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Design and Implementation of a Decentralized LoRa Mesh Network for Off-Grid Emergency Communication

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Abstract: Centralized communication infrastructure, such as cellular networks, is highly vulnerable to catastrophic failures during natural disasters. This paper presents the practical design and implementation of a decentralized, off-grid communication system utilizing Long Range (LoRa) radio technology. The hardware architecture integrates a Seeed Studio XIAO ESP32-S3 microcontroller with a Semtech SX1262 LoRa transceiver, powered by a 1200mAh Li-Po battery. Using the Meshtastic protocol, the system bridges with commercial smartphones via Bluetooth to enable encrypted text messaging without internet connectivity. Practical field tests were conducted, achieving a communication range of 1 Kilometer in a semi-urban environment with an RSSI of -128 dBm. The paper also discusses real-world hardware troubleshooting and the observation of asymmetric RF links during extreme-range testing.
Keywords: LoRa, Mesh Network, ESP32-S3, Off-grid Communication, Asymmetric Link, Disaster Management.

I. INTRODUCTION

In emergency scenarios such as floods or earthquakes, the primary communication infrastructure often collapses due to power outages or physical damage to cellular towers. During such times, establishing a reliable, low-power, and decentralized communication link becomes critical for rescue operations. While Wi-Fi and Bluetooth offer high bandwidth, their range is severely limited. Conversely, **LoRa (Long Range) modulation**, based on Chirp Spread Spectrum (CSS) technology, allows for multi-kilometer transmission using minimal power. This project focuses on building a functional, portable two-node LoRa communication system operating in the 865-868 MHz ISM band, designed specifically for rapid deployment in off-grid situations.

II. HARDWARE ARCHITECTURE AND ASSEMBLY

Unlike purely software-based simulations, this project involved the physical assembly and packaging of deployable communication nodes.

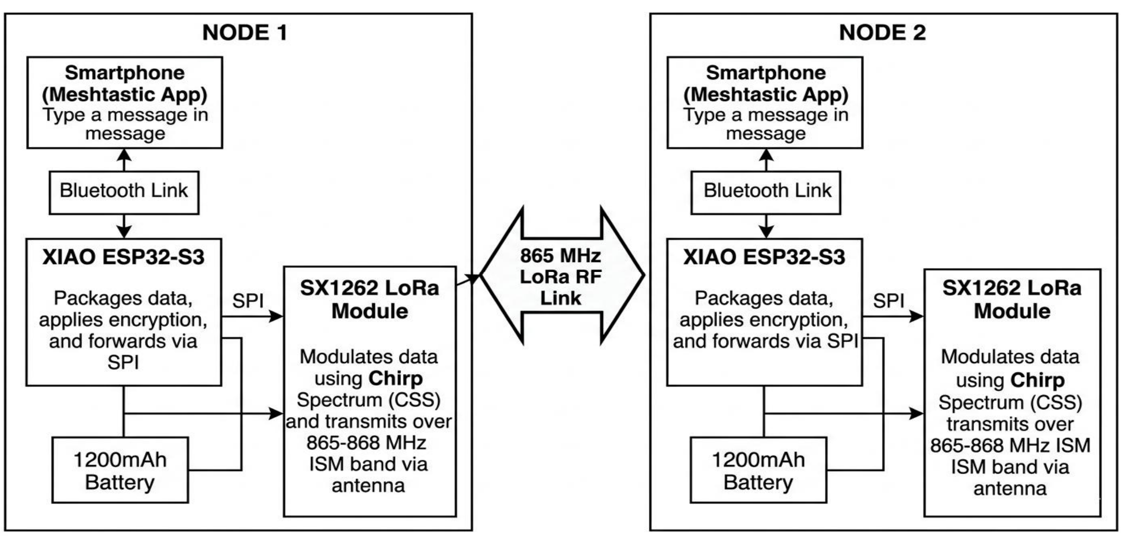

Fig. 1. Block Diagram Of A System

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A. Core Components

The central processing unit is the Seeed Studio XIAO ESP32-S3, chosen for its ultra-compact form factor and native Bluetooth Low Energy (BLE) capabilities. The RF transmission is handled by the Semtech Wio-SX1262 module, which communicates with the ESP32-S3 via the SPI protocol. The system is powered by a 3.7V 1200mAh Li-Po battery, ensuring extended operational uptime.

