

IOT Based Environment Monitoring System Using STM32

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Abstract: — The rapid degradation of environmental quality driven by industrialization and urbanization demands continuous, real-time monitoring of key atmospheric and ecological parameters. This paper presents the design and implementation of a low-power, solar-powered IoT-based environmental monitoring system built around the STM32 microcontroller. The proposed system integrates a suite of sensors to measure temperature, humidity, atmospheric pressure, air quality, UV radiation, and soil moisture. Data is transmitted wirelessly over Wi-Fi and LoRa protocols to a cloud-based dashboard for real-time visualization and historical analysis. The system is entirely powered by a solar photovoltaic panel coupled with a lithium-ion battery and a power management unit, ensuring uninterrupted autonomous operation in remote locations without access to the electrical grid. Experimental results demonstrate reliable data acquisition with a sampling accuracy exceeding 97%, an end-to-end data transmission latency of less than 2 seconds, and continuous operation exceeding 72 hours on battery backup under cloudy conditions. The proposed system offers a cost-effective, scalable, and energy-autonomous alternative to conventional environmental monitoring stations.

Keywords: Internet of Things, Environmental Monitoring, STM32, Solar Energy Harvesting, Wi-Fi, LoRa, Air Quality, Cloud Dashboard, Low-Power Design.

I. INTRODUCTION

The environment is undergoing unprecedented change, with air pollution, climate shift, and soil degradation posing serious threats to public health, agriculture, and biodiversity. Traditional environmental monitoring systems rely on large, stationary, expensive laboratory-grade instruments that require skilled personnel, continuous grid electricity, and complex maintenance schedules. These constraints make them unsuitable for deployment in remote forests, agricultural fields, disaster-prone zones, or developing-world communities where monitoring is most critically needed.

The emergence of the Internet of Things (IoT) has transformed the paradigm of environmental sensing. IoT-based systems combine low-cost sensors, energy-efficient microcontrollers, wireless communication protocols, and cloud computing to create distributed, scalable monitoring networks. Such systems can operate autonomously for extended periods, relay data in real time, trigger alerts when thresholds are breached, and integrate with decision-support tools for environmental management.

The STM32 family of microcontrollers, manufactured by STMicroelectronics and based on the ARM Cortex-M architecture, has emerged as a preferred choice for IoT edge devices due to its exceptional balance of processing performance, rich peripheral support, and ultra-low-power operating modes. In particular, the STM32L series is specifically engineered for battery-operated and energy-harvesting applications, featuring dynamic voltage scaling, multiple sleep states, and a power consumption as low as 2 μ A in standby mode.

Coupling the STM32 with solar energy harvesting eliminates the need for grid power or frequent battery replacement, enabling truly autonomous deployment in remote environments. A well-designed solar power subsystem, comprising a photovoltaic panel, maximum power point tracking (MPPT) charge controller, and rechargeable lithium-ion battery, can sustain system operation indefinitely as long as the solar resource is adequate.

This paper presents the end-to-end design of such a system, covering hardware architecture, sensor selection, firmware development, communication protocols, power management strategy, cloud integration, and field evaluation. The remainder of the

paper is organized as follows: Section 2 reviews related work; Section 3 describes system architecture; Section 4 details hardware design; Section 5 covers firmware and software; Section 6 presents power analysis; Section 7 discusses experimental results; Section 8 compares the proposed system with prior art; and Section 9 concludes the paper.

A. Motivation and Background

Existing weather forecasting methods were generally based on observed patterns of events and are called pattern recognition. For example, one could observe that if the sunset was red and normal, the next day often brought nice weather. This experience gathers more than generations to produce the tradition of time. However, not all these predictions are reliable, and since then many of them have been able to withstand rigorous statistical testing. The simplest way to predict time, persistence, depends on today's conditions to predict tomorrow's conditions.

II. RELATED WORK

Environmental monitoring using embedded electronics and wireless communication has been an active area of research for over two decades, with the IoT paradigm dramatically accelerating development in the last decade.

Rao et al. (2020) presented an Arduino Uno-based system for monitoring temperature, humidity, and CO₂ concentration in indoor agricultural environments. The system used an ESP8266 Wi-Fi module to push data to the ThingSpeak cloud platform. While functional and low-cost, Arduino's limited processing power and absence of advanced low-power modes made it unsuitable for solar-powered field deployment. The system was also confined to three parameters, limiting its environmental coverage.

Kumar and Singh (2021) developed a Raspberry Pi 4 -based monitoring station capable of processing data from multiple sensors and running local machine learning inference for pollution forecasting. Data was transmitted over 4G LTE to a custom cloud backend. Although computationally powerful, the Raspberry Pi consumes approximately 3 –5 W continuously,

making solar-only operation expensive and impractical without large panel and battery arrays.

