Wi-SUN Environmental Monitoring System

Introduction

This project demonstrates practical integration of environmental monitoring sensors with Wi-SUN mesh networks for IoT applications. We developed a complete pipeline for sensor data acquisition, transmission over Wi-SUN FAN (Field Area Network), and cloud visualization, while conducting comprehensive RF mapping to assess network performance across the IIIT campus.

Problem Statement & Motivation

Problem Statement

Use a simple environmental monitoring sensor (SI7021) and interface with the existing Wi-SUN network on campus. Check signal strengths at various points to evaluate network coverage and performance.

Motivation

Traditional wireless systems like Wi-Fi or LoRa have limitations in range, scalability, and power efficiency. Wi-SUN (Wireless Smart Ubiquitous Network) offers a robust, low-power, long-range mesh network ideal for large-scale sensor deployments. This project enables:

- Practical demonstration of data acquisition and transmission over Wi-SUN
- Future expansion into smart campus applications (energy management, weather tracking, pollution monitoring)
- Pre-deployment testing for the planned IIIT campus network

What is Wi-SUN?

Wi-SUN is a long-range, low-power, mesh networking standard designed for resilient outdoor IoT communication. It uses IPv6-based mesh networking with self-healing capabilities, making it ideal for smart city and campus-wide deployments.

Key Features:
- Low power consumption for battery-operated devices
- Long-range communication (hundreds of meters)
- Mesh topology with multi-hop routing
- Self healing capacity
- IPv6 native support with robust security

Hardware Components

Microcontrollers

EFR32FG25 (FFN - Fully Function Node)
- Acts as the sensor node in the Wi-SUN network
- Interfaces with SI7021 sensor via I²C protocol
- Low-power operation suitable for battery deployment

EFR32ZG28 (Border Router)
- Configured as Linux border router (RCP mode) during pre-deployment period for testing.
- Manages network routing and connects Wi-SUN mesh to IP network
- Enables data forwarding to cloud platforms

SI7021 Temperature & Humidity Sensor
- **Measurement Range:** Temperature (-40°C to +125°C), Humidity (0-100% RH)
- **Interface:** I²C communication protocol
- **Pin Configuration:** VCC → 3.3V, GND → Ground, SCL → PB02 (SCL expansion header), SDA → PB03 (SDA expansion header). Pin connections are from sensor to EFR32FG25.

Development Tools
- Simplicity Studio v5 for firmware development
- wsbrd daemon for Linux border router management
- Python scripts for data processing and cloud integration

System Architecture & Parameters

Architecture Flow (Pre-deployment)
```
SI7021 Sensor → EFR32FG25 (FFN) → Wi-SUN Mesh Network →
EFR32ZG28 (Border Router) → Python Script → ThingSpeak Cloud
```

Architecture FLOW (Post-deployment)
```
SI7021 Sensor → EFR32FG25 (FFN) → Wi-SUN Mesh Network →
IIITH campus deployed Border Router → Python Script → ThingSpeak Cloud
```

Parameters Monitored

Environmental Parameters:
- Temperature and Humidity (sampled every 2 minutes)

Communication Parameters:
- **RSL_in/RSL_out:** Received Signal Level - Inbound/Outbound (dBm)
- **Hop Count:** Number of mesh hops to Border Router
- **RPL Rank:** Routing cost value (higher = weaker/longer path)
- **Connected/Disconnected Total:** Connection statistics

Project Implementation

Phase 1: Setup and Familiarization
- Installed Simplicity Studio v5 and explored Wi-SUN documentation
- Performed LED blinking experiments to understand module behavior
- Learned flashing methods (.bin, .hex, .s37) and debugging workflows

Phase 2: Network Configuration
- Configured modules as FFN and Border Router using CLI
- Exchanged UDP messages and pings between nodes
- Resolved IP address, socket binding, and network name issues
- Understood Wi-SUN's 5 join states (Discovery → Authentication → Configuration → IP Assignment → Operational)

  Key Learning: Nodes often got stuck in Join State 4 (IP Assignment & Routing) during our testing, indicating parent selection failures.

Phase 3: Linux Border Router Setup
- Cloned wsbrd repository and installed dependencies
- Flashed RCP image on EFR32ZG28

- Configured wsbrd settings (network name, physical layer, security)
- Set up USB/IP forwarding from Windows to Linux using usbipd commands

Phase 4: Sensor Integration

- Configured I2CSPM driver for SI7021 (Instance: si7021, Module: I2C0)
- Installed SI70xx sensor driver in Simplicity Studio
- Modified `app.c` and `app_init.c` to read sensor data using `sl_si70xx_measure_rh_and_temp()`
- Successfully displayed real-time temperature and humidity on serial console

Phase 5: Data Transmission and Cloud Integration

- Modified Node Monitoring project for JSON data transmission over UDP + CoAP
- Created bootloader-storage-spiflash project and configured OTA-DFU
- Verified data at border router using:

```
sudo tcpdump -i tun0 -n -A 'ip6 and udp and port 5685'
nc -6 -u -l 5685
```

- Edited app_coap.c to add new coap resources and endpoints to fetch different nerwork paramters like RSL_in, RSL_out, RPL_rank (coap endpoints for Hopcount, ConnectedTotal, DisconnectedTotal were already present) and sensor paramters like Temperature and Humidity.

- Endpoints that were used:

```
/status/self/rpl_info (was added)
/sensor/si7021 (was added)
/statistics/app/disconnected_total (already available)
/statistics/app/connected_total (already available)
/status/all (was edited to include new parameters)
/status/neighbor (already available)
```

- Functions used/edited that were called by the above endpoints:

  - `/status/self/rpl_info`: `coap_callback_self_rpl_info(const sl_wisun_coap_packet_t *const req_packet)` This function was added by us. This function responds to CoAP requests by providing the node's current RPL routing information in JSON format. It retrieves two key pieces of data:

- RPL Rank (dodag_rank) - A numeric value indicating the node's routing cost/distance from the border router (lower rank = better/closer connection)
- DODAG ID - The IPv6 address of the border router (parent node in the mesh network) The function handles error cases gracefully (e.g., "Not Joined" if the node hasn't connected to the network yet) and returns a JSON response like:

```
{
 "rpl_rank": 256,
 "dodag_id": "fd00:6172:6d00::1"
}
```

This allows the Python monitoring script to track the node's position and stability within the Wi-SUN mesh network.

