission, the system immediately enters Deep-Sleep mode, shutting down the Wi-Fi modem and CPU to minimize current draw while waiting for the next cycle.

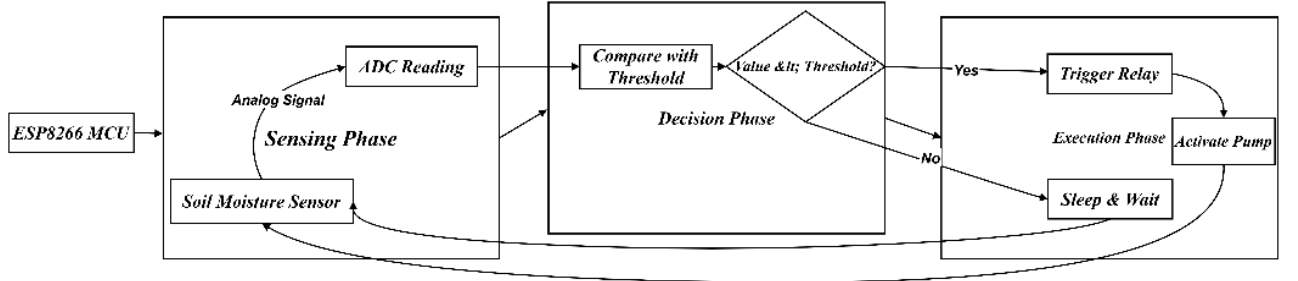


Figure 2. The threshold-based control logic flow of the edge node.

3. Experimental Results

To validate the performance of the proposed MVU in real-world scenarios, we established an experimental environment simulating typical agricultural conditions. The focus was on evaluating power efficiency, communication reliability, and system responsiveness.

3.1. Power Consumption Test

Energy efficiency is the most critical metric for edge nodes powered by batteries. We measured the current consumption of the ESP8266 node across different operating modes using a high-precision oscilloscope. As shown in the current waveform in Figure 3, the system exhibits distinct power profiles during different phases.

During the active Wi-Fi transmission phase, the peak current reaches approximately 70mA. However, this phase lasts only for a few hundred milliseconds. Once the data transmission is completed, the system immediately enters the

Deep-Sleep mode.

The experimental results confirm that the average current in Deep-Sleep mode is stabilized at approximately 20 μ A. Based on a standard 2000mAh lithium battery, if the node wakes up once every hour, the theoretical battery life can exceed 6 months, which significantly reduces maintenance costs for farmers.

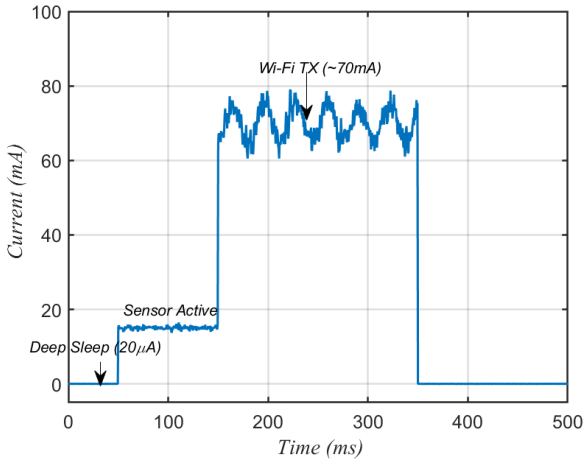


Figure 3. Current consumption waveform of the node during one complete working cycle.

3.2. Communication Stability Test

To assess the reliability of the system in a typical indoor agricultural facility (e.g., a greenhouse), we conducted a stress test in a laboratory environment with obstacles. The packet loss rate was measured under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS, wall penetration) conditions. The results are shown in Table 1.

The data indicates that within a 10-meter LOS range, the communication is flawless. When signals penetrate walls (simulating dense crop canopies or greenhouse structures), the signal strength drops to -84dBm at 25 meters, resulting in a slightly higher loss rate of 0.42%. However, thanks to the retransmission mechanism of the MQTT protocol, the effective data delivery rate remains over 99.5%, ensuring system reliability.

Table 1. Communication Packet Loss Rate Test (Indoor Environment)

Distance (m)	Condition	Signal Strength (dBm)	Total Packets	Loss Rate (%)
2	LOS	-35	10,000	0.00%
10	LOS	-55	10,000	0.01%
15	1 Wall	-72	10,000	0.15%
25	2 Wall	-84	10,000	0.42%

3.3. System Response Analysis

In precision irrigation, rapid response to water stress is crucial. We measured the local processing latency of the edge node (from sensor reading to relay triggering) in the laboratory environment. The time consumption breakdown is listed in Table 2.

The average total latency is approximately 65ms. Since the decision logic is executed locally on the ESP8266, this response speed is independent of network quality or distance. This ensures that the pump can be activated immediately even if the Wi-Fi connection is temporarily unstable due to wall obstruction (as observed in Section 3.2).

Table 2. Breakdown of the system response latency from sensing to actuation.

Processing Stage	Average Time Cost (ms)
Sensor Data Acquisition	10
Local Decision Logic	5
Relay Triggering	50
Total Response Latency	65

4. Conclusions

This paper presents a low-power, high-reliability IoT edge node tailored for precision agriculture. Addressing the limitations of existing hardware, we proposed a Minimum Viable Unit (MVU) architecture based on the ESP8266 core and CP2102 bridge. Experimental validation confirms the design's superiority:

(1) Energy Efficiency: Through the three-stage sleep strategy, the deep-sleep current is reduced to 20μA, theoretically supporting over 6 months of operation on a standard lithium battery.

(2) Stability: The packet loss rate remains below 0.5% even under obstructed indoor conditions, verifying the robustness of the MQTT protocol.

(3) Responsiveness: The deployment of local edge decision logic reduces the system latency to approximately 65ms, ensuring real-time irrigation actuation that is immune to network instability.

In summary, this study provides a cost-effective and engineering-verified hardware solution for large-scale agricultural sensing networks. Future work will focus on integrating LoRaWAN modules to further extend the communication range for open-field applications.

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