Zhang et al. (2022) proposed an ESP32-based system incorporating temperature, humidity, atmospheric pressure, and particulate matter (PM_{2.5}) sensing, with solar charging and a 3,000 mAh LiPo battery. The system achieved an estimated 48 hours of battery backup. The ESP32, while capable, lacks the ultra -low-power standby modes of the STM32L series, resulting in higher idle consumption and shorter battery life. Almeida et al. (2022) explored LoRa WAN-based environmental monitoring for large-scale agricultural deployments. Their system achieved communication ranges exceeding 5 km in open terrain, demonstrating the viability of long-range, low-power wide area networks for environmental IoT. However, the system used a generic ARM MCU without the specialized low-power features of STM32L devices.

Patel and Mehta (2023) investigated solar energy harvesting for IoT sensor nodes, demonstrating that an MPPT-based charging circuit can improve solar energy utilization efficiency by 15–30% compared to simple resistive charging methods. They validated this with an ESP8266 -based node but did not address multi-parameter environmental sensing.

The present work builds upon and advances these contributions by combining the STM32L476RG ultra -low-power microcontroller, a comprehensive five-parameter sensor suite, dual-mode Wi-Fi and LoRa connectivity, MPPT solar charging, and cloud-based real-time analytics into a single, cohesive, field-validated system.

III. SYSTEM ARCHITECTURE

This project monitors temperature and humidity using the DHT22 sensor. This section described the approach to the project.

A. Microcontroller STM32L476RG

The STM32L476RG was selected as the core processing unit for this system. It is based on the ARM Cortex-M4 core with a floating-point unit (FPU),

operating at up to 80 MHz. Its ultra-low-power architecture makes it especially well-suited for solar-powered IoT applications.

Key specifications relevant to this design include a 12-bit ADC with up to 16 channels for interfacing with analog sensors, hardware I2C, SPI, and UART peripherals for digital sensor communication, a rich set of low-power modes including Sleep, Low-Power Sleep, Stop 1, Stop 2, Standby, and Shutdown, a real-time clock (RTC) with independent power domain for wake-up scheduling, and operating voltage down to 1.71 V, enabling operation from a partially discharged battery. The NUCLEO-L476RG development board was used during prototyping, with migration to a custom PCB for field deployment.



Fig. 1. STM32L476RG MICROCONTROLLER.

B. Environmental Sensor Suite

The system incorporates five categories of environmental sensors, selected for their accuracy, low power consumption, and compatibility with the STM32 peripheral interface.

Air Quality — MQ-135: The MQ-135 gas sensor detects a range of harmful gases including ammonia (NH_3), nitrogen oxides (NO_x), alcohol, benzene, smoke, and carbon dioxide (CO_2). It produces an analog output voltage proportional to gas

concentration. The STM32's 12-bit ADC converts this to a digital value, which is then processed using the sensor's calibration curve to calculate equivalent CO_2 concentration in parts per million (ppm). A warm-up time of 20 seconds is required after power-on before stable readings can be obtained.



Atmospheric Pressure and Altitude — BMP280: The BMP280 by Bosch Sensortec is a high-precision digital pressure and temperature sensor communicating over I2C or SPI. It covers a pressure range of 300–1100 hPa with ± 1 hPa accuracy. Altitude is derived from the pressure reading using the international barometric formula. Its ultra-low power consumption of $2.7 \mu\text{A}$ during normal operation makes it ideal for battery-powered applications.



Ultraviolet Radiation — GUV-A-S12SD: The GUV-A-S12SD UV photodiode sensor measures UV radiation intensity and outputs a proportional analog voltage. This is converted by the STM32's ADC to a UV index value ranging from 0 (minimal) to 15+ (extreme). UV index monitoring is valuable for agricultural, meteorological, and public health applications.



Soil Moisture — FC-28: The FC-28 capacitive soil moisture sensor provides both analog and digital outputs indicating volumetric water content in the soil. The analog output is read by the STM32 ADC and calibrated against known dry and saturated soil conditions. Soil moisture monitoring is essential for precision irrigation and agricultural decision-making.



Temperature and Humidity — DHT22: The DHT22 (also known as AM2302) provides calibrated digital output for both temperature and relative humidity via a single-wire protocol. It covers a temperature range of -40°C to $+80^{\circ}\text{C}$ with an accuracy of $\pm 0.5^{\circ}\text{C}$, and a humidity range of 0–100% RH with $\pm 2\%$ RH accuracy. Its 2-second sampling interval is adequate for environmental monitoring.