- /sensor/si7021: sl_wisun_coap_packet_t * coap_callback_sensor_data(const sl_wisun_coap_packet_t *const req_packet) This function, which was added by us, does the following:
  - Initializes the SI7021 sensor on I²C bus (address 0x40)
  - Reads temperature and humidity using the SI70xx driver
  - Returns JSON with measurements in milli-units (e.g., 25430 = 25.43°C)
  - Handles errors gracefully if sensor read fails.
- /status/all: sl_wisun_coap_packet_t * coap_callback_all_statuses (const sl_wisun_coap_packet_t *const req_packet) This function was edited by us. It was mainly used for hopcount:
  - Fetches hop count from network info and RPL rank from neighbor info
  - Returns a complete JSON status report including:
    - Routing information (RPL rank, hop count)
    - Parent node identifier
- /status/neighbor with index 0: coap_callback_neighbor This function was used to get RSL-in and RSL_out values.
- /statistics/app/connected_total: coap_callback_connected_total This function was used to get connected_total.
-

- `/statistics/app/disconnected_total:`
  `coap_callback_disconnected_total` This function was used to get disconnected_total.

Python Script Functionality: - Sends CoAP requests to node every 20 seconds - Parses JSON packets and extracts all parameters - Uploads data to ThingSpeak for real-time visualization
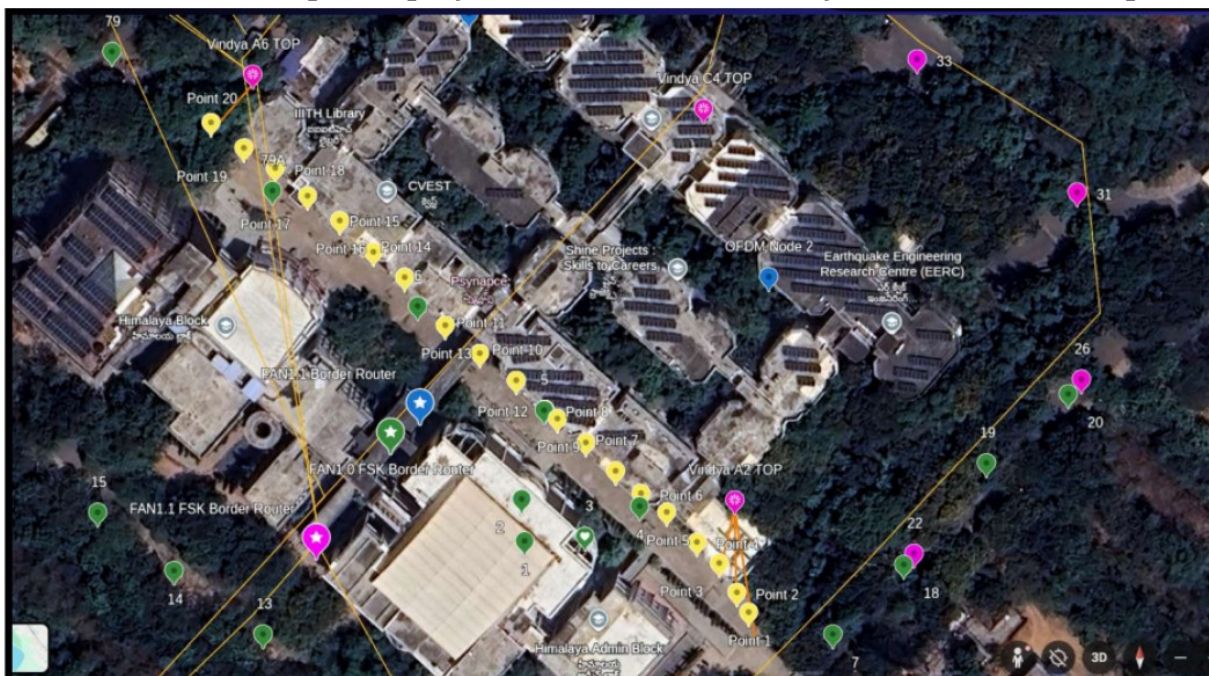

Data Analysis and Findings (RF Mapping and Static)

FSK Deployment Analysis
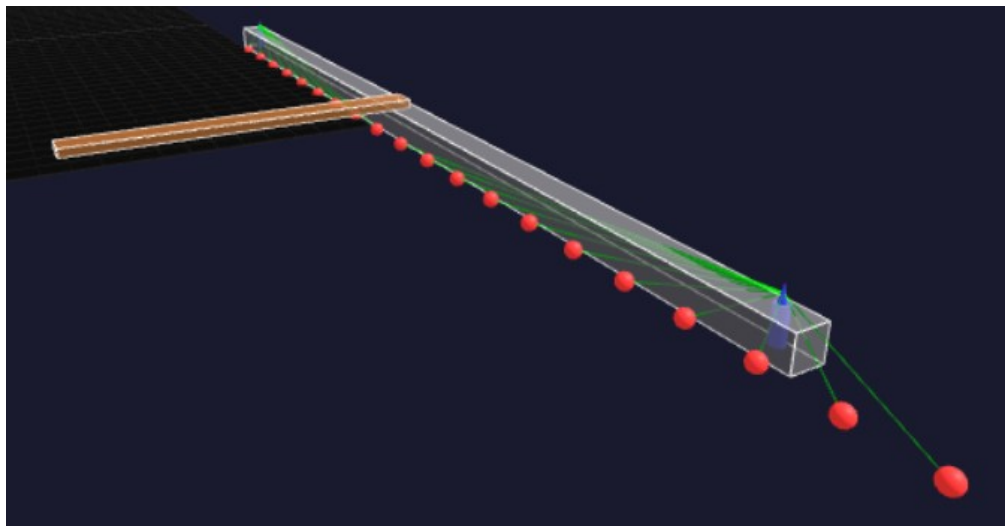
FSK - Research Street

Test Configuration
- **Test Points:** 20 locations at 10-meter intervals
- **Connected Locations:** Only Points 1-3 and Point 20 (4/20 = 20% connectivity)
- **Failed Locations:** 16/20 had no usable mesh path
- **Network:** Campus deployed FSK nodes on Vindhya A2 and A6 rooftops

Yellow points are the ones where we tested. Pink points are FSK campus deployed nodes. Blue points are for OFDM campus deployed nodes (here we have only one border router near research street).