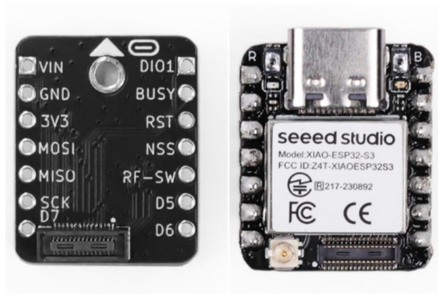

Fig. 2. XIAO ESP32-S3 & Wio-SX1262 module

B. Innovative Weatherproofing (Radome)

To protect the delicate 868MHz omnidirectional U.FL antenna from environmental damage during outdoor deployment, a cost-effective radome was fabricated. This was achieved by repurposing the hollow plastic casing of a discarded 2.4GHz Wi-Fi router antenna. All internal metal components were stripped out to prevent RF interference, providing a structurally rigid, weather-resistant housing without compromising signal transparency.

C. Hardware Troubleshooting

During the prototype assembly, a significant hardware challenge was encountered. Due to thermal stress during soldering, the primary Battery Negative (B-) pad on the underside of the ESP32-S3 was lifted and damaged. Instead of discarding the microcontroller, a schematic analysis was performed. It was determined that the B- pad shares a common ground with the main board. The issue was successfully mitigated by routing the battery’s negative terminal directly to an alternative primary GND pin on the top side of the board, restoring full power management and charging functionality.

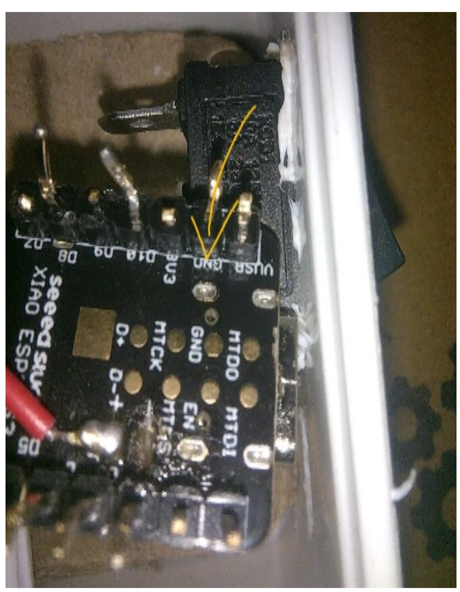

Fig. 3. Hardware Troubleshooting

Fig. 4. Final assembled LoRa Mesh Nodes with custom weatherproof enclosure.

III. SOFTWARE AND FIRMWARE CONFIGURATION

The nodes were flashed with the open-source Meshtastic firmware (Version 2.7.15 Beta) using the Web Serial API flasher. The ESP32-S3 was configured to operate at a baud rate of 115200 bps. Once initialized, the microcontroller establishes a BLE bridge with an Android smartphone, allowing users to send AES256 encrypted text messages through the Meshtastic mobile application.

IV. FIELD TESTING AND RESULTS

To evaluate the real-world performance, range testing was conducted in a semi-urban environment characterized by concrete structures and Wi-Fi noise.

A. Signal Strength Observations

The mobile node was moved to various distances while transmitting text payloads. At close ranges (0–500 meters), communication was instantaneous. The test was extended to a linear distance of 1 Kilometer. At this range, the Receiver Signal Strength Indicator (RSSI) was recorded at -128 dBm, pushing the SX1262 module near its operational sensitivity limit.

B. The Asymmetric Link Phenomenon

At the 1-kilometer mark, an interesting real-world RF phenomenon was observed. The transmitting node's application displayed a "Delivery Failed" status (ACK timeout). However, physical inspection of the receiving base station confirmed that the text message was successfully received and decoded at the exact timestamp.

This discrepancy was identified as an Asymmetric Link. The primary data packet transmitted by the mobile node had sufficient energy to reach the base station. However, the automated, low-power hardware Acknowledgement (ACK) packet generated by the base station lacked the required link margin to penetrate back through the physical obstacles. This practical result proved that the system remains functional for critical one-way emergency alerts even when operating at its extreme theoretical boundary.

