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Design and Implementation of a Smart Weather Station with Intelligent Communication Interface Selection for Reliable Data Transmission

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ABSTRACT

This paper presents the design and implementation of a smart weather monitoring system featuring an adaptive network interface selection algorithm for reliable environmental data transmission. The system combines IoT-based sensing with intelligent communication switching logic that automatically selects between Wi-Fi and GSM network interfaces base on connectivity strength and availability. This adaptive approach ensures uninterrupted operation and efficient data delivery even under unstable network conditions. Each station integrates sensors for temperature, humidity, pressure, rainfall, wind parameters, and UV index, managed by an ESP32-based controller. A cloud-hosted API service built on FastAPI handles secure data reception, while a web dashboard provides real-time visualization and historical data analysis. The firmware includes automatic configuration, selective sensor power control, and deep-sleep cycles to optimize power consumption. Experimental results show that the adaptive interface selection improves transmission reliability, reduces data loss, and maintains consistent latency across variable network conditions, ensuring up to 100% transmission success rate within the simulated network conditions. The system thus establishes a robust and scalable model for autonomous, self-optimizing weather stations, particularly suited for deployment in areas with inconsistent network coverage.

Keywords - *Adaptive communication, API services, Crowd sourced data, Internet of things, Weather station, Wireless sensor networks*

I.INTRODUCTION

Accurate and timely weather data underpin critical decisions in agriculture, transportation, energy management, and disaster mitigation (WMO, 2024). Conventional weather monitoring systems typically rely on manual observation stations and automated data loggers that transmit measurements through wired telemetry or radio links to centralized processing centres. Although effective for long-term climatological records, these systems are expensive to deploy and maintain, offering limited spatial coverage—particularly across developing regions.

In parallel, satellite-based remote sensing has become an essential complement to ground-based observations. Meteorological satellites equipped with multispectral and infrared sensors provide large-scale atmospheric data such as cloud distribution, temperature gradients, and precipitation patterns. However, their accuracy at localized scales is constrained by spatial resolution limits, atmospheric interference, and longer revisit intervals, making them less effective for real-time, high-resolution monitoring at microclimate levels.

Consequently, ground-based IoT sensor networks have emerged as practical tools for enhancing spatial granularity and temporal resolution in environmental data acquisition.

The Internet of Things (IoT) enables affordable, distributed weather stations that integrate sensors, microcontrollers, and cloud interfaces for continuous, real-time monitoring (Pal et al., 2023, Chakraborty et al., 2023). Despite these advances, network reliability remains a major operational constraint. While existing literature frequently treats Wi-Fi and GSM as isolated silos, this work bridges the gap through a synchronized dual-interface architecture designed for high-availability sensing. Unlike traditional systems that suffer from "blind handovers," our approach implements cross-layer optimization by enabling the application layer to dynamically monitor physical-layer link quality (RSSI). By utilizing a real-time failover logic, the system proactively mitigates connectivity gaps—transitioning to GSM only when Wi-Fi stability thresholds are breached. This integration ensures uninterrupted data flow in intermittent environments while simultaneously optimizing energy consumption, addressing a critical oversight in current single-interface or uncoordinated communication models. Wi-Fi offers low-power, high-speed connectivity within limited range, while GSM provides broader reach at higher data and energy costs.

The system maintains uninterrupted, low-latency data transmission integrated to a cloud-based platform for secure data management and visualization.

Weather monitoring has evolved from centralized, high-cost systems toward distributed, IoT-based architectures that integrate distributed sensor nodes and centralized cloud platforms. Early implementations such as Vujović & Maksimović (2015) demonstrated Raspberry Pi–based weather and environmental stations capable of local data processing, but their high energy demand limited portability. Hybrid designs using Arduino for sensing and Raspberry Pi for hosting (Cortes Leon et al., 2017) improved modularity yet remained tethered to mains power and Ethernet connectivity. These early systems, while technically feasible, were unsuitable for unattended or rural deployment where power and network access are constrained.

The shift to lightweight microcontroller-based systems marked a major turning point. Works such as Predolin et al. (2017) and Pal et al. (2023) leveraged NodeMCU and ESP32 modules to deliver low-cost, multi-sensor weather stations communicating via Wi-Fi. Similar implementations (Babalola et al., 2022; Chakraborty et al., 2023) demonstrated scalability and affordability but revealed persistent weaknesses: reliance on single-interface (Wi-Fi) connectivity, limited power optimization, and lack of long-term validation. As a result, these systems remain vulnerable to communication failures and energy depletion in remote field conditions.

Recent efforts have focused on enhancing modularity and sensing diversity. Albuali et al. (2023) and Bernardes et al. (2023) developed flexible IoT weather platforms supporting add-on sensors, while Megantoro et al. (2021) and Serrano et al. (2022) validated low-cost air quality and UV sensors with encouraging accuracy. However, most studies stopped short of full integration into self-sustaining, multi-network systems. Kairuz-Cabrera et al. (2024) addressed interoperability through unified cloud APIs but assumed stable infrastructure, leaving unaddressed how such systems perform under fluctuating connectivity.