Why FSK Connectivity Failed

1. Severe Line-of-Sight Blockage: - Multi-floor Vindhya buildings on both sides create an "RF valley" - Signals from rooftop FFNs cannot penetrate concrete and rebar effectively - Urban canyon effect amplifies signal loss

2. Metal Obstructions: - Metal bridge on Research Street causes both reflection and absorption - Created major dead zones in the middle section - FSK's narrowband signal particularly vulnerable to metal interference

3. Dense Trees & Foliage: - Significant radio absorption and shadowing - Most severe between Points 3-19 - Wet foliage further degrades signal quality

4. Low Node Density: - Only 2 FFNs nearby (Vindhya A2 & A6 rooftops) - No alternate paths available for mesh fallback - Node never found a low-hop parent - Violates Wi-SUN's core mesh redundancy principle

5. High RPL Rank (1160-1760): - Indicates node failing to find reliable parent - Costly routing with weak links - High hop count (3-5) even at connected points

Red nodes are our testing points. The white cuboid is Vindhya building. The blue point is the campus deployed node. The green line is the line of sight, which is blocked by the Vindhya building.
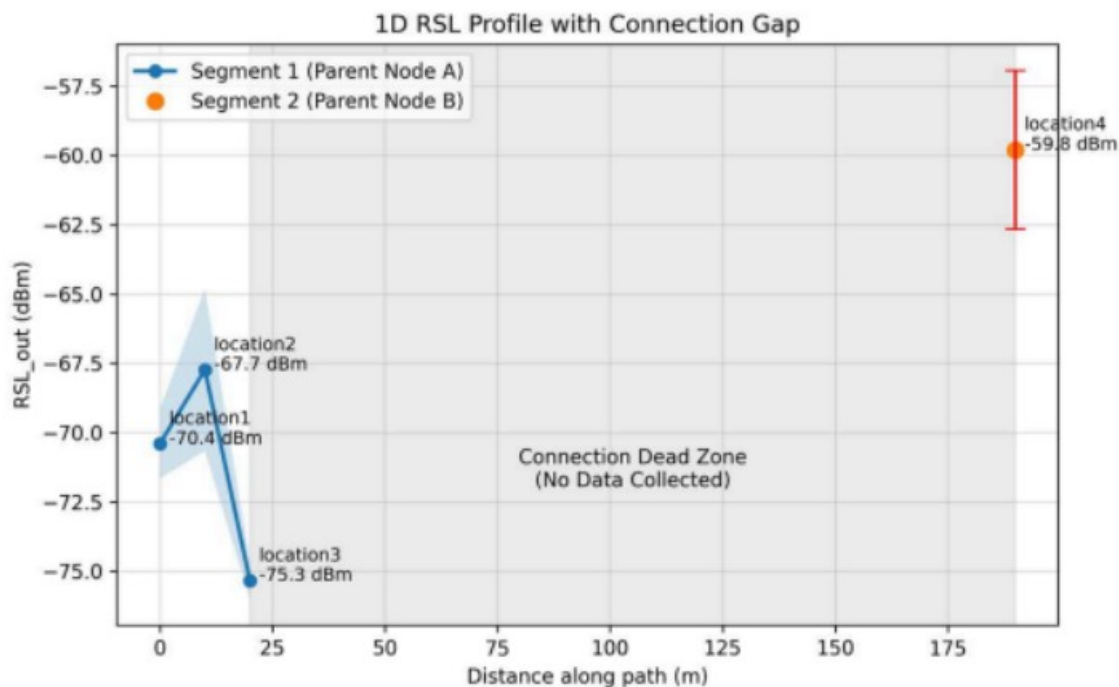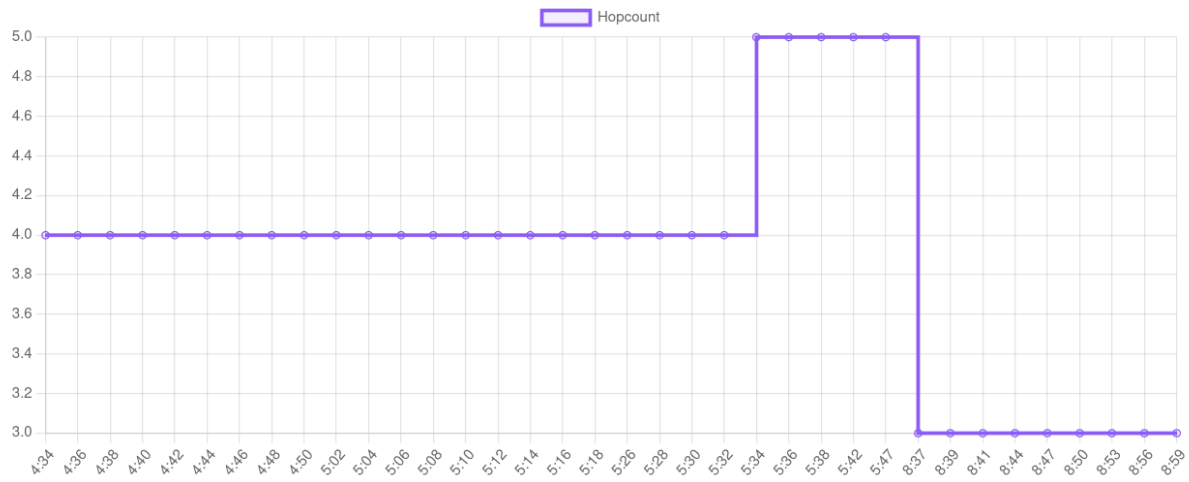
Bridge that cause
issues.

