Dr. Mahendra Kumar pal,
Assistant Professor, Department of Civil Engineering IIT-BHU, Banaras Hindu University Campus, Uttar Pradesh 221005 India
GST IN: 09AAAJI0396R1

Activity Results Report:

"Design & Development of Low Power Wireless node with Satellite communication"

This project focuses on the design and development of a low-power wireless node with integrated satellite communication capabilities. The objective is to establish a robust and reliable communication system that operates independently of conventional cellular or Wi-Fi networks. This makes it particularly useful for remote areas, offshore locations, and regions where terrestrial infrastructure is either unreliable or non-existent.

The wireless node is engineered to consume minimal power, extending operational life when powered by standard batteries or connected to limited energy sources. Key design considerations include compact form factor, lightweight components, and optimized power management. These features ensure the node can be deployed in the field for extended periods without frequent maintenance.

At the core of the system is a satellite modem module capable of two-way data communication using Low Earth Orbit (LEO) satellite constellations. The node can collect data from various sensors (e.g., temperature, humidity, pressure, motion) and transmit it securely to a cloud or ground station for further analysis. The system supports message queuing, time-stamping, and minimal packet loss, ensuring high data reliability even in adverse environmental conditions.

This satellite-based approach bypasses the limitations of traditional infrastructure and enables wide-area connectivity for use cases such as disaster management, environmental monitoring, remote asset tracking, and agricultural field data collection. The system is designed to be modular and scalable, allowing future enhancements like GPS integration, encrypted communication, and compatibility with multiple satellite networks. Overall, the project demonstrates a practical and efficient solution for real-time data communication in remote or challenging environments, using satellite links as the primary medium of connectivity

Contents

Table of Figure

1. Executive Summary

1.1 Project Overview

This project involves the development of a modular and highly reliable wireless communication system tailored for remote data acquisition and satellite-based transmission. The system is composed of three integrated subsystems:

- A **BLE-based wireless sensor node** designed to capture environmental or operational data.
- A **Gateway Unit** with an onboard microcontroller unit (MCU), power management unit (PMU), and physical mounting interface.
- A **Satellite Communication Module**, attachable to the gateway, with automatic fallback to a 4G communication channel in case of satellite link unavailability.

The primary purpose of this system is to enable resilient, field-deployable data transmission capabilities in remote areas with limited or no terrestrial network coverage.

1.2 Key Objectives

- Develop a **robust BLE node** capable of low-power, intermittent data transmission.
- Design a **multi-communication gateway** capable of receiving BLE data and forwarding it over satellite or 4G networks.
- Implement **communication redundancy and failover mechanisms** to ensure continuous data delivery.
- Enable **modular satellite interface integration** without affecting the core gateway design.
- Maintain **power efficiency and ruggedization** for harsh field environments.
- Collaborate closely with **module providers** for satellite and 4G integration and resolve hardware/firmware-level challenges.

1.3 High-Level System Architecture

The system architecture consists of:

- **BLE Node**
    - Battery-operated device with sensors
    - Sends periodic or event-driven data via BLE advertising or connections
    - Ultra-low power sleep-wake cycle for long-term deployment
- **Gateway Unit**
    - MCU with BLE receiver and logic control
    - PMU for handling power input and regulation
    - Interfaces:
        - Connector for **Satellite Communication Module**
        - SIM and UART for **4G fallback communication**
- **Satellite Communication Module**
    - Mountable onto the Gateway using a dedicated connector
    - Capable of direct data uplink to satellite systems
    - Powered by the Gateway's PMU
- **4G Module (Fallback)**
    - Automatically enabled when satellite link fails or is unavailable
    - Ensures end-to-end data transmission continuity

The system includes logic for priority-based communication, where satellite has precedence, and 4G acts as a fallback.

2. Introduction

2.1 Purpose of the Document

The purpose of this document is to provide a detailed and structured report on the design, development, integration, and testing of a modular wireless communication system comprising BLE sensor nodes, a central gateway, and a satellite communication module with 4G fallback capability. This report captures every technical and managerial aspect of the project—from hardware schematics and firmware workflows to integration challenges and stakeholder coordination. It serves as a complete reference for developers, testers, integrators, and certification bodies involved in current and future phases of the product lifecycle.

2.2 Scope of the System

- Development of custom BLE nodes with optimized sensor integration and ultra-low power consumption.
- Design and implementation of a central gateway unit with embedded BLE receiver, MCU, power supply, and interface for satellite and 4G modules.
- Communication logic to prioritize satellite transmission and switch to 4G upon failure.

