Adaptive IoT-Enabled Node for Multi-Parameter Environmental Sensing and Cloud-Based Analytics

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***Abstract*: Environmental monitoring is increasingly important due to rising pollution levels, climate variability, and sustainability concerns. This paper presents a compact IoT enabled environmental sensing node that integrates a Beetle ESP32-C6 microcontroller with a DF Robot Fermion multifunctional sensor for continuous measurement of temperature, humidity, barometric pressure, ambient light, and ultraviolet index. The sensed data are periodically transmitted over Wi-Fi 6 to a cloud analytics platform, where they are stored, visualized, and analyzed for anomaly detection and user notification via web or mobile dashboards. Along with a description of the hardware architecture, communication pipeline, and software implementation, the paper briefly reviews recent smart environmental monitoring solutions that leverage IoT, wireless sensor networks, and data analytics for air quality monitoring, water quality supervision, and precision agriculture. Experimental results from a prototype deployment demonstrate that the proposed design simplifies the realization of distributed, low power monitoring nodes and supports scalable, data driven environmental management in both urban and rural settings.**

Index Terms— environmental monitoring, Internet of Things (IoT), ESP32-C6, smart sensor, wireless sensor networks (WSNs)

I. INTRODUCTION

The condition of the environment strongly influences human health, ecosystem stability, and long-term economic development. Rapid growth of cities, intensive industrial processes, and shifts in climate patterns has intensified issues such as air pollution, extreme temperature events, and degradation of natural resources. Traditional approaches that depend on sparse sampling stations and laboratory based analysis often yield delayed and geographically coarse information, making proactive mitigation challenging.

The emergence of the Internet of Things (IoT), wireless sensor networks (WSNs), and embedded intelligence has enabled smart environmental monitoring (SEM) platforms that can gather, process, and disseminate data continuously from spatially distributed locations. Low-cost embedded boards with built-in wireless interfaces are now capable of sensing parameters such as temperature, humidity, pollutant concentration, and radiation, and forwarding these measurements to cloud services for storage and analytics. Incorporating machine learning further enables functionalities like anomaly detection, trend analysis, and risk prediction.

Several reported systems employ Arduino or NodeMCU class controllers with discrete modules such as DHT11, BMP180, and MQ135 to implement low-cost monitoring, often with visualization through Android applications or simple web interfaces. While these designs prove the feasibility of inexpensive sensing, they frequently suffer from larger physical size, increased wiring complexity, and reliance on earlier generation Wi-Fi chipsets with higher power consumption. Recently introduced microcontrollers, such as the ESP32-C6, combined with compact multifunctional environmental sensor boards, offer a pathway to more integrated and energy efficient sensing nodes.

In this work, we develop and demonstrate a smart environmental monitoring device based on the Beetle ESP32-C6 and a DF Robot Fermion environmental sensor module. The node captures multiple environmental variables, transmits them to a cloud platform for analytics and visualization, and supports rule based alert generation accessible via mobile or web interfaces. In parallel, the paper presents a concise survey of representative SEM solutions from recent literature, emphasizing application domains, enabling technologies, and unresolved research issues. The goal is to showcase compact, extensible node architecture and relate it to current trends in IoT based environmental monitoring.

II. LITERATURE SURVEY AND BACKGROUND

Environmental monitoring practices have evolved from manual sample collection with offline laboratory processing to automated sensor based infrastructures with remote data access. Early systems often relied on isolated instruments with minimal communication support, limiting both spatial coverage and temporal resolution. The introduction of WSNs enabled denser deployment of sensing nodes and remote data acquisition but introduced challenges in power management, data fusion, and network scalability.

The integration of IoT platforms, cloud computing, and edge analytics has significantly reshaped SEM system architectures. Recent solutions commonly employ microcontroller or SoC based nodes that measure physical or chemical variables and relay the data via Wi-Fi, cellular links, or low power wide area networks (LPWANs) to cloud services such as ThingSpeak, Blynk, or custom dashboards for long term storage and visualization. Numerous studies report IoT nodes using ESP8266 or NodeMCU boards with sensors like DHT11 or MQ series gas sensors for monitoring temperature, humidity, and air quality, with results accessible through mobile applications or web portals. Similar concepts have been extended to weather stations, air quality networks, and water quality platforms.

Survey type papers have provided comprehensive overviews of SEM systems that combine IoT, modern sensing devices, and machine learning across domains including air and water quality, ionizing radiation, and agricultural environments. These reviews highlight that improved sensor technology and data driven algorithms have made environmental monitoring more adaptive and predictive, while also pointing out open questions related to standardization of communication protocols, robust noise reduction, and reliable classification techniques. Other contributions focus on real-time IoT frameworks using low-cost microcontrollers and cloud dashboards, demonstrating practical deployments for pollution monitoring, local weather reporting, and crop supervision.

More recent projects emphasize new microcontroller families such as the ESP32-C6 and integrated environmental sensor modules offered by vendors like DF Robot. These platforms combine WiFi6, Bluetooth 5-series radios, and IEEE 802.15.4 support with compact multi parameter sensing (e.g., temperature, humidity, and pressure, light, and UV exposure), making them suitable for battery powered or remote installations. However, the literature still reports persistent issues related to secure data transmission, interoperability among heterogeneous IoT devices, and long term energy aware operation. These limitations motivate further exploration of lightweight communication protocols, edge side processing, and adaptive power management strategies.

III. PROPOSED WORK:

The proposed solution is a smart environmental sensing node that tightly integrates the Beetle ESP32-C6 development board, a DF Robot Fermion multifunctional environmental sensor, and a cloud hosted analytics platform. The design objective is to support continuous multi parameter monitoring in a compact, low power form factor that can be deployed in agricultural plots, industrial sites, or urban micro-environments.

The system can be conceptualized in three logical layers:

1. Sensing layer: The Fermion module measures parameters such as temperature, relative humidity, barometric pressure, ambient light intensity, and UV index, providing digital outputs over an I2C interface.
2. Processing and communication layer: The Beetle ESP32-C6 periodically acquires the sensor readings, performs basic pre-processing (unit conversion, sanity checks, and threshold comparison), and uploads the data via Wi-Fi 6 using application protocols such as MQTT or HTTP to a cloud server.
3. Cloud and application layer: A cloud service (for example, ThingSpeak or a comparable IoT platform) maintains the data streams, generates visualization dashboards, and enables historical trend analysis, statistics, and alert rules.

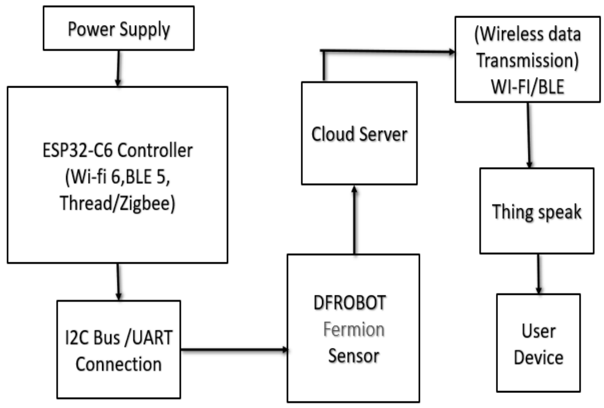

Fig. 1. Working of smart environmental sensor analyzer using IoT

The node operates in a duty cycled mode: the ESP32-C6 wakes from a low power state, acquires the latest sensor values, transmits the packet to the cloud, and then returns to sleep to conserve energy. Whenever a parameter exceeds a predefined threshold, the cloud application can issue notifications to end users through Android or web interfaces, and can be extended to actuate external devices such as ventilation fans or alarms. With suitable analytics models running in the cloud or at the edge, the system can also be adapted for short-term forecasting of heat waves, high UV exposure periods, or abnormal micro-climatic conditions based on recent trends.

IV. SYSTEM DESCRIPTION

A. Beetle ESP32-C6 Development Board

The Beetle ESP32-C6 is a miniaturized development board that exposes the capabilities of the ESP32-C6 SoC in a very small footprint. The underlying microcontroller features a 32-bit RISC-V core clocked up to 160 MHz, with on-chip SRAM and ROM sufficient for typical IoT applications, alongside integrated Wi-Fi 6, Bluetooth Low Energy 5.3, and IEEE 802.15.4 radios supporting Thread and Zigbee protocols. General purpose I/O pins and serial interfaces such as UART, SPI, and I2C allow easy connection of digital sensors and peripherals, while low power modes enable battery operated use cases.

Key technical characteristics include:

- 32-bit RISC-V CPU running up to 160 MHz
- On-chip memory (SRAM and ROM) suitable for compact IoT firmware
- Wi-Fi 6 support on 2.4 GHz with improved throughput and efficiency

- Bluetooth 5.3 Low Energy for short-range, low-power communication
- IEEE 802.15.4 interface enabling Thread and Zigbee operation
- Operating voltage typically around 3.3 V with low-power design considerations
- Wide operating temperature range appropriate for outdoor environments

These features make the board suitable for scenarios that demand compact size, multi-protocol wireless connectivity, and low energy consumption.

B. DF Robot Fermion Environmental Sensor

The DF Robot Fermion series comprises modular sensors optimized for high-precision environmental measurements in IoT applications. Depending on the specific model, these modules can capture parameters such as temperature, humidity, air-quality indices, gas concentrations, and particulate matter. In the context of this work, a Fermion environmental module is used to sense temperature, humidity, barometric pressure, ambient light, and UV index. The sensor communicates with the microcontroller through standard digital interfaces (typically I2C), simplifying integration.

The main advantages of Fermion modules are:

- Compact form factor for easy inclusion on small PCBs or prototypes
- Low power consumption suitable for battery-operated IoT nodes
- High sensitivity and quick response for timely environmental assessment
- Standardized interfaces (I2C or UART) that reduce hardware complexity

When combined with the ESP32-C6, these sensors provide real-time multi-parameter environmental data that can be streamed to cloud platforms for visualization and analytics, supporting scenarios such as outdoor air-quality monitoring, greenhouse supervision, or environmental auditing in industrial plants.

C. Power Supply Considerations

A stable and efficient power subsystem is essential for reliable node operation. The ESP32-C6 typically operates at 3.3 V, though the board may accept a higher input voltage (e.g., 5 V) which is internally regulated. Possible power sources include USB adapters, DC supplies, or rechargeable battery packs (Li-ion/Li-Po). For portable or remote deployments, battery capacity and efficiency become critical, and the firmware must exploit low-power modes to extend operating lifetime. Voltage regulators and decoupling capacitors help maintain a clean supply and mitigate voltage fluctuations. For long-term outdoor installations, the system can be augmented with solar panels and suitable charge-management circuits.

D. Cloud Platform: ThingSpeak

ThingSpeak, a cloud-hosted IoT analytics service by MathWorks, is used as a representative platform in this work. It supports secure ingestion of data from IoT devices, real-time visualization through charts, and server-side execution of MATLAB scripts for analysis and post-processing. By using ThingSpeak, developers can rapidly prototype end-to-end IoT solutions without maintaining their own web servers or databases. For small to medium-scale deployments, it offers an integrated environment for data logging, visualization, and basic analytics, which aligns well with the requirements of the proposed environmental monitoring node.

V. Flow of Operation

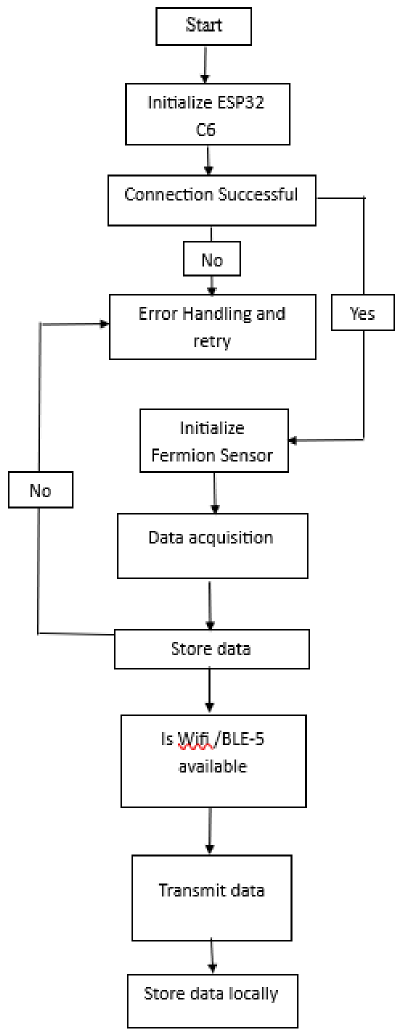

Fig. 2. Flowchart of Smart Environmental Sensor Analyzer

The logical flow of the smart environmental sensor analyzer can be summarized as follows:

1. Initialize the ESP32-C6, configure Wi-Fi credentials, and set up communication with the Fermion sensor via I2C.
2. Periodically wake the microcontroller from low-power sleep and acquire sensor readings for all required parameters.
3. Perform basic data processing, including unit conversion, range checks, and comparison with predefined thresholds.