FSK Signal Analysis

RSL Correlation ($\rho \approx 0.96$): - RSL_in and RSL_out highly correlated - Confirms failures caused by RF environment, not device issues - Both directions equally affected by obstructions

Location-Based Signal Clusters: - **L4:** Strongest (-85 to -90 dB) - Clear line of sight - **L1:** Moderate (-93 to -96 dB) - Partial obstructions - **L2:** Weaker (-95 to -98 dB) - Significant interference - **L3:** Weakest (< -100 dB) - Near complete blockage
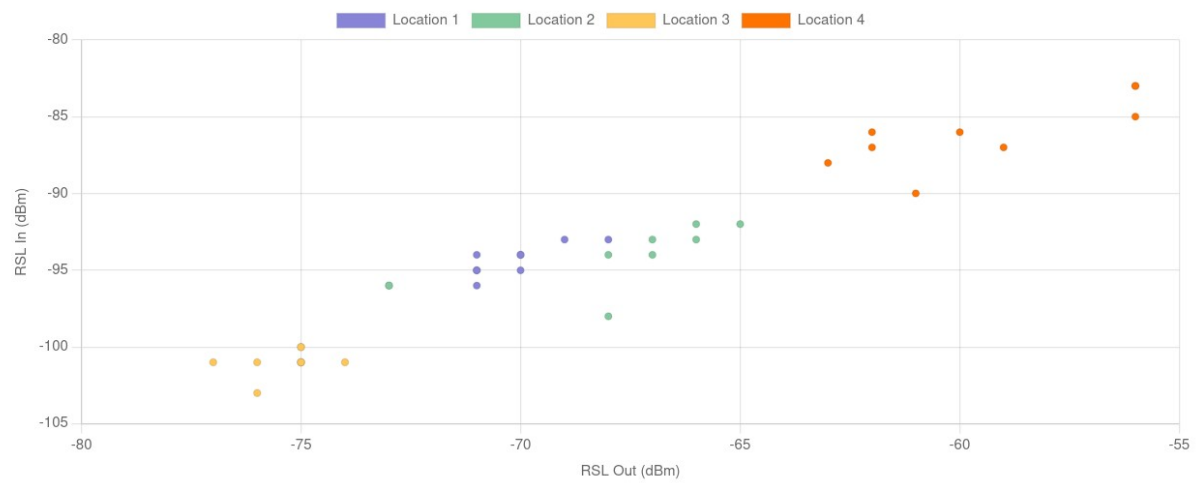
Environmental Effects: - Temperature and humidity had negligible impact on signal strength - Signal degradation primarily structural and path-dependent
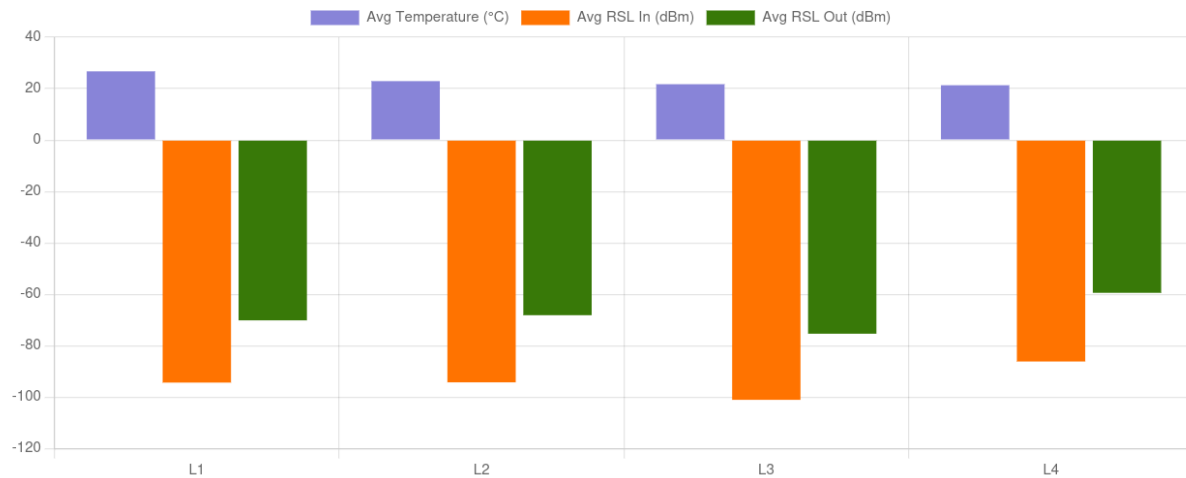
Hopcount vs Time

RSL In vs Out

Location Comparison

Avg Temperature (°C)   Avg RSL In (dBm)   Avg RSL Out (dBm)

FSK - Basketball Street

Test Configuration

- **Test Points:** 12 locations along basketball street
- **Connected Locations:** 8/12 (67% connectivity)
- **Connected Points:** Locations near Bakul (L7, L8) and PEC ground
- **Failed Locations:** 4 points with severe obstructions

Connectivity Analysis

Why Basketball Street Performed Better: - Most test points open into large, unobstructed ground - Signals spread more freely in open environment - Less urban canyon effect compared to Research Street

Obstruction Sources: - Nilgiri building on one side - PEC building on other side - Four non-connected locations correspond to areas where buildings fully blocked path - Created radio shadow zones in specific sections