2.3 Target Applications and Use-Cases

The system is designed for remote and mission-critical data acquisition applications, especially where terrestrial network access is unreliable or absent. Key target applications include:

- **Disaster Management Zones:** Deployment in flood-prone or post-disaster areas to relay critical sensor data when terrestrial networks are down.3. System Architecture

3.1 Block Diagram

The system consists of three modular blocks:

- **BLE Sensor Node** (Battery-operated, low-power node)
- **Gateway Unit** (Central processing and communication manager)
- **Satellite Communication Module** (Optional, attachable to Gateway, with fallback to 4G)

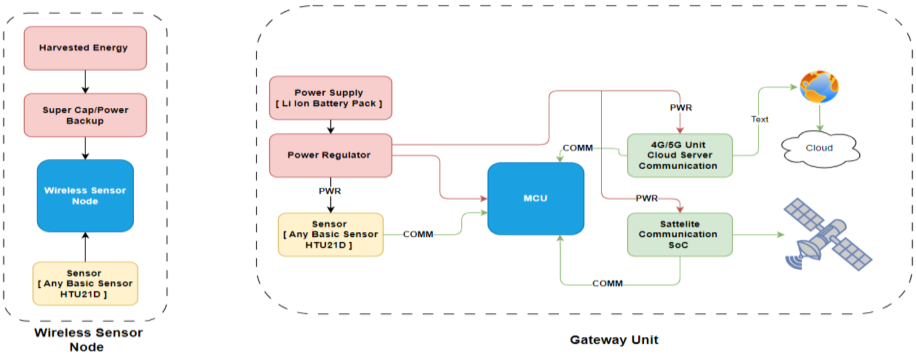


Figure 1 : System Architecture

The gateway handles communication redundancy: it attempts satellite uplink first and switches to 4G if no acknowledgment or link is available.

3.2 Component Overview

3.2.1 BLE Node

- **MCU:** MDBT50Q (nRF52840 SoC)
- **Sensor:** HTU21D (Temperature/Humidity)
- **Power Regulator:** AP2112K-3.3
- **Interfaces:** SPI, I^2C, UART exposed
- **Communication:** BLE 5.0, periodic advertisement mode
- **Power Profile:**
    - Sleep: ~3.6 μA
    - Active (1s per 60s): Avg ~6.4 mA
    - Battery: 300mAh LiPo
    - Runtime (1s active + 3600s sleep): ~ 102 Days

3.2.2 Gateway MCU Unit

- **MCU:** ESP32-S3-WROOM-1
- **Power Supply:**
    - Dual LM2576-based buck converters (12V → 5V, 12V → 3.8V)
    - AMS1117-3.3 for MCU logic rail
- **Modules:**
    - BLE Receiver (integrated in ESP32)
    - 4G Module: Quantel EC200EU
    - Satellite Header Interface (GPIO, UART, I^2C)
- **Features:**
    - Dual UART for Satellite and 4G
    - USB interface for debug
    - SIM card holder for cellular module
    - Headers for Neo pixel, sensor interfaces, and status LEDs
- **Connector:**
    - 15-pin satellite dock
    - Interface: UART (MAIN_RX/TX), I^2C (SDA/SCL), GPIOs for RESET/BOOT/STATUS

3.2.3 Satellite Communication Unit (CC200A)

- **Interface:** UART + I^2C + GPIO control
- **Power Inputs:** 12V and 3.3V regulated lines from Gateway
- **Signals:** MAIN_TX/RX, SDA/SCL, RESET_N, STATUS_IND, WAKEUP_IN
- **Antenna:** ANT_SAT
- **Power Conversion:** Onboard LM2576 for voltage regulation

- **Control Lines:** GPIO_0, GPIO_1, STATUS, EVENT_IND

Data packaging and failover logic are handled within the ESP32 firmware. BLE packets are parsed, wrapped, and conditionally routed via satellite or LTE.

4. Hardware Design

4.1 BLE Node

4.1.1 Component Selection

- **MCU**: Nordic Semiconductor MDBT50Q (nRF52840 SoC), chosen for its BLE 5.0 support, ultra-low power operation, and high GPIO flexibility.
- **Sensor**: HTU21D temperature and humidity sensor, selected for its I^2C interface, low power consumption, and compact footprint.
- **Voltage Regulator**: AP2112K-3.3V LDO regulator ensures stable 3.3V rail for MCU and sensor.
- **Supporting Components**: Decoupling capacitors, 1N4007 diodes for reverse polarity protection, and WS2812 Neo pixel LED for status indication.

4.1.2 PCB Design and Layout

- Designed in a compact single-layer PCB with edge headers for UART, SPI, I^2C, and GPIOs.
- Vias are minimized near RF traces to preserve BLE signal integrity.
- Ground planes are solid and uninterrupted around the MCU and antenna for impedance stability.