C. Communication Module

Wi-Fi — ESP8266: The ESP8266 Wi-Fi module is interfaced with the STM32 via UART using the AT command set. It operates on 2.4 GHz 802.11 b/g/n and supports TCP/IP stack functions, enabling direct

connection to an MQTT broker over Wi-Fi. The module is powered down between transmissions using the STM32's GPIO-controlled power switch to conserve energy.

LoRa — SX1278: For deployment beyond Wi-Fi range, the SX1278 LoRa transceiver module is used. Communicating with the STM32 via SPI, the SX1278 operates in the 433 MHz or 868 MHz ISM bands and achieves communication ranges of 2–15 km depending on terrain and antenna configuration. The LoRa modulation technique (chirp spread spectrum) provides excellent sensitivity (-137 dBm) and interference immunity, making it well-suited for rural and forested environments.

B. Local Display

A 0.96-inch 128×64 OLED display (SSD1306 driver) is interfaced over I2C to provide a local readout of all sensor parameters without requiring network connectivity. The display is activated on-demand via a pushbutton to avoid continuous power draw.

C. Solar power subsystems

The power subsystem is the most critical enabler of autonomous operation and consists of four key components.

Solar Panel: A 10 W, 12 V monocrystalline silicon solar panel is used. Monocrystalline panels were chosen for their superior efficiency (typically 20–22%) compared to polycrystalline or thin-film alternatives. The panel is mounted at a fixed tilt angle optimized for the deployment latitude to maximize annual energy capture.

MPPT Charge Controller — CN3791: The CN3791 is a single-cell lithium-ion MPPT charge controller. It continuously adjusts the operating point of the solar panel to extract maximum power regardless of illumination level and temperature variations. The MPPT algorithm improves solar energy utilization by 15–30% compared to simple series resistor-based charging. The controller also provides overcharge and over-discharge protection for the battery.

Battery — 3.7V 10,000 mAh LiPo: A 10,000 mAh lithium polymer rechargeable battery provides energy storage for nighttime and cloudy day operation. At the measured average system current of approximately 50 mA (accounting for the duty-cycled operation and sleep intervals), this battery capacity provides over 200 hours of backup in the complete absence of solar input, comfortably exceeding the requirement.

Power Regulation — AMS1117-3.3: A low-dropout (LDO) linear voltage regulator steps down the battery output (3.7–4.2 V) to a stable 3.3 V supply for the STM32 and digital sensors. The MQ-135 sensor requires a 5 V supply, provided by a small boost converter driven from the battery rail.

D. Software Design

1. Firmware Architecture

The firmware was developed in C using STM32CubeIDE with the HAL (Hardware Abstraction Layer) library provided by STMicroelectronics. The software is structured around a cooperative task scheduler rather than a full real-time operating system (RTOS) to minimize memory overhead and simplify power management.

The main program loop follows a fixed sequence: wake from Stop mode upon RTC alarm interrupt, initialize peripherals, execute the sensor reading task, execute the communication task, update the local display if the button is pressed, check battery state, and re-enter Stop mode with the RTC set for the next alarm. Each task is modular and independently testable.

2. Sensor Reading Task

Each sensor type requires a specific reading protocol. The DHT22 uses a single-wire protocol implemented via bit-banging on a GPIO pin with precise microsecond-level timing using the STM32 hardware timer. The BMP280 is read over I2C using the HAL I2C driver. Analog sensors (MQ-135, GUVVA-S12SD, FC-28) are read via the STM32 ADC with an oversampling factor of 16 to reduce noise and improve effective resolution. All raw sensor values are converted to physical units using calibration coefficients stored in flash memory.

3. Communication Task

The communication task first attempts Wi-Fi transmission using the ESP8266 module. If the Wi-Fi connection fails after three retries, the system falls back to LoRa transmission. The data packet is structured as a lightweight JSON payload containing a device identifier, UTC timestamp from the RTC, and the five environmental parameter values. The payload is transmitted over MQTT (port 1883 or 8883 for TLS) to the cloud broker.

4. Power Management

The STM32's Stop 2 mode is used during the measurement interval sleep periods. In Stop 2 mode, all clocks except the RTC are stopped, and the core supply is switched to a low-power regulator, reducing consumption to approximately 1.0 μ A. The RTC generates a periodic wake-up interrupt to trigger the next measurement cycle. Peripheral power gating is implemented such that the ESP8266 module, the OLED display, and non-essential sensors are powered off between measurement cycles using GPIO-controlled transistor switches.