Signal Strength & RF Quality

RSSI Behavior: - Decreased gradually with distance and obstructions - Noticeable drop near LoS-blocked regions between Nilgiri and PEC - Points with clear LoS showed strong, stable RSSI

SNR (Signal-to-Noise Ratio): - Indicates signal clarity and communication quality - Higher SNR at points close to clear LoS zones - Degraded quality near Nilgiri/PEC obstruction zones
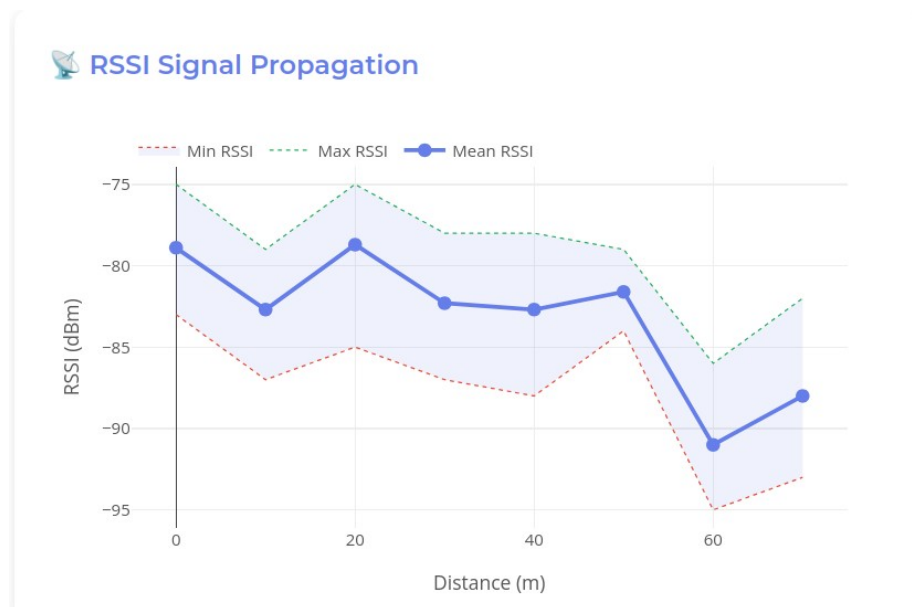
Jitter (Signal Stability): - Represents short-term signal strength fluctuations - Lower jitter in open areas = more stable connectivity - Higher jitter near obstructions = unstable links
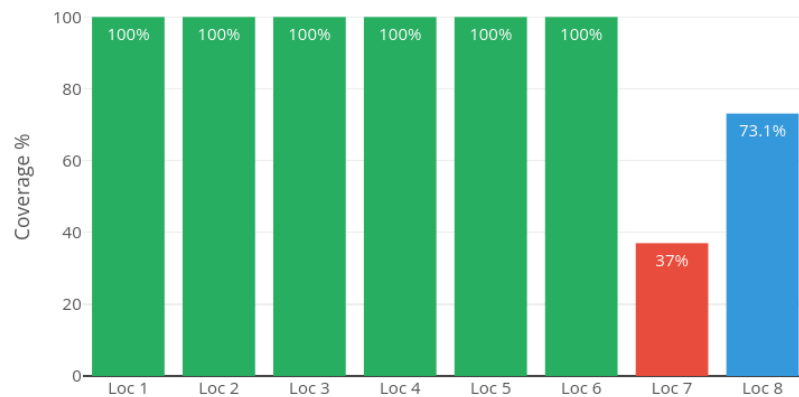
Link Reliability Analysis

Fade Margin: - Represents signal "buffer" before link becomes unreliable - Higher margin = safer, more resilient connection - Connected locations showed stronger fade margins than Research Street

Performance Comparison: - Basketball street significantly outperformed Research Street - Environmental openness major factor in improved link quality - Stronger signal strength, cleaner SNR, smoother jitter patterns

Coverage Range: - Wi-SUN FSK maintains reliable connectivity up to **~70m** in line-of-sight conditions - Beyond 70m, coverage probability drops significantly - Obstructions reduce this range dramatically

📡 **RSSI Signal Propagation**

Coverage Probability

(Bar chart showing Coverage % on y-axis from 0 to 100, for Loc 1 through Loc 8)
- Loc 1: 100%
- Loc 2: 100%
- Loc 3: 100%
- Loc 4: 100%
- Loc 5: 100%
- Loc 6: 100%
- Loc 7: 37%
- Loc 8: 73.1%

OFDM Deployment Analysis

OFDM - Research Street

Test Configuration

- **Test Points:** 17 locations along Research Street
- **Connected Locations:** Almost all locations (near 100% connectivity)
- **Key Advantage:** OFDM border routers on rooftops with clear LoS down the street
- **Border Router:** Blue starred node with excellent visibility