Connectivity alternatives beyond Wi-Fi have been explored using GSM (Kusuma et al., 2020, Parvez et al., 2016), LoRaWAN and NB-IoT (Ballerini et al., 2020, Centenaro et al., 2016). Each offers trade-offs among range, energy consumption, and cost. GSM extends reach to rural regions but consumes more power, while LoRaWAN achieves efficiency at the cost of dependency on gateways. These limitations have inspired growing interest in hybrid or adaptive communication approaches—yet only a few implementations combine multiple interfaces dynamically. The absence of such adaptive mechanisms leaves most systems susceptible to data loss in unstable networks.

Energy efficiency has also received considerable attention. Studies by Kim & Kim (2020) and Leelavinodhan et al. (2021) demonstrated that deep sleep and threshold-based transmission can significantly reduce consumption, while Mokhtarzadeh et al. (2025) and Xia et al. (2022) integrated solar harvesting to sustain off-grid operation. Nevertheless, most of these techniques remain isolated from communication-layer decisions, missing opportunities to jointly optimize energy use and connectivity.

At a broader scale, citizen-driven networks such as Weather Underground and sensor Community (Giazzi et al., 2022) illustrate the potential of open, distributed data ecosystems. However, these platforms rely on user-maintained hardware and stable connections, underscoring the need for autonomous IoT stations that can self-manage energy and communication selection while remaining API-compatible.

While existing literature demonstrates extensive progress in IoT-based weather monitoring, a critical gap exists in the dynamic coordination of communication interfaces. Most systems rely on a single interface or require manual selection of interfaces, making them vulnerable to network instability (Ogunbunmi, 2024). Furthermore, cross-layer optimization that involves active exchange of state information between the physical and application layers remains largely underexplored in this context (Abubakar et al., 2022).

This work directly addresses these gaps by implementing a smart weather station featuring an autonomous interface selection algorithm. The system monitors real-time link quality from the physical layer to trigger application-layer decisions, such as switching between Wi-Fi and GSM interfaces. This approach ensures uninterrupted data transmission and optimized power consumption under varying field conditions, providing a level of reliability and energy efficiency that single-interface or non-coordinated dual-interface systems cannot achieve.

II. MATERIALS AND METHODS

2.1 System Overview

The system is a smart IoT-based weather monitoring platform designed to ensure reliable, sustained data transmission under varying network conditions. Its architecture integrates three functional layers. The data sensing and transmission node, and the cloud-based service layer together ensure end-to-end weather monitoring over a data visualization application such as a web dashboard.

