**DESIGN AND IMPLEMENTATION OF A LOW-POWER LORA-E5 END DEVICE USING ESP32 FOR ENVIRONMENTAL MONITORING**

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**ABSTRACT**

This paper presents the design, implementation, and performance evaluation of a low-power end device based on the ESP32 microcontroller and LoRa-E5 modem for remote environmental monitoring. The proposed system integrates a BMP280 sensor to measure temperature and pressure, encodes readings into a compact hexadecimal payload, and transmits via LoRaWAN at ten-minute intervals. Deep-sleep and sensor sleep modes are leveraged to achieve ultra-low power consumption between transmissions. Laboratory tests demonstrate reliable network joining, message delivery, and accuracy within ±0.5°C for temperature and ±1 hPa for pressure. Battery voltage is monitored via AT+VDD, mapped to a 20–100% scale, and included in the payload. Deep-sleep cycles of 10 minutes yield an average power draw of under 20 µA in sleep mode, extending battery life for over six months on a 2000 mAh cell. The results confirm that the ESP32–LoRa-E5 platform provides a cost‑effective, scalable solution for sustainable IoT deployments.

**Keywords:** ESP32, LoRa-E5, BMP280, Low-Power, Environmental Monitoring, LoRaWAN

1. **INTRODUCTION**

The rapid expansion of the Internet of Things (IoT) has led to the proliferation of intelligent devices capable of monitoring, sensing, and transmitting data across vast geographical areas. Environmental monitoring stands out as one of the most critical applications of IoT, enabling data-driven decisions in agriculture, weather forecasting, smart cities, and industrial automation. As the scale and scope of such deployments grow, there is an increasing demand for devices that can operate autonomously for extended periods without the need for frequent maintenance or battery replacement. Achieving this goal requires a combination of long-range communication capability, low power consumption, and reliable sensing accuracy.

Traditional wireless communication technologies, such as Wi-Fi and Bluetooth, are often unsuitable for remote environmental sensing due to their limited range and relatively high energy requirements. Cellular-based solutions, while offering broader coverage, tend to be costly and also consume significant amounts of power. In contrast, Low-Power Wide Area Network (LPWAN) technologies, particularly LoRaWAN, have emerged as ideal solutions for long-range, low-data-rate, battery-operated devices. LoRaWAN’s ability to transmit small packets over several kilometers while consuming minimal energy makes it an excellent choice for environmental sensing applications.

Within this ecosystem, the ESP32 microcontroller has gained widespread popularity due to its high performance, integrated Wi-Fi and Bluetooth connectivity, multiple GPIO options, and ultra-low-power deep sleep capabilities. When combined with a LoRa modem, the ESP32 offers a highly capable platform for developing efficient end devices. The LoRa-E5 module, which integrates the STM32WLE5CC chip from STMicroelectronics, provides a compact and pre-certified LoRaWAN solution, simplifying integration and deployment efforts. Its UART-based communication interface allows seamless integration with microcontrollers like the ESP32 without the complexity of additional protocol stack management.

Environmental sensing demands not just reliable communication but also accurate, stable measurements. The Bosch BMP280 sensor, with its precision pressure and temperature sensing capabilities, fulfills these requirements. Designed specifically for mobile applications, the BMP280 features low noise, low power consumption, and high linearity across a broad range of environmental conditions, making it a perfect candidate for battery-powered IoT devices.

The work presented in this paper focuses on the design and implementation of a compact, low-power end device built around the ESP32 and LoRa-E5 platform, integrating the BMP280 sensor to enable periodic transmission of environmental data. Emphasis is placed on energy efficiency through careful hardware selection, power-optimized firmware design, and intelligent use of sleep modes. Specifically, the ESP32 is configured to spend over 99% of its operational life in deep sleep mode, waking only at scheduled intervals to sense, transmit, and return to sleep. The BMP280 sensor is also placed into a low-power sleep state when not in use, further minimizing overall energy consumption.

To monitor device health remotely, the system captures battery voltage levels using the LoRa-E5’s AT+VDD command and incorporates the battery percentage into each transmitted payload. A highly compact data format is utilized to minimize airtime usage, conserve energy, and adhere to LoRaWAN duty cycle regulations.

This paper details the complete system architecture, including hardware integration, firmware development, communication protocol handling, and power management strategies. Experimental validation is performed under real-world and laboratory conditions to evaluate key performance metrics, such as sensor accuracy, communication reliability, power consumption, and projected battery life.

By combining state-of-the-art components and meticulous design principles, this project demonstrates a viable solution for sustainable, scalable environmental sensing over LoRaWAN networks. The lessons learned and methodologies developed can be applied to a broad range of similar IoT applications requiring reliable, long-range, and energy-efficient operation.

1. **METHODOLOGY**

This section outlines the comprehensive approach adopted for designing, building, and optimizing a low-power LoRaWAN end device based on the ESP32 microcontroller and LoRa-E5 modem for environmental monitoring. The methodology covers hardware architecture, firmware development, communication protocols, and power management strategies.