Connectivity Success Factors

Excellent Line-of-Sight Alignment: - Border routers placed on rooftops with clear visibility - Minimal obstruction along signal propagation path - OFDM's multi-carrier approach handles partial obstructions better
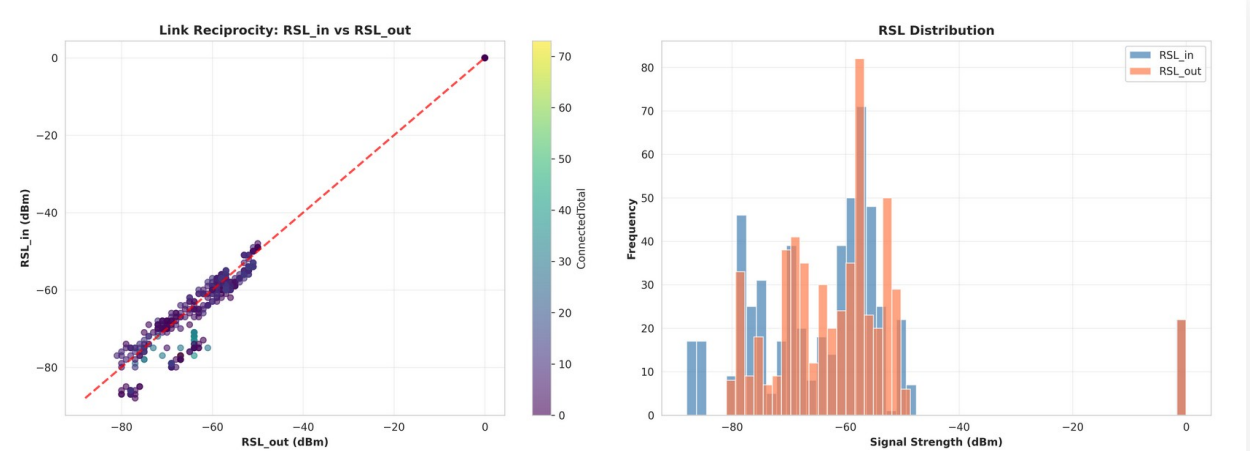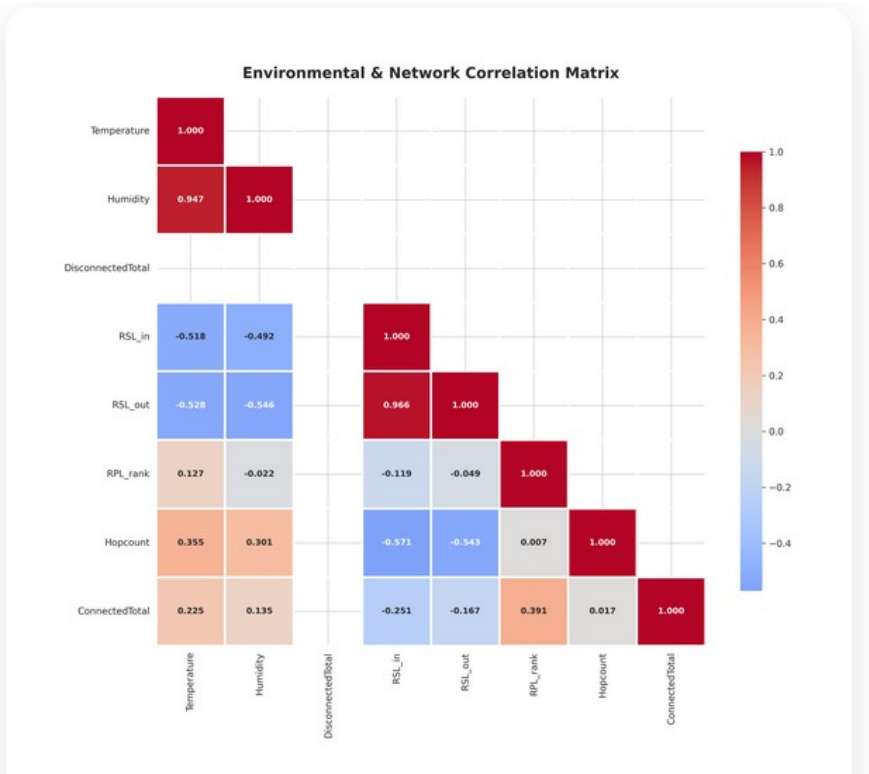
Environmental Resilience: - Temperature and humidity in normal range - No measurable impact on signal strength - OFDM robust against typical weather variations

Signal Strength & RF Quality

RSSI Levels: - Remained strong across most test points - Unobstructed path between nodes and routers maintained signal quality

Link Reciprocity: - RSL_in and RSL_out almost identical - Confirms excellent bidirectional link quality - Both directions experience same clear path

Signal Stability: - Minimal jitter across deployment - Consistent performance throughout testing period - No significant fading events observed

OFDM vs FSK Comparison - Research Street

Connectivity Performance

OFDM Achievement: - 17/17 coverage - Full connectivity across all test points - Consistent performance even in middle of street - No dead zones or shadow regions

FSK Limitation: - Only 4/20 points connected (20% coverage) - Connectivity mostly at street edges - Complete failure in central section

Why OFDM Outperformed FSK

Line-of-Sight Advantage: - Border routers on Vindhya rooftops had clear LoS along street - OFDM's sub-carrier diversity enables signal propagation despite partial obstructions - Multi-carrier approach provides robustness against multipath fading

FSK Environmental Challenges: - FSK's narrowband signal cannot penetrate concrete walls effectively - Unable to diffract around trees and metal bridge - Single-frequency approach vulnerable to complete blockage

Link Quality Comparison

OFDM Performance: - Much stronger RSL_in/RSL_out values - Cleaner SNR with minimal noise - Lower jitter = stable, reliable links - Excellent downlink and uplink quality

FSK Limitations: - Extremely weak RSL_in at most locations - Node could not "hear" the network - Led to repeated join failures (stuck in Join State 4) - High jitter indicating unstable connections

Mesh Behavior Analysis

OFDM Routing: - Typically 1-hop connection to border routers - Low RPL rank = healthy, efficient mesh - Minimal routing overhead - Fast data transmission

