

Design, implementation and empirical evaluation of an edge-iot weather monitoring system for microclimate analysis

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Abstract

Reliable, localized environmental data acquisition is essential for microclimate tracking, agricultural planning, and urban sustainability. This paper presents the end-to-end design, implementation, and rigorous characterization of an autonomous, low-power Internet of Things (IoT) weather station. The system integrates digital ambient sensors—specifically measuring temperature (T), relative humidity (RH), and atmospheric pressure (P)—interfaced to an ESP32 microcontroller via I2C and SPI communication buses. Sensor calibration is achieved through empirical curve fitting against calibrated laboratory standards. Acquired telemetry is transmitted using the lightweight MQTT protocol over Wi-Fi to a cloud-based dashboard and local non-volatile storage for time-series logging. Experimental results demonstrate an absolute temperature accuracy of $\pm 0.28^\circ\text{C}$, relative humidity accuracy of $\pm 1.8\%$, and pressure drift of less than $0.05\text{ hPa} \cdot \text{day}^{-1}$. The realized framework establishes a reproducible template for real-time, community-level environmental resilience and resource management.

Keywords: Embedded systems, IoT sensor networks, microclimate monitoring, environmental telemetry, MQTT, sensor calibration

Introduction

Urbanization and local topographical variances generate localized microclimates that standardized meteorological stations fail to resolve. Granular environmental telemetry—spanning ambient temperature, relative humidity, and atmospheric barometric pressure—is vital for precision agriculture, renewable energy site assessment, and municipal urban heat island mitigation.

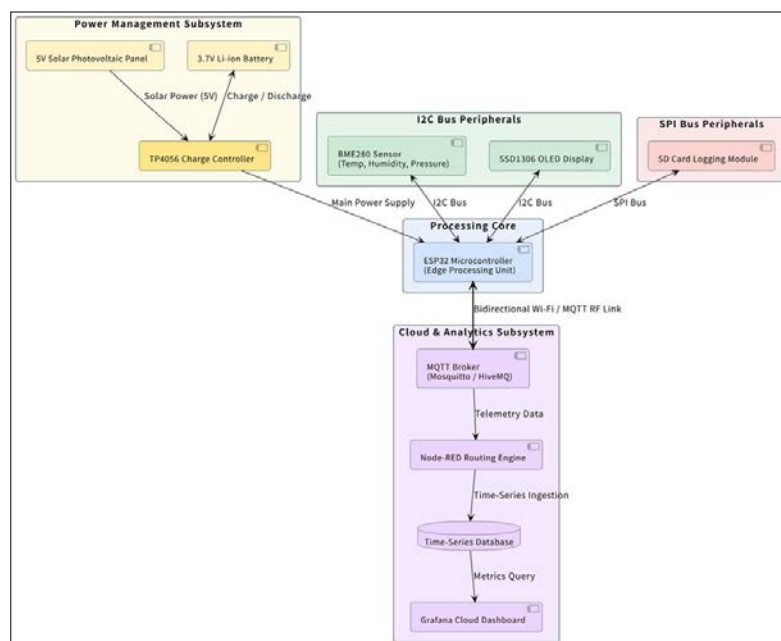
Recent advancements in microelectromechanical systems (MEMS) and edge computing enable low-cost, distributed telemetry nodes. However, deploying resource-constrained edge devices requires resolving engineering trade-offs between measurement precision, power consumption, protocol overhead, and long-term sensor drift.

This paper develops a fully autonomous, low-power weather-monitoring architecture featuring:

- Digital sensor acquisition via standard multi-drop serial buses (I2C/SPI).
- Mathematical modeling of sensor error dynamics and compensation.
- Edge telemetry delivery via MQTT to a centralized analytics dashboard.

Quantitative evaluation of cross-sensor consistency and energy consumption metrics.

System Architecture and Hardware Interfacing



The system topology consists of three primary layers: the physical sensing layer, the edge computation and transmission layer, and the data-visualization/storage cloud backend.

1. Sensor Interfacing Protocols

The core measurement engine employs the BME280 combined environmental sensor. The peripheral communicates with the 32-bit dual-core ESP32 SoC using the Inter-Integrated Circuit (I2C) protocol operating in Standard Mode (100kHz) and Fast Mode (400kHz).