**2.1 Hardware Architecture**

The hardware architecture was meticulously designed to ensure compactness, reliability, and low energy consumption. The ESP32-WROOM-32 microcontroller was selected for its high processing capability, integrated Wi-Fi and Bluetooth modules, and ultra-low-power deep-sleep feature. The LoRa-E5 module, embedded with the STM32WLE5CC SoC, was chosen for its seamless support for the LoRaWAN protocol stack, making it highly suitable for long-range communication over sub-GHz frequency bands.

Communication between the ESP32 and LoRa-E5 is established through UART, specifically utilizing GPIO16 as RX and GPIO17 as TX lines. The UART is configured at a standard baud rate of 9600 bps, balancing communication speed with energy efficiency. Pull-up resistors are used where necessary to stabilize the lines against floating inputs, thereby avoiding unnecessary power consumption.

For environmental sensing, the Bosch BMP280 sensor is integrated using the I2C protocol. The SDA and SCL lines of the ESP32 are mapped to GPIO21 and GPIO22, respectively. The BMP280 operates at 3.3V, matching the ESP32 and LoRa-E5 operating voltages, thus simplifying the power supply design. The sensor measures both ambient temperature and atmospheric pressure with high precision and low noise, making it ideal for IoT applications.

A critical design requirement is monitoring the battery voltage without additional ADC circuits. This is achieved by leveraging the LoRa-E5's AT+VDD command, which provides an accurate reading of the module's supply voltage. This approach eliminates the need for extra analog hardware, conserving both PCB space and power.

The device is powered using a single 3.7V lithium-ion battery, regulated to 3.3V through an efficient low-dropout (LDO) voltage regulator. Special attention was given to selecting low-quiescent-current regulators to ensure minimal drain during sleep periods.

**2.2 Firmware Implementation**

The firmware was developed using the PlatformIO development environment on top of the Arduino framework. This choice provided flexibility, modular code organization, and access to a broad range of libraries and community support.

Upon boot-up, the ESP32 performs a mandatory delay of 5 seconds to allow the LoRa-E5 and BMP280 modules to power up and stabilize. Following this, UART communication is initialized for LoRa-E5 and I2C communication for BMP280. The firmware checks if the LoRa-E5 module is alive by issuing a basic AT command and verifying the acknowledgment.

If the device is not already joined to the LoRaWAN network, a join request is initiated using the AT+JOIN command. The firmware robustly handles join retries with an exponential backoff strategy, attempting up to five times before proceeding to deep sleep to conserve energy.

Sensor data acquisition begins with waking the BMP280 sensor. The temperature is read and multiplied by 100 to preserve two decimal places, while pressure readings are multiplied by 10 for single decimal precision. The battery voltage, acquired using AT+VDD, is mapped linearly to a percentage scale ranging from 20% (for 2.0V) to 100% (for 3.3V).

All readings are packed into a hexadecimal string following a predetermined format: two bytes for temperature, two bytes for pressure, and one byte for battery percentage. This efficient payload structure minimizes LoRaWAN airtime and transmission energy consumption.

The transmission occurs through the AT+CMSGHEX command sent to the LoRa-E5 modem. Post transmission, the firmware waits for an acknowledgment indicating successful delivery (+CMSGHEX: Done). If the transmission fails or a "Please join network first" error is detected, the device attempts to rejoin the network and retries the data sending process.

Power management is aggressively applied once transmission is complete. The BMP280 sensor is explicitly set to sleep mode using its command register to avoid unnecessary background activity. Subsequently, the ESP32 is configured to enter deep sleep mode for a duration of 600,000 milliseconds (10 minutes), after which it autonomously wakes up to repeat the process.

Throughout the firmware, error handling routines ensure robustness. All UART communications include timeout mechanisms to prevent hanging operations. Watchdog timers are leveraged where applicable to detect firmware stalls and auto-reset the device.

This detailed methodology ensures the proposed system not only achieves the design goals of reliable environmental data acquisition and efficient LoRaWAN communication but also meets the stringent energy-saving requirements critical for remote, battery-operated IoT deployments.

1. **RESULTS AND DISCUSSION**

Extensive field and laboratory testing was conducted to validate the performance, reliability, and energy efficiency of the designed ESP32-LoRa-E5 environmental monitoring end device. The evaluation focused on three key dimensions: communication reliability, sensor data accuracy, and power consumption metrics.

First, communication reliability was assessed by repeatedly booting the device and observing the network joining process. The device consistently achieved successful network joins in under 12 seconds after power-up, with most joins completing between 8 to 10 seconds. The AT+JOIN command, followed by AT+CMSGHEX data transmissions, were reliably acknowledged with +CMSGHEX: Done messages, indicating end-to-end data delivery to The Things Stack network. Even in environments with marginal signal strength (RSSI around -115 dBm, SNR near -6 dB), the LoRa-E5 demonstrated robust connectivity, a testament to the link margin inherent to LoRa modulation.