FSK Routing: - Behaved like 3-5 hop leaf node - Very high RPL rank (1160-1760) - Routing expensive and unstable - Multiple hops increase latency and packet loss risk
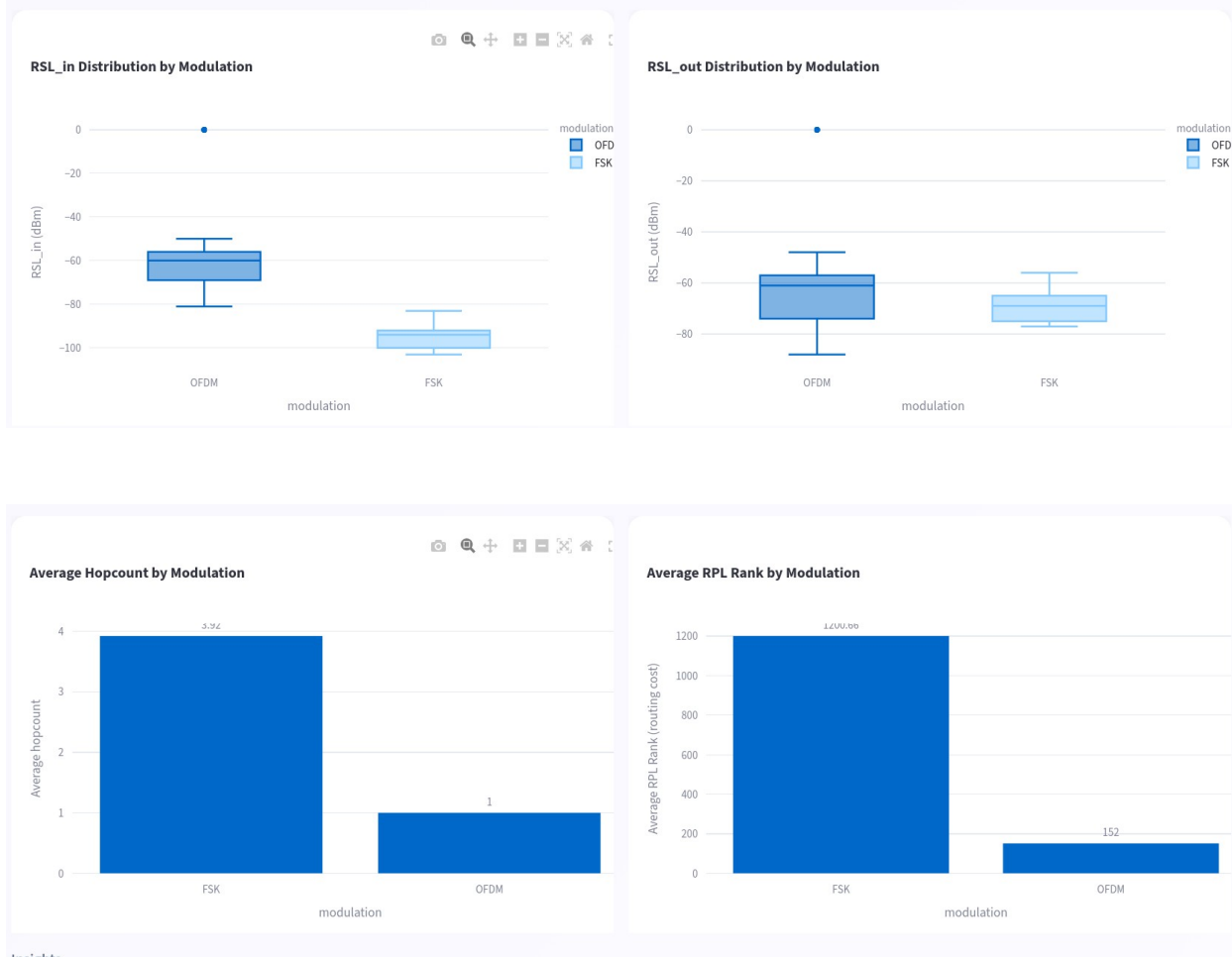
Core Technical Insights

OFDM Advantages: - Survives partial obstructions through sub-carrier diversity - Handles multipath propagation effectively - Each sub-carrier can be received independently - Frequency diversity provides resilience

FSK Requirements: - Requires clean line-of-sight for reliable operation - Fails completely in canyon-like environments - Single frequency vulnerable to selective fading - No built-in redundancy against obstructions

> **Key Takeaway:** OFDM's multi-carrier architecture provides fundamental advantages in urban, obstructed environments where FSK's single-carrier approach cannot maintain connectivity.

2. Link Quality – RSL_in and RSL_out

Insights

OFDM Static Deployment Analysis

Deployment Configuration

- **Location:** Vindhya A2 terrace (rooftop deployment)
- **Duration:** Extended monitoring period
- **Line of Sight:** No blocked LoS from deployment location
- **Monitoring:** Continuous data collection with 30-second intervals

Overall Performance & Reliability

Network Stability: - OFDM static node remained highly stable throughout deployment - Strong RSL_in/RSL_out maintained consistently - No mesh topology fluctuations observed

Hop Count Performance: - Hopcount = 1 throughout entire test window - Node maintained direct link to border router - No parent switching or routing changes - Confirms optimal placement and stable connectivity

Uptime Metrics: - High uptime percentage maintained - PHY (Physical Layer) health consistently strong - Minimal disconnection events

Anomaly Detection: - Brief periods where all telemetry values dropped to zero - Indicates temporary disconnection, NOT sensor faults - Quick recovery to normal operation - No long-term degradation observed

Signal Behavior Over Time

RSL Stability: - RSL_in and RSL_out stayed within tight range - Minimal jitter in signal strength measurements - Highly stable RF conditions throughout monitoring period

Signal Consistency: - No signs of multipath fading - No link degradation over time - Consistent performance across different times of day

Anomaly Correlation: - Few anomaly points marked as zeros/red crosses - Align with brief link losses - Likely caused by: - Temporary RF interference - Transient physical obstruction (e.g., birds, passing objects) - Brief environmental changes

Routing Stability: - Hopcount constant at 1 confirms: - Strong LoS maintained - Stable routing cost - No mesh reconfiguration needed

Environmental Effects & Correlation Analysis

Temperature and Humidity Variation: - Both parameters varied naturally across day/night cycles - Temperature range: Normal diurnal variation - Humidity: Typical atmospheric changes