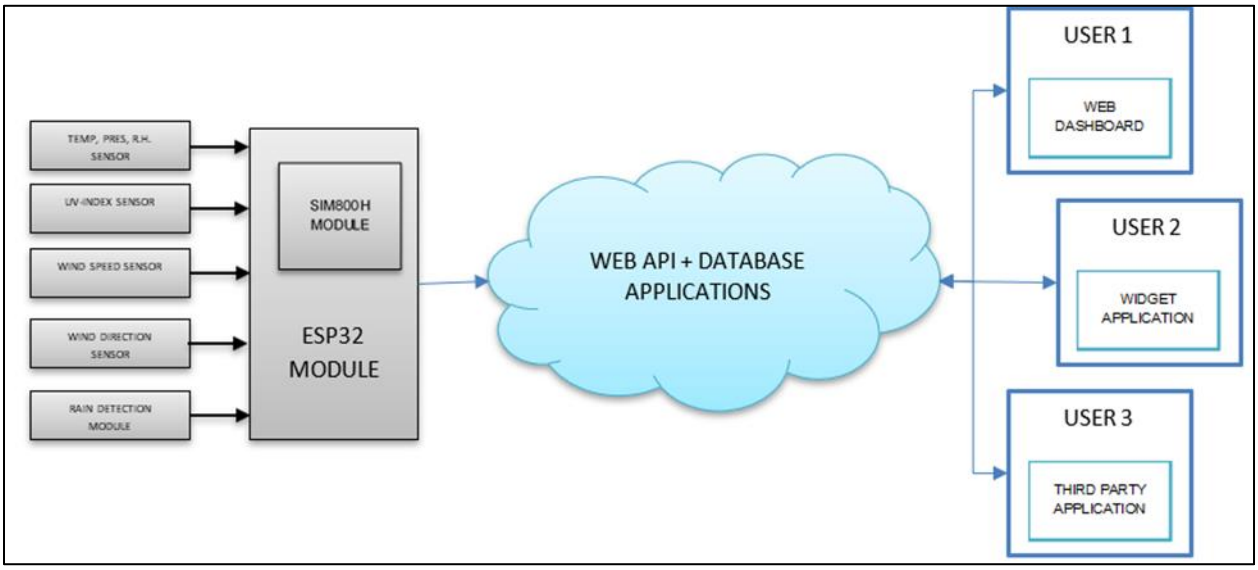

Figure 1. Block Diagram of the Weather Monitoring System

At the field level, each weather station operates as an autonomous edge node built around the ESP32 TTGO T-Call V1.4 microcontroller, which features dual connectivity through Wi-Fi and an embedded SIM800H GSM modem (igure 1). This combination allows the device to intelligently select the most suitable communication interface based on availability and reliability, ensuring continuous data transmission. The adaptive firmware implements a decision algorithm that continuously evaluates connection success, retry counts, and signal feedback to determine whether to transmit via Wi-Fi or fall back to GSM.

Sensor modules integrated with the controller measure temperature, humidity, pressure, uv-index, rainfall, and wind parameters. These sensors feed data to the firmware's acquisition routine, which preprocesses the readings, packages them into a standard JSON payload, and initiates secure transfer through the selected interface. The entire operation is governed by an energy-aware firmware that coordinates sampling, transmission, and deep-sleep cycles to balance accuracy and power efficiency.

The cloud layer comprises a FastAPI-based application with a PostgreSQL database and a web dashboard application serves for data monitoring and visualization. Once data packets reach the API application, they are authenticated using API keys, validated, and stored in structured tables within the database for both real-time and historical data access. The dashboard displays current conditions and data trends from the connected weather station nodes.

2.2 Hardware Implementation

The hardware implementation integrates the ESP32 TTGO T-Call V1.4 microcontroller, its onboard SIM800H GSM modem, environmental sensing modules, and a solar-assisted power subsystem into a compact unit suitable for autonomous field deployment. The ESP32 serves as the central controller for data acquisition, processing, and communication, while supporting both GSM and Wi-Fi connectivity to ensure reliable data transmission under varying network availability.

Table 1: Operational specification of the weather station

Parameter	Value	Unit	Description
Sampling interval	User configurable	minutes	Time between consecutive data acquisition cycles
Communication retry count	3	-	Maximum number of transmissions retries per cycle
Wi-Fi connection timeout	5	seconds	Maximum time allowed for Wi-Fi connection attempt
GSM connection timeout	20	seconds	Maximum time allowed for GSM network registration

The power subsystem is built around a 3.7 V 18650 Li-ion battery, charged via a TP4056 charging module and supported by a 6 V solar panel for autonomous recharging. Battery output is routed through an MT3608 boost converter that generates a regulated 5 V rail for the ESP32 board and the embedded SIM800H modem, with logic-level power subsequently derived from the ESP32's onboard 3.3 V regulator. A second MT3608 boost converter supplies 12 V to the FSJT-I20 wind speed sensor and FXJT-I20 wind direction sensor. The BME280, VEML6075, and CJMCU-606 sensors are powered directly from the ESP32's regulated 3.3 V output.

Energy efficiency is a core design consideration for sustained field operation. Power consumption is reduced through the use of ESP32 deep-sleep modes between acquisition cycles and microcontroller-controlled power switching, which energizes external sensor modules only during measurement windows. Component-level power estimation indicates an active-mode power draw of approximately 745 mW and a deep-sleep consumption of about 4 mW, corresponding to an idle current below 1 mA. Based on these estimates, a 3000 mAh battery (≈ 11.1 Wh) can support roughly 14–15 hours of continuous active operation, with operational lifetime extending to several days under the implemented power management strategy.

All sensing and communication modules interface directly with the ESP32 through its GPIO, I^2C, UART, and ADC peripherals, as illustrated in Figure 2. The BME280 environmental sensor communicates over the I^2C bus and provides temperature, relative humidity, and barometric pressure measurements. The VEML6075 UV sensor produces an analog voltage output that is sampled using the ESP32's 12-bit ADC, while the CJMCU-606 rain sensor delivers a digital HIGH/LOW signal indicating precipitation presence. Wind measurements are obtained from the FSJT-I20 and FXJT-I20 sensors, which provide 4–20 mA current loop outputs. Each signal is terminated with a precision 150 Ω shunt resistor, converting the current to a 0.6–3.0 V voltage range compatible with the ESP32's 3.3 V ADC inputs. These voltages are digitized and linearly mapped in firmware to wind speed (0–60 m/s) and wind direction (0–360°). Sensor readings are sampled according to the acquisition routine and packaged into structured payloads for transmission via the automatically selected Wi-Fi or GSM interface.