4. Format the data into an appropriate message structure and transmit it to the cloud platform using MQTT or HTTP.
5. On the cloud side, store the incoming data, update graphs and dashboards, and evaluate alert rules.
6. Send notifications to users or actuate connected devices when abnormal conditions are detected.
7. Return the node to a low-power state until the next sensing interval.

This flow can be represented in a standard flowchart, including initialization, sensing, communication; decision (threshold) blocks, and sleep states.

VI. PROTOTYPE MODEL

The physical prototype consists of the Beetle ESP32-C6 board interfaced with the DF Robot Fermion environmental sensor, mounted on a small PCB or breadboard, and powered via USB or a battery pack. The node is configured with Wi-Fi credentials to connect to a local access point and communicate with the ThingSpeak cloud. The compact size of the Beetle board, combined with the integrated sensor module, yields a small and easily deployable unit that can be installed indoors or outdoors (with suitable enclosure protection). The model demonstrates how the proposed architecture can be realized using off-the-shelf components.

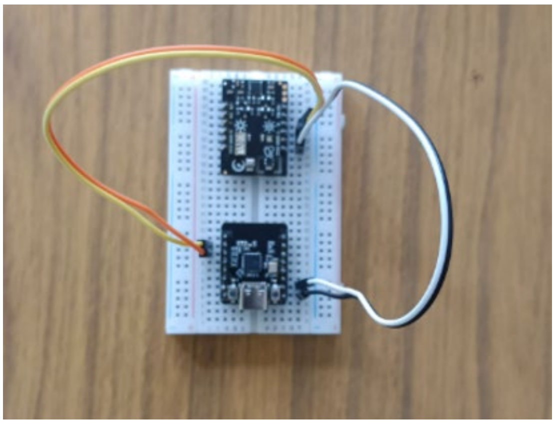

Fig. 3. Model of Smart environmental monitoring device using IOT analytics

VII. EXPERIMENTAL RESULTS

During experimental evaluation, the node was deployed in a representative environment and configured to upload sensor data at regular intervals to the ThingSpeak platform. The dashboards displayed real time plots of temperature, humidity, pressure, ambient light, and UV index, allowing visual inspection of diurnal patterns and short term fluctuations. The alert mechanism was tested by configuring threshold limits, after which notifications were generated when selected parameters exceeded the configured ranges.

The results confirm that the Beetle ESP32-C6 and Fermion sensor combination provides stable measurements and reliable connectivity using Wi-Fi 6. The duty cycled operation reduced average power consumption, suggesting that the node is suitable for battery powered deployments. The experiments also highlight the importance of robust network configuration and appropriate enclosure design for long term field operation.

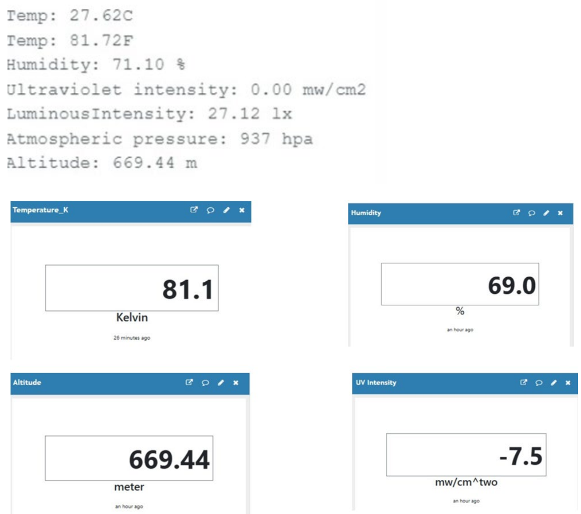

Fig. 4. Experimental Results

VIII. CONCLUSION

This paper presented an IoT enabled smart environmental monitoring node that integrates the Beetle ESP32-C6 microcontroller, a DF Robot multifunctional environmental sensor, and a cloud based analytics backend. The prototype supports real time acquisition and transmission of key environmental parameters such as temperature, humidity, pressure, ambient light, and UV index, while leveraging modern Wi-Fi 6 connectivity for flexible deployment. The design illustrates how multi parameter sensing, compact form factor, and cloud dashboards can be combined to support continuous monitoring in urban, industrial, and agricultural contexts, enabling early detection of environmental anomalies.

At the same time, the work underscores ongoing challenges involving secure data handling, long term energy management, and interoperability across heterogeneous IoT ecosystems. Future extensions may include integrating edge side anomaly detection, stronger encryption and authentication mechanisms, and additional sensing modalities (e.g., gas concentration or particulate matter) to broaden the scope of environmental assessment.

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