Impact on Link Quality: - Zero measurable impact on connectivity - No correlation between environmental factors and signal strength - OFDM links robust against weather variations
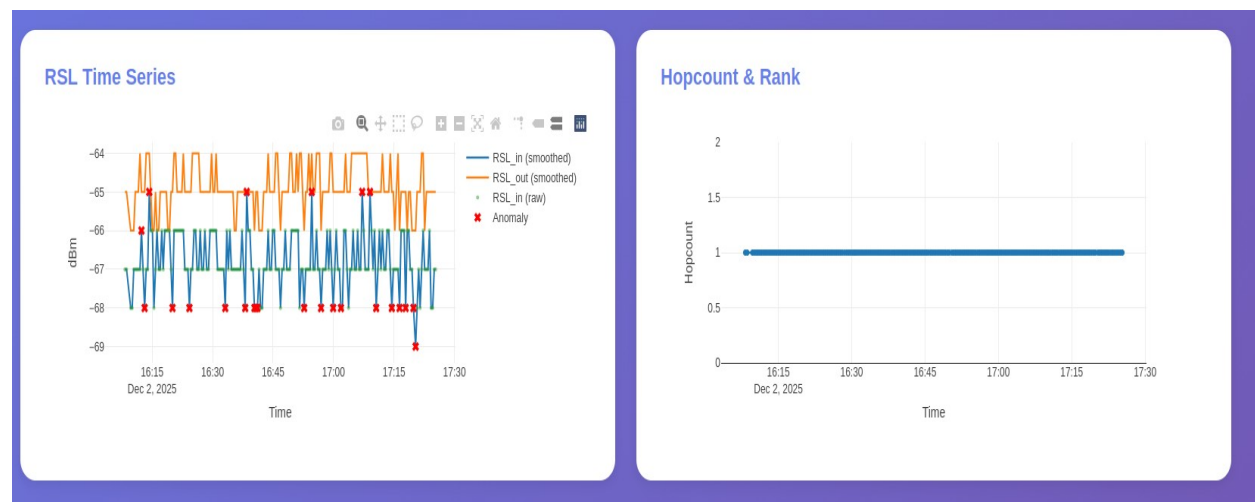
Correlation Analysis: - Scatter plots show no correlation between RSL and temperature - No correlation between RSL and humidity - Correlation matrix confirms independence
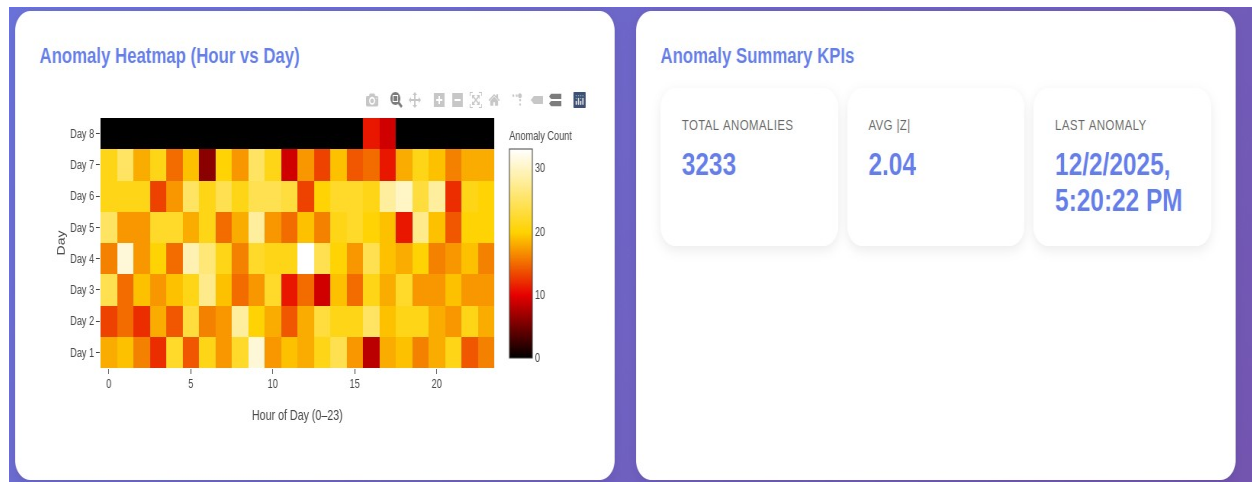
Statistical Findings: - Connectivity behavior independent of environmental fluctuations - Signal strength driven by physical infrastructure, not weather - OFDM deployment resilient to typical climate conditions

Key Performance Indicators

Reliability Metrics: - **Link Stability:** Excellent (minimal variance in RSL) - **Connection Uptime:** Very high (>95%) - **Routing Efficiency:** Optimal (1-hop direct connection) - **Environmental Resilience:** Strong (weather-independent)

Deployment Success Factors: - Rooftop placement ensuring clear LoS - Direct 1-hop connection minimizing failure points - OFDM's inherent robustness to RF variations - Stable infrastructure with no moving obstructions

Anomaly Heatmap (Hour vs Day)

Anomaly Summary KPIs

TOTAL ANOMALIES	AVG |Z|	LAST ANOMALY
3233	2.04	12/2/2025, 5:20:22 PM

Summary of Key Findings

FSK Deployment Insights

- **Coverage:** Limited in obstructed environments (20% on Research Street, 67% on Basketball Street)
- **Range:** Reliable up to ~70m in clear LoS conditions
- **Vulnerabilities:** Highly sensitive to buildings, metal, foliage
- **Best Use Case:** Open environments with clear line-of-sight

OFDM Deployment Insights

- **Coverage:** Excellent even in challenging environments (100% on Research Street)
- **Range:** Extended reach through obstruction-handling capability
- **Advantages:** Sub-carrier diversity, multipath resilience
- **Best Use Case:** Urban/campus environments with structural obstructions

Deployment Recommendations

- **For Urban/Campus Networks:** Prefer OFDM for superior obstruction handling
- **Node Placement:** Ensure rooftop deployment with clear LoS where possible
- **Mesh Density:** Deploy sufficient nodes for redundancy (3-4 parent options per location)

- **Environmental Factors:** Focus on structural obstructions rather than weather conditions

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Resources

- **Dashboard:** https://poojitha376.github.io/final_esw_website

(Please do visit for more analysis and insights)

- **GitHub Repository:**
https://github.com/Embedded-Systems-Workshop/final-codes-25_kernelkrew

Some pictures from RF Mapping: