LoRa-Based Wireless Localization with Error Reduction

System Documentation & Final Report

Team LoRa Localization Group

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1 Abstract

Wireless localization is critical for applications ranging from agricultural monitoring to search-and-rescue operations in environments where GPS is unreliable or unavailable. This project presents the design and implementation of a low-power, long-range wireless localization system using LoRa (Long Range) technology. By utilizing Received Signal Strength Indicator (RSSI) values from three fixed anchor nodes, the system estimates the position of a mobile node in real-time. To mitigate the inherent instability of RSSI readings caused by environmental noise and multipath interference, the system integrates a Log-Distance Path Loss model, a 1D Kalman Filter for noise reduction, and 2D Trilateration for coordinate estimation. The final output is visualized on a dynamic web-based dashboard.

2 Introduction

2.1 Problem Statement

Tracking assets or individuals in vast outdoor spaces (such as farms or forests) or GPS-denied environments (such as indoors or underground) is a significant challenge. Traditional GPS solutions are power-hungry and often fail without a clear line of sight to satellites. Short-range technologies like Wi-Fi and Bluetooth lack the necessary coverage range, while cellular solutions are costly and dependent on infrastructure.

2.2 Proposed Solution

We propose a self-contained localization system using LoRa SX1278 modules operating at 433 MHz. LoRa offers an optimal balance of long-range communication (several kilometers) and minimal power consumption. The system employs three fixed "Anchor" nodes to triangulate the position of a "Mobile" node. The project emphasizes mathematical error reduction to turn noisy signal strength data into reliable positional coordinates.

3 System Architecture

3.1 Hardware Components

The physical layer of the system consists of four identical nodes, each comprising:

- **Microcontroller:** Arduino UNO for processing logic.
- **Communication Module:** SX1278 LoRa Module (433 MHz) for transmitting and receiving packets.
- **Antenna:** Custom 17 cm wire antennas optimized for 433 MHz.
- **Power Supply:** Battery packs for the mobile node and stable DC sources for anchors.

3.2 Software Stack

The system is powered by a modern web-based dashboard for visualization:

- **Backend:** Node.js with Socket.io for real-time data streaming.
- **Frontend:** HTML5 Canvas for the localization map.

- **Styling:** Tailwind CSS for a responsive, "sci-fi" aesthetic.
- **Data Visualization:** Chart.js for plotting real-time RSSI and latency graphs.

4 Methodology & Mathematical Modelling

4.1 RSSI to Distance Conversion

The core of the localization logic lies in converting the received signal power into distance. We utilize the **Log-Distance Path Loss Model**. The relationship is defined as:

$$RSSI = A - 10 \cdot n \cdot \log_{10}(d) \tag{1}$$

Where:

- **RSSI:** Received Signal Strength Indicator (measured in dBm).
- **A:** Reference RSSI value at a distance of 1 meter (Calibrated constant).
- **n:** Path loss exponent, representing environmental signal decay (Calibrated constant).
- **d:** Distance between the transmitter and receiver.

4.2 Error Reduction: The Kalman Filter

Raw RSSI data is highly volatile due to multipath fading and environmental noise. To smooth these values without introducing significant lag, we implemented a 1-Dimensional Kalman Filter. The filter operates in two steps recursively:

- **Prediction:** Projects the current state estimate forward.
- **Update:** Corrects the predicted state using the new noisy measurement.

The simplified update logic used in our code:

```
K = P / (P + R)                // Calculate Kalman Gain
X = X + K * (Measurement - X)  // Update Estimate
P = (1 - K) * P                // Update Error Covariance
```

Where R is the process noise and Q is the measurement noise.

4.3 2D Trilateration

Once distances (d_1, d_2, d_3) to the three anchors (A_1, A_2, A_3) are filtered, the position (x, y) is determined by solving the intersection of three circles:

$$(x - x_i)^2 + (y - y_i)^2 = d_i^2 \quad \text{for } i = 1, 2, 3 \tag{2}$$

Our system solves these simultaneous equations numerically to pinpoint the mobile node's location on the Canvas map.

5 Implementation & Results

5.1 Deployment Configuration

The three anchors (Alpha, Beta, Gamma) are placed at fixed coordinate points (e.g., $(0, 0)$, $(10, 0)$, $(5, 10)$). The mobile node moves within this triangular area, broadcasting packets. The web interface visualizes this movement in real-time.

5.2 Web Interface Features

The developed dashboard (v2.1) provides:

- **Real-time Map:** A dynamic HTML5 canvas drawing the anchors, the mobile node, and the triangulation geometry.
- **Data Monitoring:** Live cards displaying Raw vs. Filtered RSSI and distances for all three gates.
- **Latency Tracking:** Real-time graphs showing communication delay.
- **Interactive Elements:** Hover effects on team profiles and detailed project write-ups available via modals.

5.3 Observations

During testing, raw RSSI values showed fluctuations of $\pm 5 - 8$ dBm. After applying the Kalman filter, the fluctuation was reduced to $\pm 1 - 2$ dBm, significantly stabilizing the calculated position on the map.

6 Conclusion

The ”LoRa Localization System v2.1” successfully demonstrates that low-cost IoT hardware can achieve reliable localization when paired with robust mathematical modelling. By combining the Log-distance path loss model with Kalman filtering, we overcame the inherent instability of RF signals. This project serves as a scalable foundation for larger tracking networks in agriculture or logistics.