Fig. 5. Testing And Result (Meshtastic App Interface)

V. CONCLUSION

The project successfully demonstrated the practical viability of a decentralized LoRa mesh network for off-grid communication. The hardware was successfully assembled, troubleshot, and tested in real-world conditions. The observation of successful message reception at -128 dBm at a 1-kilometer distance validates the extreme sensitivity of the SX1262 transceiver. Future work will focus on introducing additional nodes to create a multi-hop mesh network, thereby extending the coverage area for village-wide emergency deployments.

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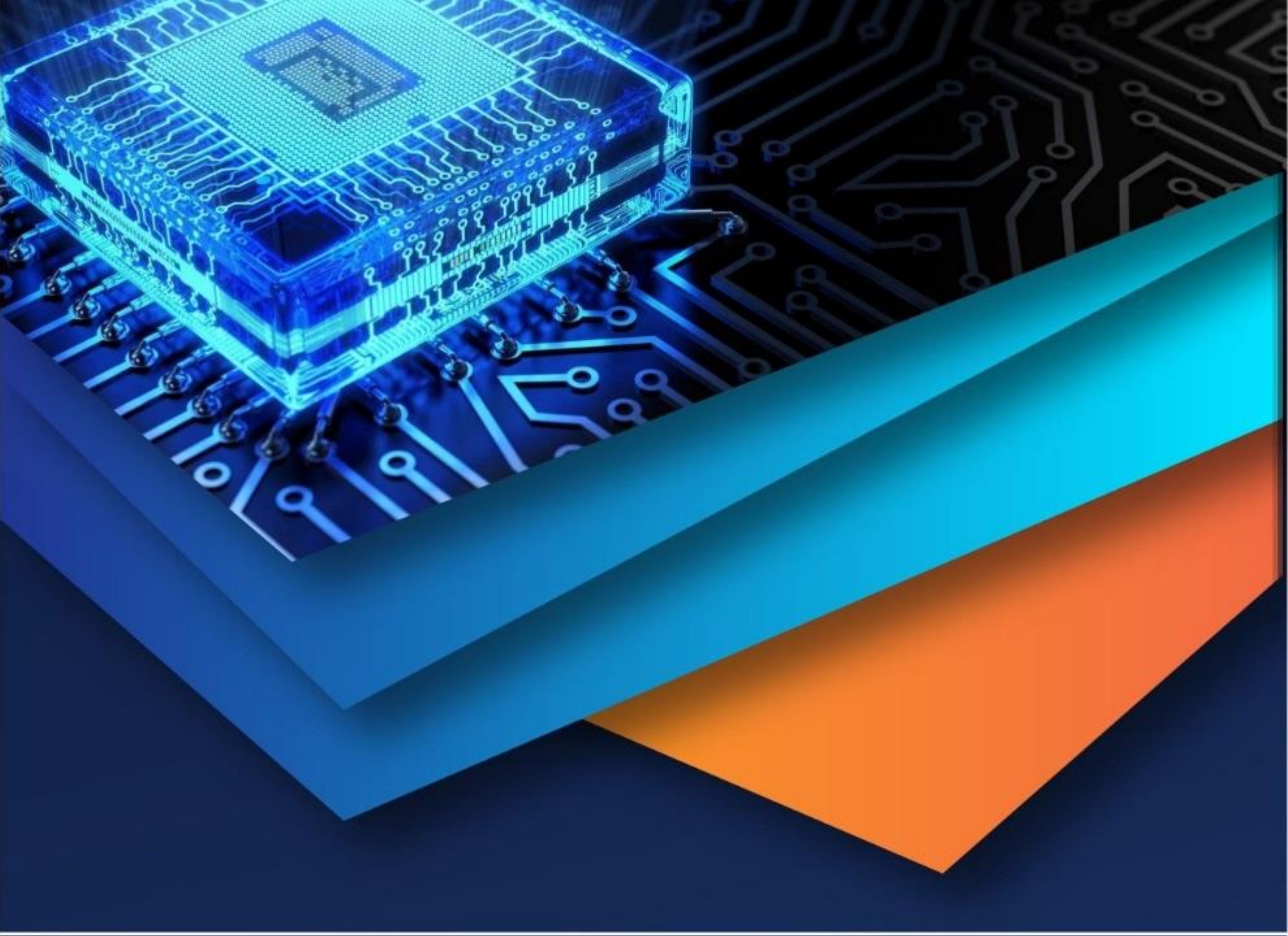

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