5. Cloud Platform and Dashboard

Sensor data is received by an MQTT broker (Eclipse Mosquitto) running on a cloud VM. A Node-RED flow subscribes to the MQTT topic, parses the JSON payload, and writes the data to an InfluxDB time-series database. Grafana connects to InfluxDB to render real-time and historical dashboards displaying trend graphs, gauge indicators, and alert annotations. Threshold-based alerts are configured for critical events such as CO₂ exceeding 800 ppm, temperature exceeding 40°C, or UV index exceeding 8. Alerts are dispatched via email and WhatsApp notification using the Twilio API.

IV. POWER CONSUMPTION ANALYSIS

Accurate power budgeting is fundamental to ensuring the system's solar supply is adequate for continuous autonomous operation. The system operates in two states: active (sensor reading and data transmission, lasting approximately 3.5 seconds per cycle) and sleep

(STM32 in Stop 2 mode, lasting 56.5 seconds per 60-second cycle).

During the active phase, the dominant power consumers are the ESP8266 Wi-Fi module (approximately 170 mA peak during transmission), the MQ-135 sensor heater (approximately 150 mA), and the STM32 core (approximately 10 mA at 80 MHz). During sleep, only the STM32 RTC and the LDO regulator quiescent current draw power.

The average current consumption, weighted over the active and sleep duty cycle, is calculated as approximately 14.8 mA at 3.3 V, corresponding to an average power of approximately 49 mW. Over a 24-hour period, this equates to an energy consumption of approximately 1.17 Wh. The 10 W solar panel, under average insolation of 4.5 peak sun hours per day, generates approximately 45 Wh per day—more than sufficient to sustain the system and recharge the battery.

V. EXPERIMENTAL RESULTS AND DISCUSSION

1. Sensor Accuracy and Calibration

The system was evaluated against calibrated reference instruments over a 30-day field trial conducted at an agricultural site. Temperature and humidity readings from the DHT22 showed a root mean square error (RMSE) of 0.38°C and 1.7% RH respectively compared to the reference Vaisala HMT120 sensor, within the manufacturer's specified accuracy limits. The BMP280 pressure readings matched the reference barometer with an RMSE of 0.6 hPa. The MQ-135 air quality sensor required careful field calibration due to its cross-sensitivity to multiple gases, and after calibration against a reference CO₂ meter, achieved a mean absolute error of 18 ppm at concentrations below 500 ppm.

2. Communication Performance

Wi-Fi connectivity was stable and reliable at the field site located within 30 meters of the access point. The average data transmission latency from sensor reading completion to cloud broker receipt was 1.4 seconds. Packet loss was below 0.5% over the 30-day trial. LoRa communication was tested at a range of 2.3 km

across open farmland, achieving a packet reception rate of 98.2% at -120 dBm signal strength.

3. Power System Performance

The solar power subsystem performed as designed throughout the trial. On fully sunny days, the battery reached full charge by approximately 11:00 AM local time and remained at full charge for the remainder of the day. On three overcast days observed during the trial, the battery discharged to a minimum of 68% state of charge before solar charging resumed the following morning. The system maintained uninterrupted operation throughout the trial.

4. System Reliability

Over the 30-day evaluation period, the system logged 43,200 data points (one per minute). Data integrity analysis revealed 98.7% of readings were transmitted successfully to the cloud on the first attempt. The remaining 1.3% were retransmitted within the next measurement cycle. No data was permanently lost. The OLED local display functioned correctly as a standalone readout during simulated network outages.

VI. CONCLUSION AND FUTURE WORK

In This paper has presented the design, implementation, and field evaluation of a comprehensive IoT-based environmental monitoring system built on the STM32L476RG microcontroller and powered by a solar photovoltaic supply with MPPT charging. The system successfully monitors five key environmental parameters, transmits data wirelessly over Wi-Fi and LoRa, and operates autonomously without grid power. Field trials confirmed reliable sensor accuracy, robust wireless communication, effective power management, and sustained solar-powered operation over 30 days.

The proposed system addresses key limitations of existing approaches by combining ultra -low-power microcontroller technology, renewable energy autonomy, dual-mode connectivity, and cloud-based analytics in a compact, cost-effective design estimated at approximately USD 85 per node in component cost.

Future work will focus on several directions. First, integration of a particulate matter sensor (PMS5003)

will extend air quality monitoring to PM2.5 and PM10 measurements, which are critical urban pollution indicators. Second, on-device machine learning using the STM32's Cortex-M4 FPU will enable edge inference for anomaly detection and pollution event classification without cloud dependency. Third, a mesh networking topology using multiple LoRa nodes will be explored for wide-area coverage in large agricultural estates. Fourth, the design will be adapted for underwater environmental monitoring, specifically for water quality parameters such as pH, dissolved oxygen, and turbidity in aquaculture and riverine applications.

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