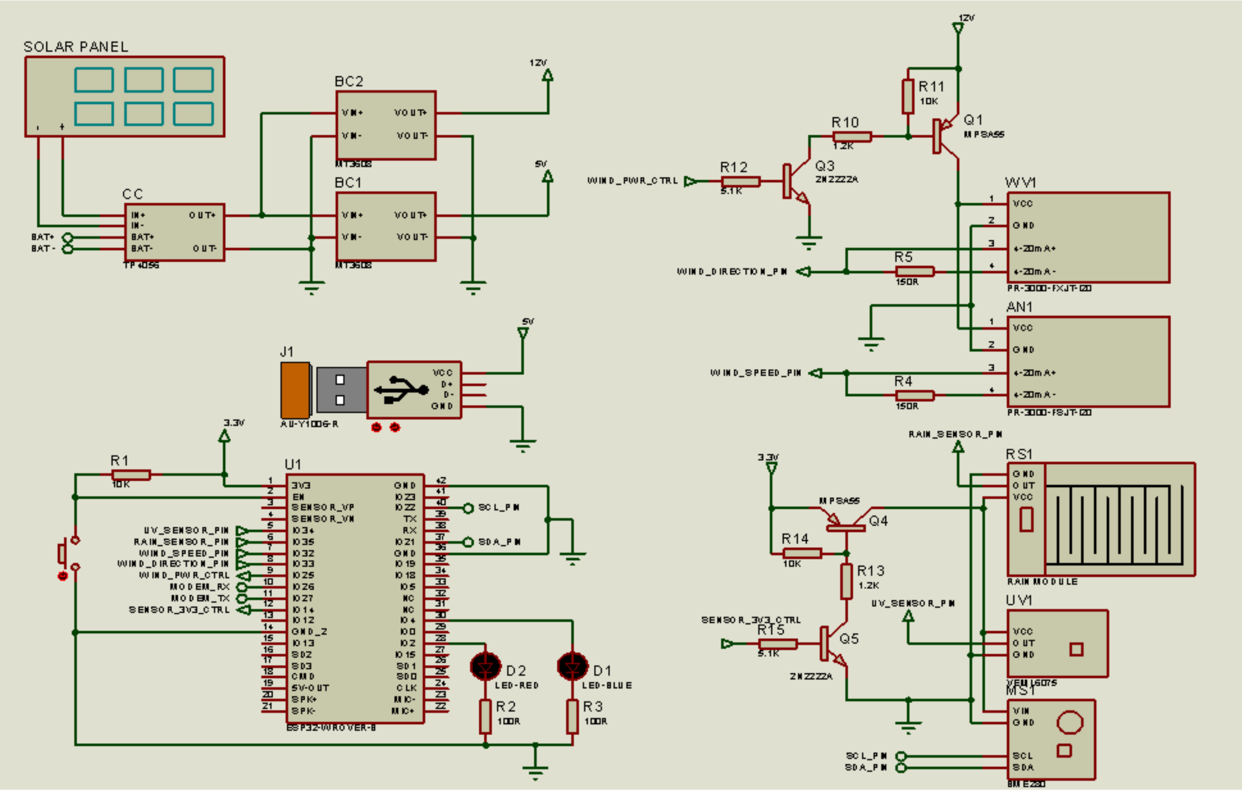

Figure 2. Complete circuit diagram of weather station

2.3 Software Implementation

The station firmware is developed in C++ using the Arduino framework. It coordinates all autonomous operations including configuration handling, sensor polling, network interface selection, data packaging and transmission, and power scheduling as described in the operational flowchart (Figure 3). At startup, the microcontroller loads stored configuration parameters which include Wi-Fi SSID, GSM APN, API URL, and API key from EEPROM. If these records are unavailable or invalid, the system enters Configuration Mode, where it hosts a temporary access point and web form for parameter entry before saving the submitted values and restarting. Configuration Mode may also be manually triggered during initialization via an integrated DIP switch. Once configuration data are available, the firmware proceeds with the operational routine.

During each cycle, the firmware conducts a network scan; attempts to connect through Wi-Fi as the primary interface and falls back to GSM if Wi-Fi fails to establish or if the received signal strength is below threshold. Temporary GSM failures (e.g., low signal) prompt the system to enter deep sleep and retry on the next wake cycle, whereas critical faults such as SIM absence return the device to Configuration Mode. Once a network connection is successfully established, the firmware activates the sensor power rails through GPIO-controlled switches and executes the polling routine. Each module is briefly powered during its sampling window to minimize energy usage, after which the acquired readings are processed, converted to proper engineering measurement units and structured into a JSON payload.

The compiled data packet is transmitted to the remote API server using the active network interface with transmission retries up to three times in case of transient communication errors. At the end of each cycle, the microcontroller enters deep sleep for a predefined interval, concluding the execution loop. Through this integrated control structure, the firmware ensures autonomous field operation, reliable data transfer, and efficient energy management across varying network and environmental conditions.