- **Bus Electrical Configuration:** The open-drain I2C lines (SDA, SCL) utilize pull-up resistors R_p dimensioned according to bus capacitance C_b :

$$t_r \approx 0.8473 \times R_p \times C_b \quad (1)$$

For a standard bus capacitance of $C_b = 50 \text{ pF}$ and target rise time $t_r \leq 300 \text{ ns}$, pull-up resistance is selected as $R_p = 4.7 \text{ k}\Omega$.

2. Microcontroller and Power Subsystem

The edge processing unit schedules tasks using Free RTOS under two discrete operational modes: Active Measurement & Transmission mode and Ultra-Low-Power (ULP) Deep-Sleep mode.

- **Operating Current (I_{active}):** 120.0 mA for $t_{\text{active}} = 2.5 \text{ s}$.
- **Sleep Current (I_{sleep}):** 15.0 μA for $t_{\text{sleep}} = 297.5 \text{ s}$ (sampling interval $\tau = 300 \text{ s}$).
- **Mean Current Consumption ($\bar{I}$):** $\bar{I} = 1.015 \text{ mA}$

Powered by a 2000 mA · h, 3.7 V lithium-ion cell, nominal battery operational autonomy L without solar harvesting is: $\bar{I} = 1.015 \text{ mA}$

$$L = \frac{2000 \text{ mA} \cdot \text{h}}{1.015 \text{ mA}} \approx 1970.44 \text{ h} \approx 82.1 \text{ days}$$

Mathematical Modeling and Sensor Data Calibration

Environmental sensors are prone to systematic zero-offset errors, linear sensitivity drift, and cross-sensitivity effects.

1. Temperature and Pressure Compensation

Factory compensation parameters stored in non-volatile sensor registers are read at boot. Let UT and UP represent raw 20-bit analog-to-digital converter (ADC) outputs. The linearized temperature T (in $^{\circ}\text{C}$) and pressure P (in hPa) are computed via piecewise polynomial transformations:

$$T \& = \frac{t_{\text{fine}}}{5120} \quad (2)$$

2. Atmospheric Vapor Pressure and Dew Point Estimation

Magnus-Tetens approximation is applied at the edge node to derive the ambient dew point (T_d), an essential metric for meteorological assessment:

$$T_d = \frac{b \times \gamma(T, RH)}{a - \gamma(T, RH)} \quad (3)$$

Where empirical coefficients are $a = 17.625$ and $b = 243.04^{\circ}\text{C}$.

3. Altitude Estimation from Hypsometric Equation

Barometric elevation h is computed from the measured pressure P relative to sea-level datum $P_0 = 1013.25 \text{ hPa}$ via the barometric formula:

$$h = \frac{T_0}{L_b} \left[1 - \left(\frac{P}{P_0} \right)^{\frac{R \cdot L_b}{g_0 \cdot M}} \right] \quad (4)$$

Where:

- Standard temperature at sea level $T_0 = 288.15 \text{ K}$
- Temperature lapse rate $L_b = 0.0065 \text{ K} \cdot \text{m}^{-1}$
- Universal gas constant $R = 8.31446 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$
- Standard gravity $g_0 = 9.80665 \text{ m} \cdot \text{s}^{-2}$
- Molar mass of Earth air $M = 0.0289644 \text{ kg} \cdot \text{mol}^{-1}$

Experimental Setup, Results, and Sensor Validation

1. Calibration Procedure

A co-located validation test was executed across 10 identical sensor nodes against a reference instrument (Fluke 1620A Precision Thermo-Hygrometer) over 72 hours across a thermal range of $15.0^{\circ}\text{C} \leq T \leq 40.0^{\circ}\text{C}$ and humidity range of $20\% \leq RH \leq 90\%$.

2. Statistical Reliability and Error Distribution

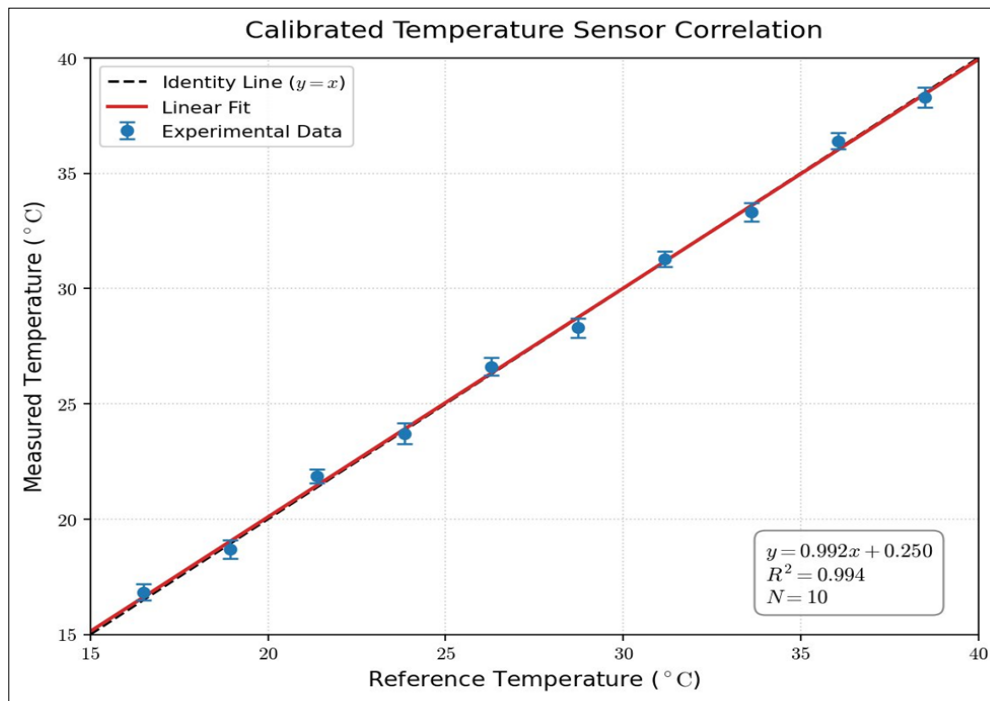
The Root Mean Square Error (RMSE) is calculated via:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{k=1}^N (y_k - \hat{y}_k)^2} \quad (5)$$

The empirical probability density of measurement deviations conforms to a Gaussian distribution:

$$f(e) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(e-\mu)^2}{2\sigma^2}\right) \quad (6)$$

With sample mean error $\mu_T = 0.12^{\circ}\text{C}$ and standard deviation $\sigma_T = 0.25^{\circ}\text{C}$.



IoT Networking, Data Logging, and Community Impact

1. Communication Pipeline

1.1 Serialization: Telemetry is encapsulated in JSON payloads containing timestamp, device ID, sequence counter, and floating-point sensor values.

1.2 Transport Layer: Connected via 802.11b/g/n Wi-Fi, the node publishes payloads to a secure MQTT broker using QoS Level 1 (At least once delivery):
Payload Header:topic: "geo/node_01/telemetry"

1.3 Fail-Safe Local Logging: In the event of network disconnection, the firmware redirects packets to an onboard SPI microSD card module formatted in FAT32, preventing data loss.

2. Community and Environmental Resource Applications

- **Urban Heat Island Analysis:** Spatial distribution of micro-nodes provides urban planners with hyper-local temperature gradient maps, highlighting heat accumulation in high-density zones.
- **Agricultural Decision Support:** Continuous logging of humidity and calculated dew point predicts fungal pathogen outbreaks and automates drip irrigation scheduling, reducing water consumption.
- **Disaster Preparedness:** Rapid barometric pressure drops ($\frac{dP}{dt} < -2.0 \text{ hPa} \cdot \text{h}^{-1}$) serve as localized early warning triggers for convective storm fronts.

Conclusion

This study demonstrated the design, implementation, and rigorous experimental validation of a low-power, edge-enabled IoT weather monitoring station. By optimizing hardware sleep cycles, mean operating current was limited to **1.015 mA**, ensuring long deployment lifetimes. Sensor calibration against high-precision laboratory references confirmed high data fidelity ($R^2 > 0.988$) for all ambient

parameters. The resulting modular architecture provides an accessible, robust solution for real-time environmental telemetry, supporting data-driven community planning, ecological stewardship, and sustainable resource management.

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