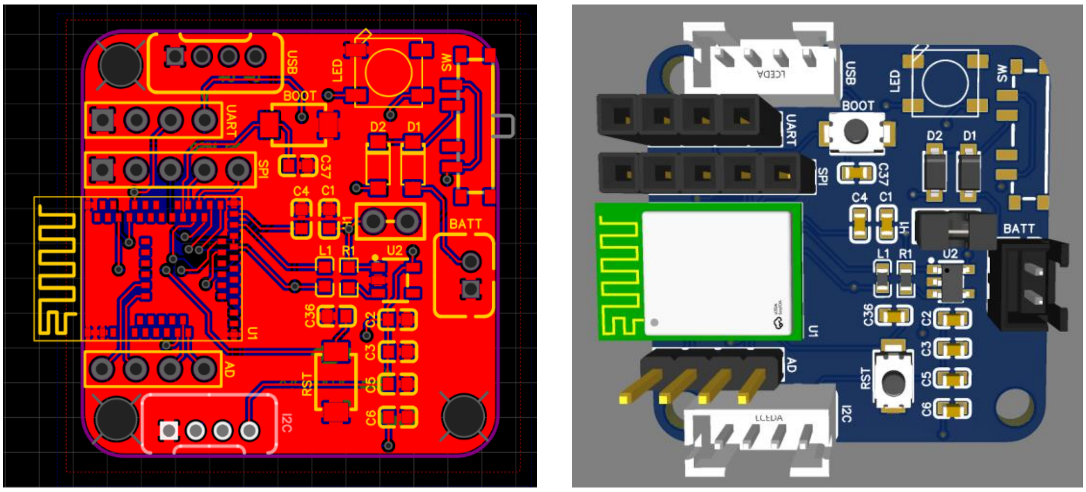


Figure 2 : PCB Layout BLE Node: 2D & 3D

4.2 Gateway Unit

4.2.1 MCU Selection (with rationale)

- ESP32-S3-WROOM-1 is selected due to:
  - Dual-core Tensilica CPU for parallel BLE and communication stack handling
  - Native BLE + Wi-Fi support
  - Sufficient UARTs for Satellite and 4G modules
  - Rich GPIO set for interfacing sensors, SIM, and control lines

4.2.2 BLE Receiver and Parsing Logic

- BLE advertising packets from nodes are captured by ESP32's BLE stack.
- Custom firmware parses payload, validates CRC, timestamps data, and buffers it for uplink.

4.2.3 Power Supply Design

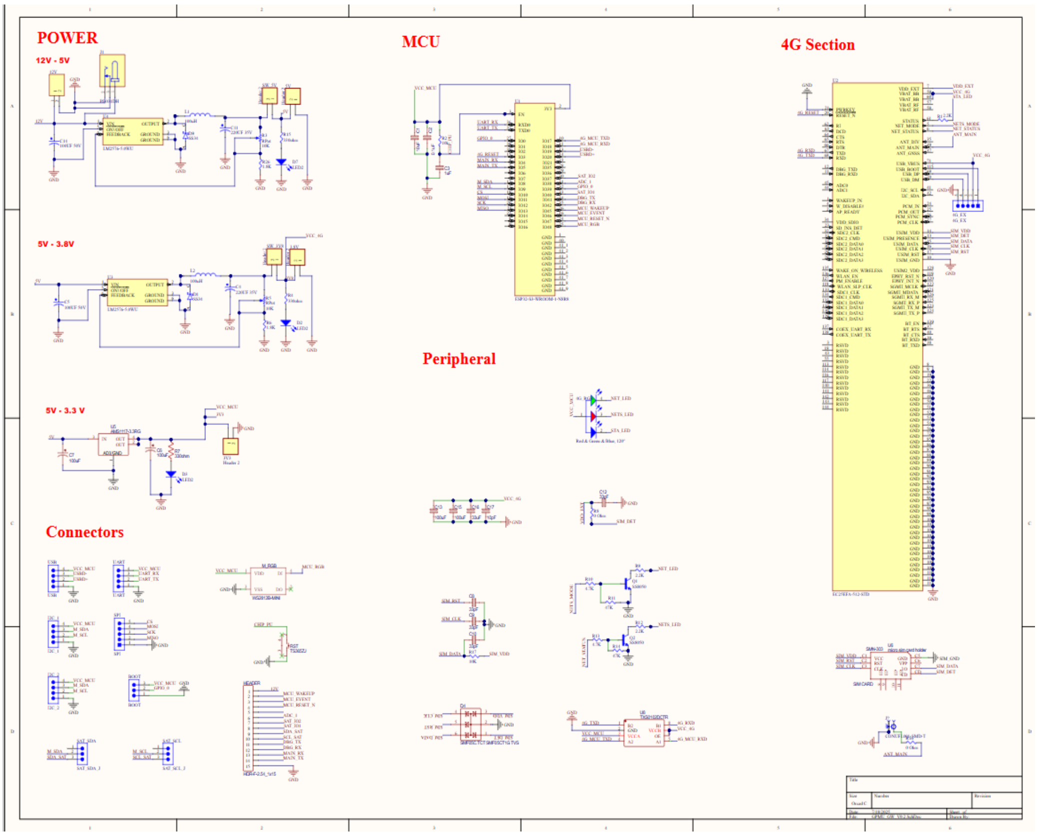
- Dual buck converters (LM2576):
- 12V input → 5V for MCU and logic
- 12V input → 3.8V for 4G power rail
- 12V input goes on to the satellite board
- AMS1117-3.3 used to power ESP32 logic and I/O
- High-capacity decoupling capacitors at SIM and radio interfaces to stabilize transient loads

4.2.4 Satellite Module Interface (Connector design, pinout)

- A 15-pin dock connector allows the Satellite module (CC200A) to interface via:
- UART (MAIN_TX, MAIN_RX)
- I^2C (SDA_SAT, SCL_SAT)
- GPIOs (RESET_N, STATUS_IND, WAKEUP)
- Power: 3.3V, 5V, VBAT routed via dock

4.2.5 4G Module Integration and Control Logic

- Module: Qtel EC200EU
- Interfaces: UART for data + AT command control
- GPIOs mapped for PWRKEY, RESET, NET_STATUS LEDs
- SIM card routed with ESD protection, voltage level shifting via TXS0102



- Status monitoring and fallback trigger logic handled in MCU firmware

Figure 3 : Schematic Design: Gateway Unit

4.2.6 PCB Design and Layout

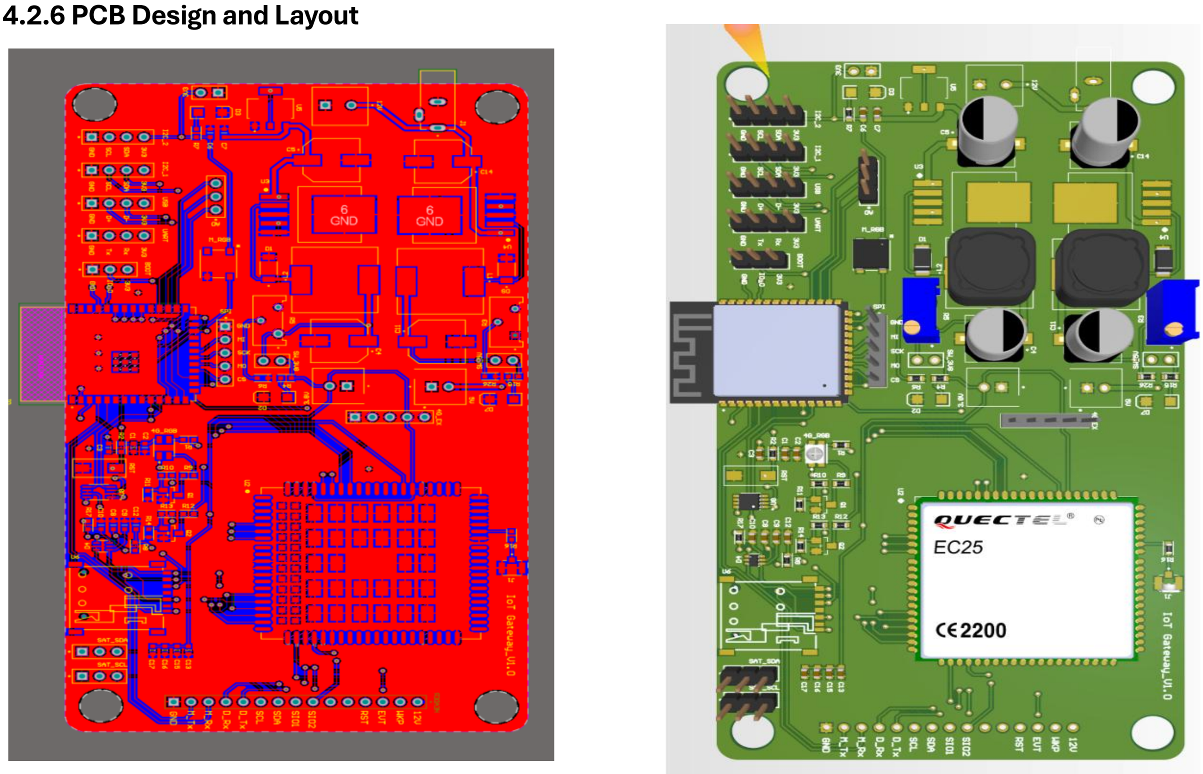


Figure 4 : PCB Layout Gateway Unit: 2D & 3D

4.3 Satellite Communication Unit

4.3.1 Module Overview

Module Name: Quectel CC200A-LB

The Quectel CC200A-LB is a compact, industrial-grade satellite communication module designed to provide reliable global connectivity in remote areas lacking cellular network coverage. It operates over the Inmarsat iSat Data Pro (IDP) satellite service, enabling two-way communication with low latency and near real-time data reporting

- Global Coverage: Utilizes the Inmarsat GEO satellite constellation for worldwide reach.
- Two-Way Communication: Supports bidirectional messaging through the IDP network with latency around 20 seconds for a 100-byte message.
- Multi-Constellation GNSS: Integrated GNSS receiver supporting GPS, GLONASS, Galileo, and BeiDou for precise positioning.
- Low Power Consumption: For energy-efficient operation with various low-power modes.

4.3.2 Antenna Placement and Interference Considerations

The Quectel CC200A-LB satellite communication module requires careful antenna placement and design to ensure optimal satellite and GNSS signal reception, reliable communication, and minimal interference. Passive antenna is strongly recommended. If an active antenna is required, contact Quectel Technical Support for customized solutions.

- **Frequency Bands:**
  - Satellite Tx: 1626.5–1660.5 MHz
  - Satellite Rx: 1518–1559 MHz
  - GNSS Rx: 1559–1606 MHz
- Ensure the antenna is mounted with its radiation surface facing towards the open sky for unobstructed signal access.
- Avoid placing the antenna near sources of EMI such as high-frequency digital circuits or power converters. Employ grounding and shielding practices as needed.
- Mount antennas at the PCB edge, away from noisy components (CPU, SDRAM, flash, DC-DCs, displays). Avoid placing near metal parts that can block or reflect signals

4.3.3 Signal Integrity Measures

- Reference design was used from Quectel to maintain UART signal quality.
- UART lines operate at 3.3V logic; earlier issues caused by 5–8V line bleed were fixed by removing R16, R20, Q6, and Q7 components which acted as faulty level shifters.

- Post-removal, logic levels restored to 3.3V and AT communication worked reliably.
- Maintain Antenna Polarization and Orientation: Use antennas with Right-Hand Circular

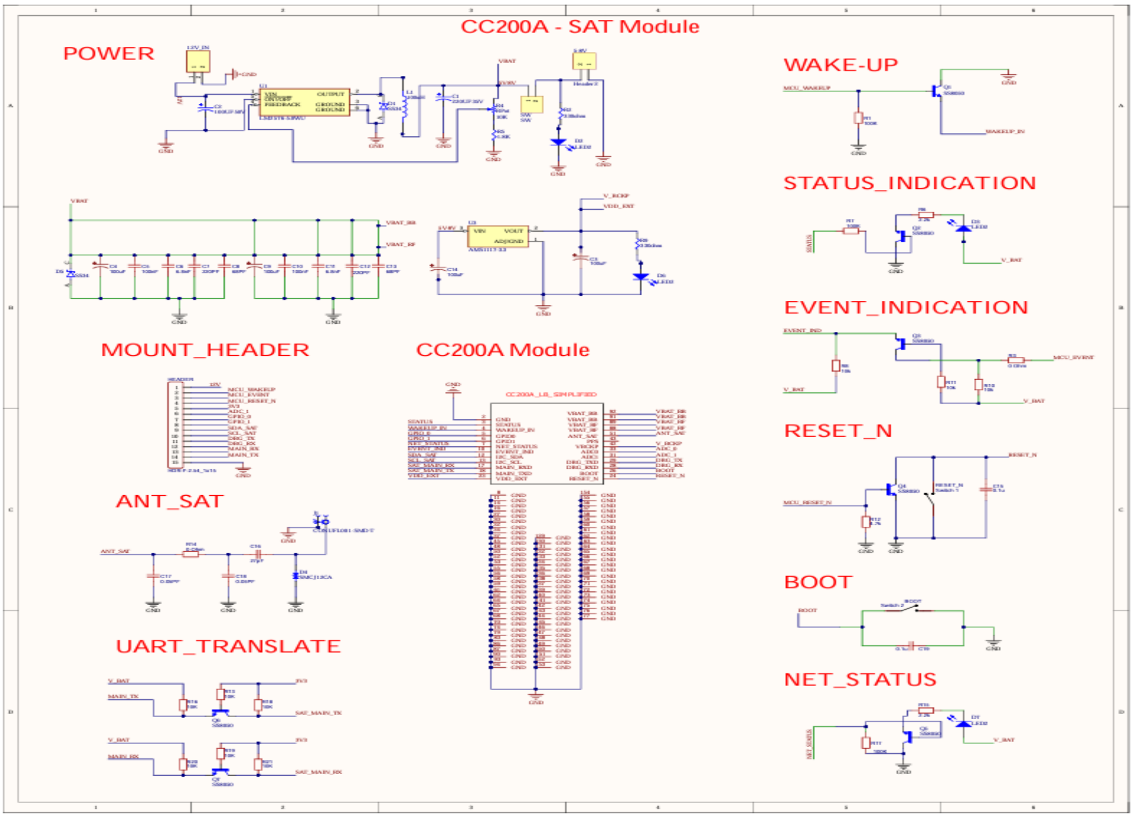


Figure 5 : Schematic Design : Satellite Module

4.3.4 PCB Design and Layout

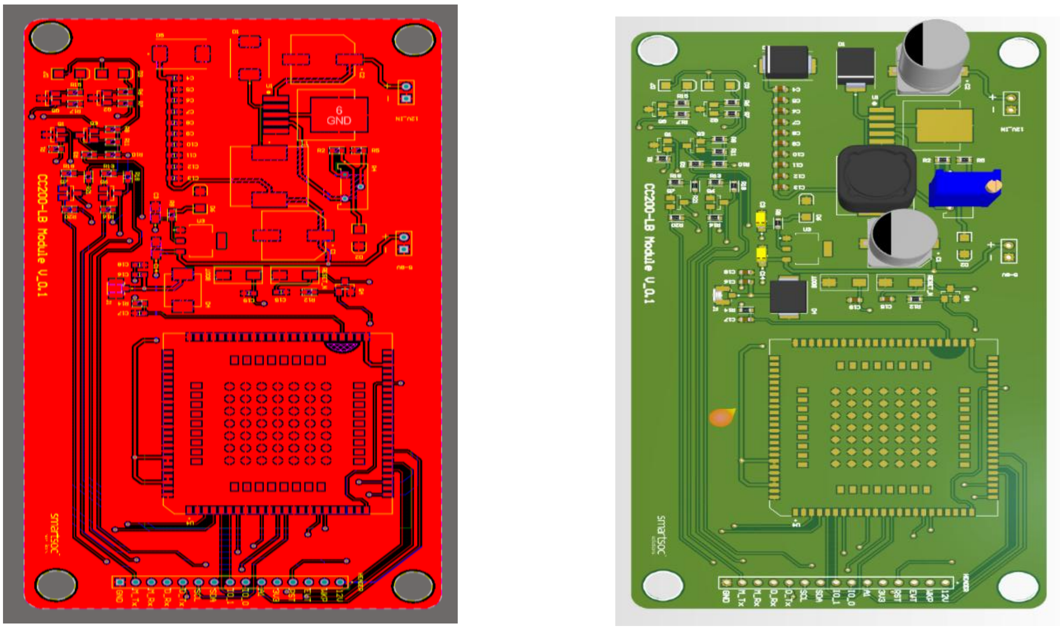


Figure 6 : PCB Layout : Satellite Module 2D & 3D

4.3.5 Real Satellite board

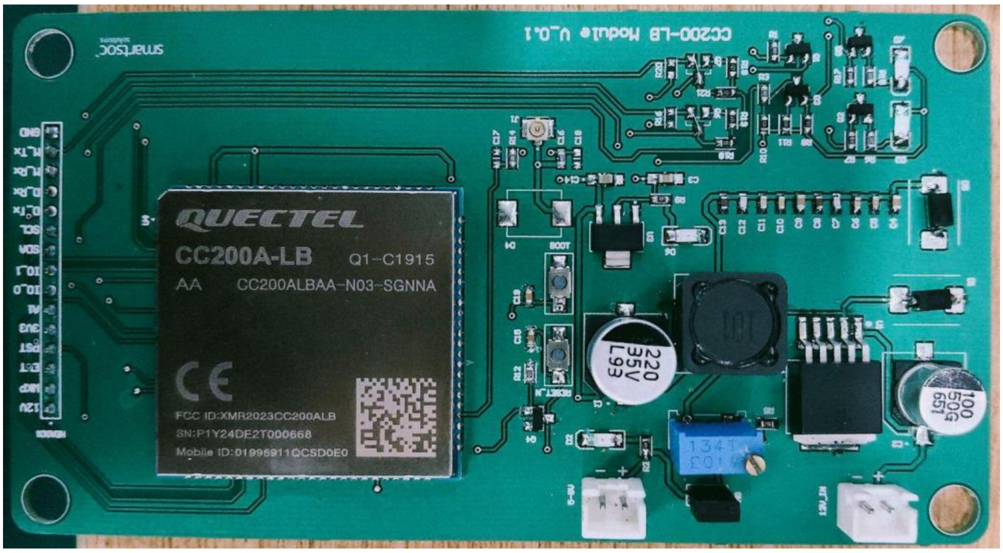


Figure 7 : Real Satellite board bring up

4.3.6 Configuration Page for Setting up Gateway Operation

Device Configuration Panel

[Wi-FiCREDENTIALS]	
(ssid):	EnterSSID
(password):	EnterPassword
[CommunicationSettings]	
(SendingviaCloud_4G/WiFi):	0:4G/1:WiFi
(SatelliteCommunication):	0/1
(DataTransmissionFrequency):	e.g.,1,2,4 1=every60s 2=every30s 4=every15s
[SIMCARDDETAILS]	
(APN):	EnterAPN
[MQTTCREDENTIALS]	
(MQTTEndpoint):	EnterMQTTEndpoint
(ClientID):	EnterClientID
(Port):	e.g.,8883
(DeviceCertificate):	PasteCertificate
(PrivateKey):	PastePrivateKey
(AWSRootCA):	PasteRootCA

Submit

Figure 8 : Configure Gateway parameter

4.3.7 4G Fallback Communication

4.3.8 Module Selection and Certification

- ➢ Module: Quectel EC200EU-EFA
- ➢ Certified for regional LTE bands and supports TCP/UDP/IP stack over AT commands.
- ➢ Data Rates: Up to 10 Mbps downlink / 5 Mbps uplink
- ➢ The EC200U-CN module holds certifications for compliance with industrial standards applicable in China and global markets, including

5. Firmware and Software Development

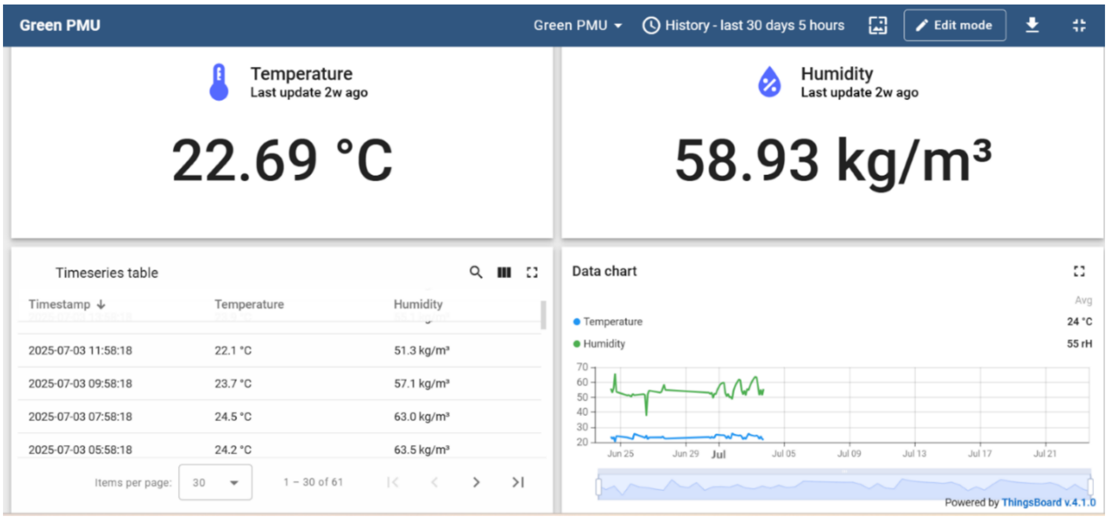
5.1 BLE Node Firmware

5.1.1 Sensor Drivers

- The HTU21D temperature and humidity sensor is interfaced via I^2C.
- A lightweight driver is implemented to support periodic readout and error checking.
- Sensor values are validated and averaged to remove outliers before packaging.

5.1.2 Advertising/Data Packaging

- Data is encoded in a custom BLE advertisement packet, containing:
- Sensor readings
- Node ID
- Timestamp
- Battery level
- BLE stack uses non-connectable advertisements to reduce handshake power costs.
- Advertising interval is configurable (e.g., every 60s, 10min).



Figu

Figure 9 : Serial Monitor - Fetching data from Sensor and broadcast on Gateway

5.1.3 Power States (Sleep/Wake Strategies)

- BLE node enters System OFF state after each advertisement cycle.
- RTC or timer interrupt wakes the system at defined intervals.
- Wake → Sensor read → BLE advertise → Sleep cycle completes in <1000ms,
- Average power consumption is ~ 3.16 μA in longest sleep cycle mode.

5.2 Gateway Firmware

5.2.1 BLE Packet Parsing

- Gateway's ESP32 uses BLE observer mode to capture advertisements.
- Each packet is validated (CRC), parsed, and timestamped.
- Data is buffered in a circular queue for uplink via satellite or LTE.