The station is supported by a cloud platform consisting of a FastAPI service and PostgreSQL database that collect store and serve data to requesting nodes for visualization and analysis. The backend exposes RESTful endpoints for weather data submission, historical and real-time data retrieval, user authentication, and weather station management. Incoming requests are validated and written to structured database tables, while authenticated clients access the stored records through dedicated query endpoints.

The web-based frontend, developed using HTML, CSS, and JavaScript, dynamically fetches data from the API and renders both real-time readings and historical trends on dashboards. This implementation supports continuous synchronization between the weather station nodes and the cloud service, maintaining reliable operation.

2.4 Packaging Design

All components are housed in a UV-resistant PVC enclosure, fitted with ventilation slots for airflow, transparent window above optical sensor, externally mounted wind sensors to minimize turbulence effects, internal compartments separating power and controller circuitry from sensor components, improving accuracy and EMI isolation. Figure 4 shows the field ready weather station hardware featuring compact, weather-sealed design that ensures operational resilience in humid or dusty environments.

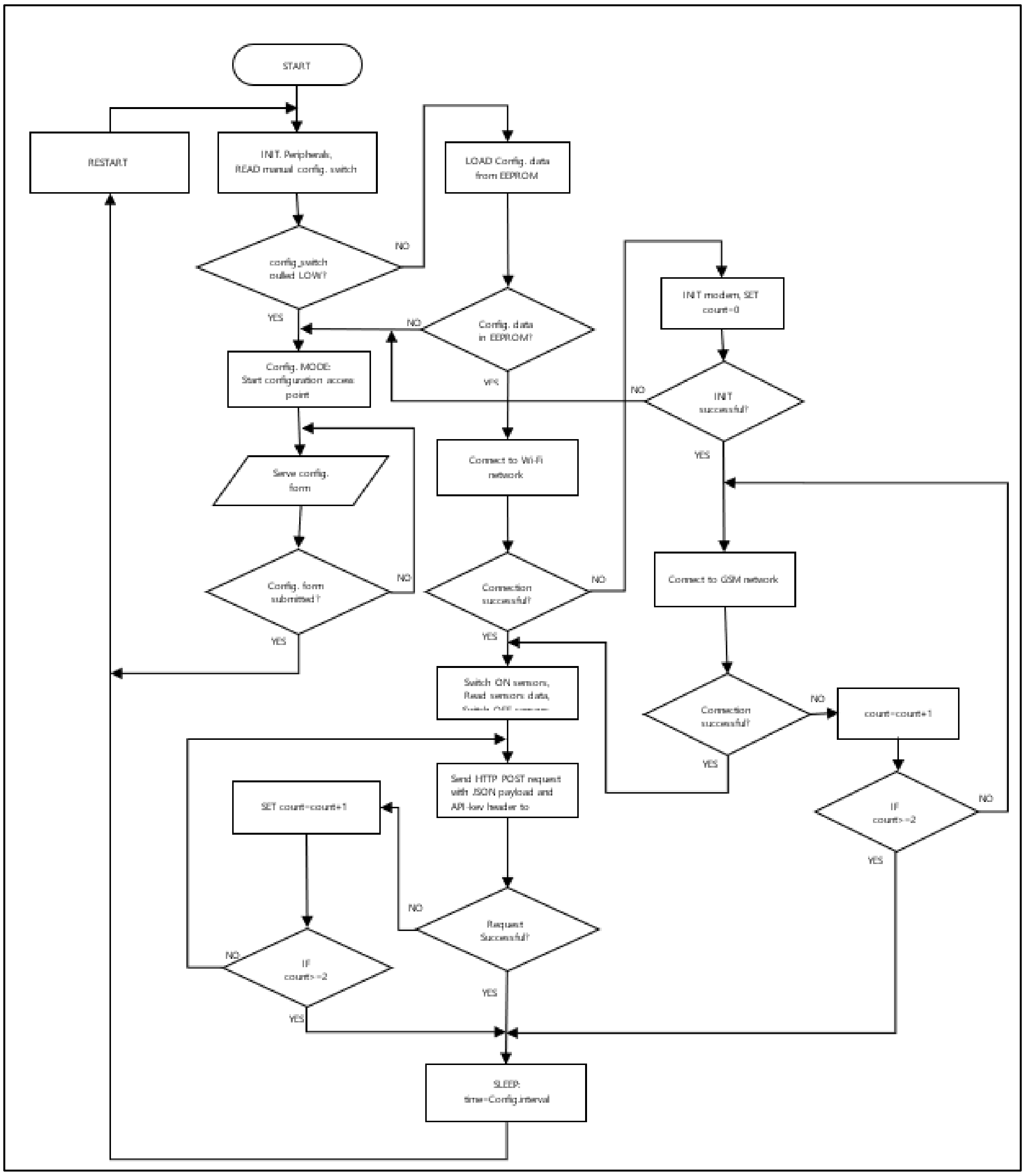

Figure 3. Operational flowchart of the weather station

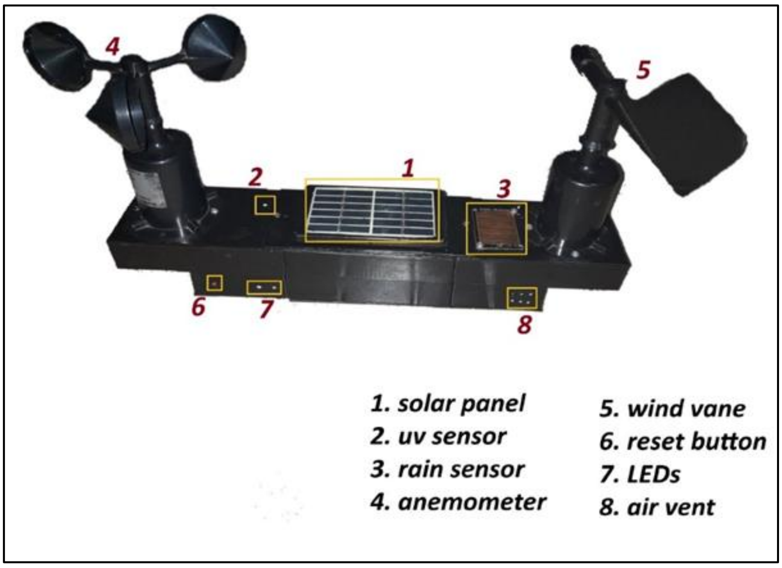

Figure 4. Weather station packaging

2.5 Testing Procedures

2.5.1 Sensor Validation Tests

Each sensing module was validated individually before integrated system testing. The BME280 sensor was assessed in an air-conditioned room by observing cooling and warming cycles and comparing the readings with a calibrated thermometer. The FSJT-I20 and FXJT-I20 wind sensors were evaluated using a multi-speed fan and manual vane rotation.

2.5.2 Adaptive Communication Test