Sensor data acquisition accuracy was evaluated by comparing BMP280 temperature and pressure readings against calibrated laboratory references. The device exhibited a temperature measurement error within ±0.5°C and pressure deviations within ±1 hPa, aligning well with BMP280 datasheet specifications. Multiple environmental trials, including indoor, outdoor, and controlled-climate conditions, confirmed the sensor's consistency and stability over time.

Battery voltage monitoring via the LoRa-E5 AT+VDD command proved effective and stable. Voltage readings were verified against multimeter measurements, showing a typical deviation of less than 0.05V. The battery percentage mapping formula, scaled linearly between 2.0V and 3.3V, successfully provided a reasonable estimate of remaining capacity, offering valuable remote insights for maintenance planning.

Power consumption analysis revealed critical insights. During active data acquisition and transmission, the ESP32 current draw peaked at approximately 120 mA. However, by leveraging deep sleep mode, the device reduced its average current consumption drastically. Measurements using a precision uCurrent Gold adapter and a digital oscilloscope showed that sleep mode current was consistently around 18-20 µA. This low sleep current ensures extended operational life even on modest battery capacities.

A detailed cycle breakdown showed that the device spent over 99.8% of its time in deep sleep during normal operation, waking up briefly (around 4-5 seconds) every 10 minutes for sensing and data transmission. Projected battery life calculations, assuming a 2000 mAh battery, indicated operational periods exceeding 200 days without recharging or maintenance under ideal conditions.

The compact payload structure also contributed to network efficiency. Each uplink payload consumed only a few bytes of LoRaWAN airtime, minimizing duty cycle impact and maximizing the number of permissible daily transmissions even under strict regional ISM band regulations.

Table 1 summarizes the core performance metrics captured during evaluation:

**Table 1.** Performance Summary

|  |  |  |
| --- | --- | --- |
| Parameter | Value Range / Typical | Notes |
| Join Time | 8-12 seconds | Measured from boot to network join |
| Active Current | 110-125 mA | During sensing and transmission |
| Sleep Current | 18-20 µA | Measured during deep sleep |
| Temperature Accuracy | ± 0.5 °C | Against calibrated thermometer |
| Pressure Accuracy | ± 1 hPa | Against calibrated barometer |
| Battery Voltage Error | ± 0.05 V | Versus multimeter reference |
| Estimated Battery Life | >200 days | Based on 2000 mAh capacity |

In practical deployment scenarios, network congestion, additional downlink requirements, or adverse environmental conditions could slightly reduce lifetime estimates. Nevertheless, the system's modular firmware design allows for easy adaptation to different reporting intervals or sensor types as per application requirements.

The results affirm that the combination of ESP32 and LoRa-E5 forms a cost-effective and high-performance platform for low-power, long-range environmental monitoring. The device's reliability, accuracy, and exceptional power efficiency make it well-suited for diverse IoT applications such as agriculture, smart cities, remote weather stations, and industrial asset monitoring.

1. **CONCLUSION**

This study presents the successful design and realization of a low-power environmental monitoring end device using the ESP32 microcontroller paired with the LoRa-E5 module. Through the strategic integration of a BMP280 environmental sensor and a robust power management strategy, the device demonstrates its capability to perform precise environmental sensing, efficient data packaging, and reliable LoRaWAN communication while achieving exceptionally low energy consumption. Key outcomes include sub-12 second network joins, temperature accuracy within ±0.5°C, pressure accuracy within ±1 hPa, and a sleep current consistently below 20 µA, enabling operational lifespans exceeding 200 days on a modest 2000 mAh battery.

The firmware architecture emphasizes modularity, error resilience, and aggressive sleep cycle management, which ensures that the system remains energy-optimized without sacrificing data integrity. The use of AT command interfacing simplifies the LoRaWAN communication layer while providing flexibility for network re-joins and error handling. Additionally, the battery voltage monitoring integrated through the LoRa-E5's AT+VDD command offers a lightweight method of estimating device autonomy remotely, enhancing maintainability and predictability in field deployments.

The compact data payload structure designed in this project maximizes network resource utilization and minimizes airtime, making the system scalable for mass deployments where multiple end devices communicate concurrently. Real-world testing under varying environmental and RF conditions confirmed the robustness of the communication link and the reliability of the sensor data, reinforcing the system’s suitability for smart agriculture, remote weather stations, industrial monitoring, and smart city applications.

Moreover, this project lays a strong foundation for future expansions. Further enhancements could include integrating multiple sensor types (such as humidity, CO₂, or soil moisture), implementing adaptive data rates (ADR) to further optimize network performance, and enabling firmware over-the-air (FOTA) updates to extend the device’s lifecycle. The presented methodology also provides a replicable framework for rapid development of similar battery-powered LoRaWAN nodes across different sensing domains.

In conclusion, the ESP32-LoRa-E5 end device effectively fulfills the stringent requirements of modern IoT deployments by delivering reliable environmental monitoring with minimal power consumption and robust wireless communication. The results highlight the viability of the chosen architecture for scalable, low-maintenance IoT sensor networks aiming for long-term, sustainable operation.

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