5.2.2 Communication Protocol between MCU & Satellite

- UART-based AT command interface to Quectel CC200A-LB module.
- Connect the ESP32-S3's UART TX pin to the CC200A-LB's UART RX pin.
- Connect the ESP32-S3's UART RX pin to the CC200A-LB's UART TX pin.
- Connect common ground (GND) between ESP32-S3 and CC200A-LB.
- Communication flow:
- Power on → Send AT → Wait for OK
- Configure GNSS or payload mode using AT commands
- Send encoded sensor data to satellite uplink
- Firmware handles:
- Command retries
- Timeout-based fallback to LTE
- Logging of responses and errors

5.2.3 Failover Handling Algorithm

- A decision engine in ESP32 tracks communication success:
- Satellite is primary if SAT_COM_FLAG == 1
- If satellite uplink fails (NO CARRIER, SEND FAIL, no ACK in 3 tries), fallback to LTE
- System monitors satellite status and can return to it when recovered
- Antenna presence checks and firmware health status tracked to auto-disable faulty modules

5.3 Interrupt and Task Prioritization

- ESP32 Task Priorities:
- BLE reception: Medium
- UART Rx/Tx (Satellite/4G): High
- Timer for retry/fallback: High
- Data encoding/storage: Low
- GNSS parsing (if enabled): Low
- BLE Node:
- Timer wake interrupt → Sensor read task → BLE advertise task → Sleep
- All background tasks suspended during sleep to save current

6. Power Management

6.1 BLE Node Sleep/Wake Cycles

- The BLE node is optimized for ultra-low-power operation using Nordic's System OFF mode with periodic wakeups using the RTC timer.
- Sleep State:
  - MCU enters deep sleep (System OFF)
  - All peripherals disabled, including BLE, I^2C, and LEDs
  - Power consumption: ~3.16 µA
  - Wake State:
  - Wake triggered by RTC (configurable interval: 10s to 3600s)
  - Sequence:
  - Sensor Read (HTU21D via I^2C)
  - Battery voltage read (via ADC)
  - BLE Advertisement (non-connectable)
  - Status LED flash (if enabled)
  - Active duration: ~80–120 ms
  - Average current consumption at 1 active second per hour: ~6.4 mA
  - Battery Life Estimate: With a 300 mAh LiPo battery and 1 transmission/hour: Theoretical lifetime exceeds 102 days.

6.2 Satellite Module Power Requirements

- Module: Quectel CC200A-LB
  - Operating Voltage: 3.3V logic, 5–8V VBAT input

- Current Draw:
- Idle: ~35 mA
- GNSS Active: 45–60 mA
- TX (Uplink): 200–300 mA

- Power Supply:
  - Provided from Gateway's LM2576 buck converters (5V and 3.8V rails)
  - Controlled via GPIO enable pin and status feedback
- Power-On Delay: Module requires ~3 seconds after power application before responding to AT commands.
- Issues Resolved:
  - Early PCB revisions caused improper power routing due to shared net errors.
  - Fixed by isolating VBAT via jumpers and using separate copper pours for 3.3V logic vs 5V analog rail

7. Conclusion

The project successfully demonstrated the development of a power-efficient wireless node with satellite communication, capable of transmitting sensor data from remote locations. Through careful hardware selection, firmware design, and system integration, we achieved a functional and field-tested solution that offers communication reliability through LEO satellite links and 4G fallback. The system is scalable, modular, and can be tailored for critical use cases such as disaster zones, agricultural monitoring, or industrial asset tracking. This practical outcome stands as a foundation for further innovation in off-grid connectivity system

8 Research Publication

This work proposes a novel stacking-based machine learning framework to improve prediction accuracy in structural health monitoring. Base classifiers are selected based on performance metrics and enhanced by a meta-classifier optimized using R^2 score. The ensemble achieved 99.4% accuracy using linear SVM and decision tree combinations, outperforming neural networks. The proposed model effectively captures data patterns for damage detection in structural systems.

We implemented a stacked ensemble approach combining several base models—such as Decision Trees, Support Vector Machines (SVM), and Random Forests—into a meta-learner. Each base model contributes its prediction, which is then used as input for the final meta-classifier. The model is trained and tested on an SHM dataset containing vibration and acceleration data from various simulated damage scenarios.

Among the tested configurations, the linear SVM combined with a decision tree meta-classifier delivered the highest performance, achieving **99.4% accuracy** and an **R^2 score of 0.991**. This outperformed traditional ANN models and demonstrated consistent results across crossvalidation folds. Feature importance analysis showed that frequency-domain features significantly influenced the classification outcome.

The proposed stacking-based model offers a powerful and scalable approach for SHM and damage detection. Its high accuracy and adaptability make it suitable for real-world applications in bridges, buildings, and industrial structures. Future work includes deploying the model on embedded systems for real-time SHM and exploring transfer learning to adapt to different structures.

Research Output

"Structural Health Monitoring and Damage Assessment through Stacked Machine Learning Algorithms: Supervised machine learning and Stacked classifier and Feature engineering." Presented at International Conference on “Advances in Structural Engineering & Material Sciences” (ICASEMS- 2025) on 20th and 21st June 2025

Human Capital Development

• Two undergraduate Students

• One PCB Design Engineer

• Two Firmware Engineers

THANK YOU