The adaptive communication algorithm was validated by simulating varying network conditions and observing real-time firmware logs. At startup, the station attempted to connect via Wi-Fi using stored credentials. Failure to establish connection with the configured Wi-Fi access point triggered GSM mode. The SIM800 module connected to cellular network, established a GPRS session using the configured APN, and transmitted data successfully. Whenever Wi-Fi connectivity was restored, the system automatically switched back to Wi-Fi for subsequent transmission cycles, validating the responsiveness of the network-selection logic. Data delivery rate and latency were recorded for both Wi-Fi and GSM interfaces (Table 5).

III. RESULTS AND DISCUSSION

3.1 Results of the Sensor Validation Test

Results demonstrated close alignment, with an average temperature deviation of approximately ±0.3°C, while humidity and pressure readings remained stable under controlled indoor conditions (Figures 5–8).

Outdoor tests of the VEML6075 module produced UV index readings that matched natural diurnal behaviour, increasing from below 1.0 in the early morning to above 8.0 around midday (Figure 9). The FSJT-I20 exhibited a linear output over the 0–8m/s range, and the FXJT-I20 correctly identified all eight cardinal directions (Tables 2 and 3). While the CJMCU-606 rain sensor provided immediate digital transitions when exposed to moisture and returned to its default state upon drying, as summarized in Table 4.

Collectively, these tests established the reliability of the sensing subsystem prior to system-wide operation evaluation.

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The results demonstrate that the system performs reliably across sensing, communication, and overall data-delivery requirements. Sensor outputs were stable and aligned with reference values, with the BME280 maintaining a narrow temperature error margin and other environmental parameters responding predictably to changing conditions.

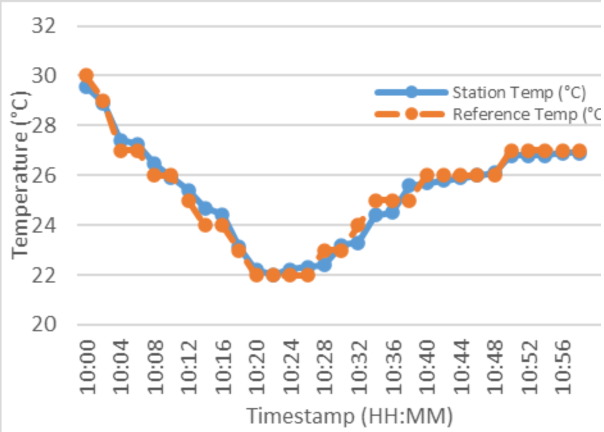

Figure 5. BME280 temperature reading closely tracking the reference temperature of the thermostat.

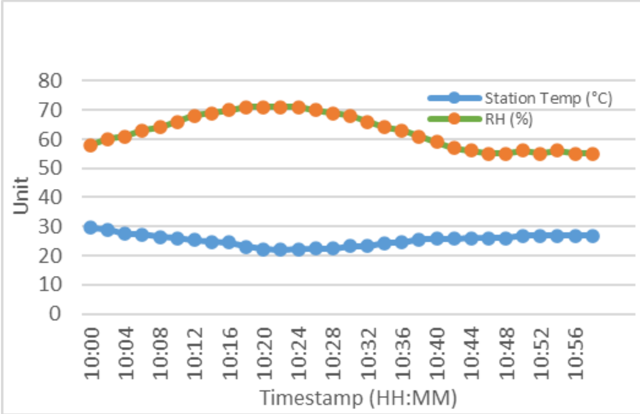

Figure 7. Observed inverse correlation between temperature and relative humidity.

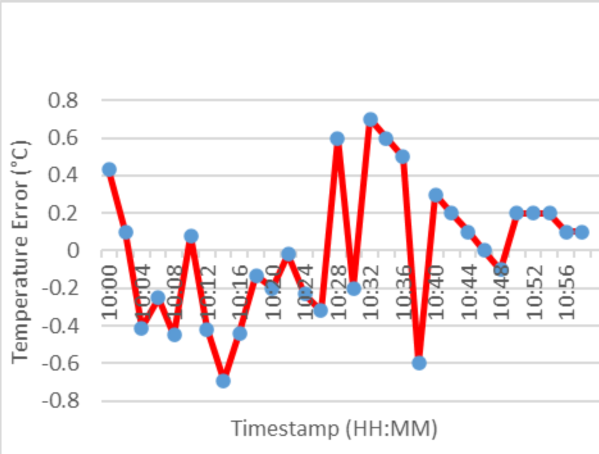

Figure 6. Deviation of BME280 temperature from reference temperature.

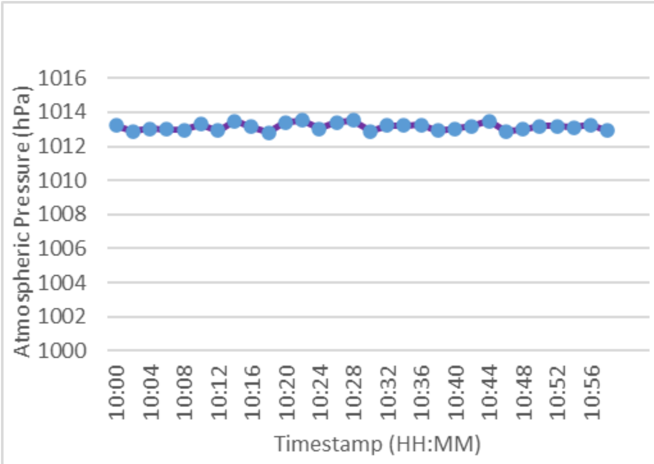

Figure 8. Stable pressure trend throughout the cooling and warming phase.

The VEML6075 produced UV index variations that matched expected solar patterns with lower values of 0.35 and 0.9 in the morning and late afternoon respectively, peaking at 8.35 during high solar exposure. Wind and rain sensors exhibited accurate, repeatable behaviour across all test scenarios. These results confirm the suitability of the selected modules for continuous IoT-based environmental monitoring.

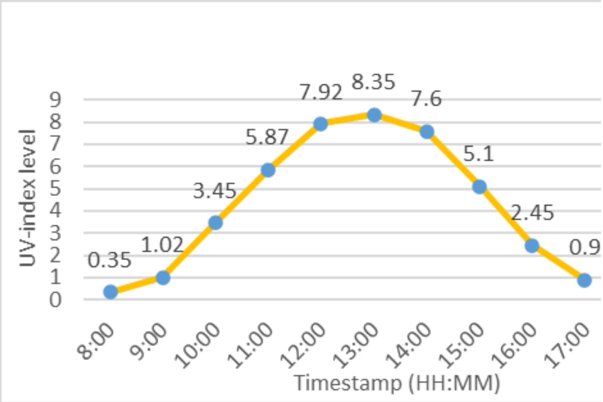

Figure 9. UV-index curve showing variation with sunlight exposure

Table 2. FSJT-I20 wind speed test results

Fan Speed	Value (m/s)	Observation
Off	0	No airflow, baseline value
Low	1.2	Sensor detected light breeze
Medium	3.5	Moderate airflow captured
High	6.7	Strong wind detected
High-Closer	8	Maximum speed achieved in test

Table 3. FXJT-I20 wind direction test results

Sensor Orientation	Reported Direction	Observation
North	N	Accurate
North-East	NE	Accurate
East	E	Accurate
South-East	SE	Accurate
South	S	Accurate
South-West	SW	Accurate
West	W	Accurate
North-West	NW	Accurate

Table 4. Rain detection module test results

Condition	Sensor Output	Interpretation
Dry surface	LOW (false)	No rain detected
Light spray	HIGH (true)	Rain detected
Continued spray	HIGH (true)	Still wet
Spray stopped	HIGH (true)	Surface still wet
Dried manually	LOW (false)	Dry, no rain
Re-sprayed	HIGH (true)	Rain detected

Communication performance further highlights the robustness of the system. Wi-Fi provided low-latency transmission in infrastructure rich environments, while GSM served as an effective connectivity backup, ensuring successful data transmission under induced Wi-Fi connectivity loss. All transitions between Wi-Fi and GSM occurred smoothly, and no data packets were lost during the cycles of simulated network disruptions, yielding a combined 100% data transmission success rate for both interfaces. This demonstrates that the adaptive communication logic provides dependable operation for both infrastructure-rich and remote deployment environments. Furthermore, Successful and consistent responses and data updates to the dashboard throughout the test indicated correct backend performance in storing and serving data through authenticated requests.

Table 5. Data Communication Metrics

Metric	Wi-Fi Mode	GSM Mode	Remarks
Transmission success rate	100%	100%	GSM retries successfully handled transient drops
Average latency	1.2s	3.8s	GSM exhibited higher latency due to relay processing

Overall, the integrated evaluation confirms that the weather station provides accurate sensing, fault-tolerant communication, and dependable end-to-end data transmission. These characteristics make it suitable for long-term, autonomous deployments across diverse environmental and connectivity conditions.

The results validate the proposed system's core objective — maintaining reliable and efficient data delivery through adaptive communication interface selection.

Wi-Fi provided the preferred low-latency path under stable network conditions, while GSM ensured continued connectivity during disconnections or weak coverage. This hybrid logic effectively combined the advantages of both interfaces: low cost and high speed (Wi-Fi) with broad accessibility (GSM).

The cloud integration further strengthened the system's resilience by ensuring every transmitted dataset was received, authenticated, and logged without duplication.

The firmware demonstrates that intelligent network adaptation is a practical solution to the reliability challenges of IoT-based weather monitoring — bridging the performance gap between urban and remote-area deployments.

IV.CONCLUSION

This work presented the design and implementation of an IoT-based weather monitoring system with a communication interface capable of selecting between Wi-Fi and GSM networks based on availability. The system combined modular hardware, adaptive firmware logic, and a cloud-based API and dashboard for environmental data collection and visualization.

Performance evaluation of the sensing subsystem indicated accurate environmental measurements. Temperature readings closely matched the reference sensor, capturing a cooling phase from approximately 30 °C to 22 °C and subsequent stabilization between 26 °C and 27 °C. The maximum deviation from the reference did not exceed ±0.5 °C, with slightly larger discrepancies during periods of rapid temperature change, consistent with expected sensor response time.

Relative humidity measurements reflected the expected inverse relationship with temperature, increasing from around 58% to 72% as temperature decreased and stabilizing between 55–57% as temperature recovered. Atmospheric pressure remained between 1012 hPa and 1014 hPa, showing minimal short-term variation and indicating stable sensor performance.

Ultraviolet radiation measurements captured diurnal trends, with the UV index rising from 0.35 at 08:00 to a peak of 8.35 at 13:00 under clear conditions, then decreasing to 0.90 by 17:00 under overcast conditions. These results suggest the UV sensor was responsive to both solar elevation and sky conditions.

Testing of the communication interface showed that the system could switch between Wi-Fi and GSM to maintain data transmission. Laboratory and field tests recorded uninterrupted data delivery, with the system engaging GSM when Wi-Fi connectivity was reduced or lost. Dashboard updates reflected the continuity of data transmission.

The system's modular architecture allows each sensor node to operate independently while contributing to a shared dataset, indicating potential for multi-station deployment and distributed environmental monitoring.

Limitations observed include the SIM800 GSM module's lack of native HTTPS support, requiring external solutions for secure data transmission, and the deterministic network selection logic, which does not currently consider historical signal quality or energy availability. Field testing was limited in duration, suggesting the need for longer deployments to assess long-term sensor stability and environmental resilience.

Future work could explore predictive or machine-learning-based network selection, alternative communication hardware such as 4G or hybrid GSM–LoRaWAN modules, and multi-node field deployments to further assess system performance and scalability.

AUTHOR(S) CONTRIBUTIONS

H. E. Amhenrior provided the project concept, academic supervision, and technical guidance throughout the study. He critically reviewed the methodology, validated the results, and contributed to refining and approving the final manuscript. U. A. Musah designed and developed the weather monitoring system, implemented the hardware and firmware, conducted experiments, collected data, and performed the analysis.
Both authors read and approved the final version of the paper.

AI DISCLOSURE

This paper was prepared primarily through the authors' independent effort. Artificial intelligence (AI) tools were used only in a limited capacity for non-technical support, such as language editing, grammar correction, and general formatting. No AI tools were used in the development of the technical content, analysis, or conclusions, which remain entirely the work of the authors.

DECLARATION OF CONFLICT OF INTEREST

Authors have no conflict of interest to declare

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