radIOTic: An intelligent, fault tolerant, AI-Enhanced Mesonet for Atmospheric Sensing

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PROJECT PAGE

GITHUB

Motivation

- Communities lack control over how environmental data is collected, stored, and shared—most existing systems are centralized and proprietary.
- High costs and complexity of traditional weather stations make dense, local-scale monitoring inaccessible for many regions.
- Environmental sensing needs vary, requiring systems that can adapt to different conditions, sensor types, and deployment scenarios.

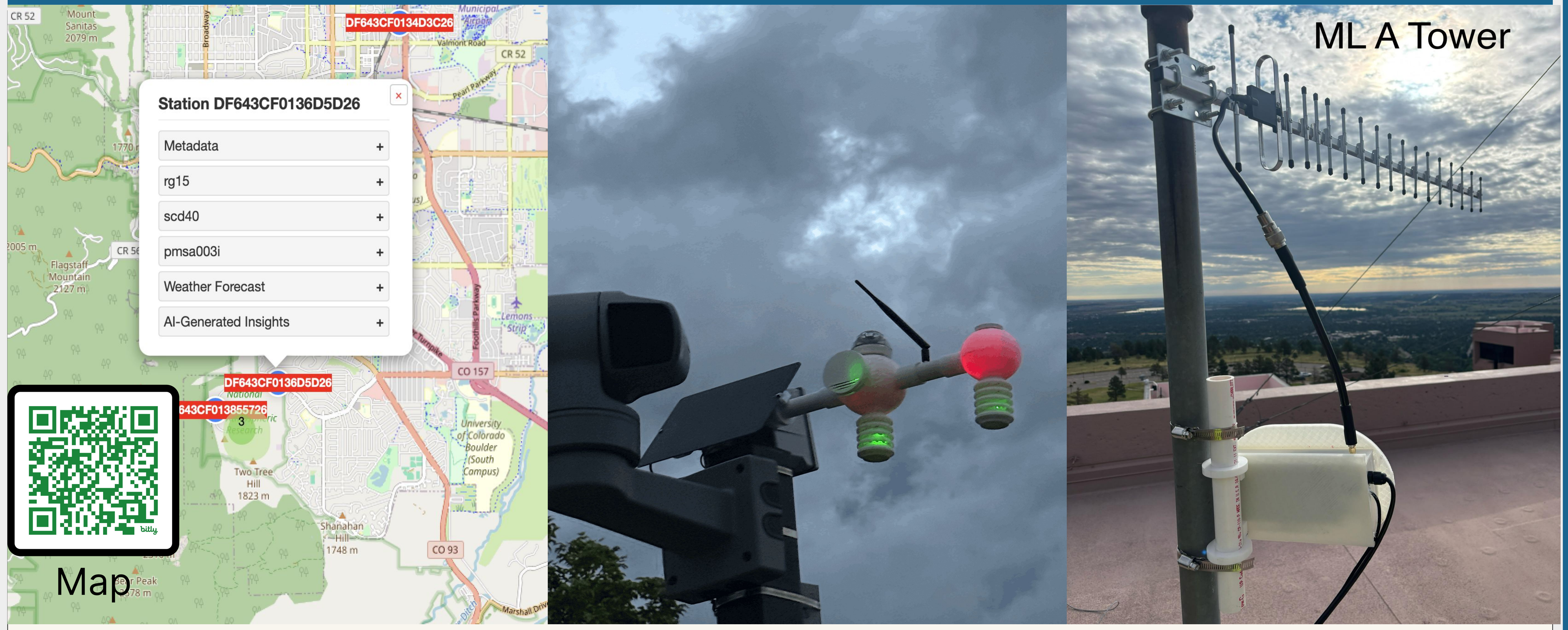
Objectives

- Enable community ownership of sensing networks with open-source, decentralized infrastructure and full control over local environmental data.
- Lower the barrier to deployment through low-cost, modular hardware and fault-tolerant mesh networking—resilient to station or gateway failures.
- Support diverse sensing needs with flexible, plug-and-play support for heterogeneous sensors and mobile or fixed deployment configurations.
- Infuse intelligence into the network with AI models that summarize sensor data, forecast the weather, and provide real-time environmental insights.

Design and Implementation

- **LoRa-Enabled Weather Stations**
  - Built on microcontrollers with modular support for diverse sensors (e.g., temperature, humidity, air quality, UV, rainfall, CO_2, GPS).
  - Use intelligent ping/pong discovery to select the optimal gateway or relay path based on signal strength and node load.
  - Support multi-hop relaying to extend network reach, using connection timeouts to detect and adapt to failed nodes or gateways.
  - Plug-and-play and GPS-aware, dynamically updating station location on the live map.
- **Raspberry Pi Gateways**
  - Serve as LoRa-to-IP relays, forwarding data from multiple stations to the cloud.
  - Include load-awareness, enabling fair distribution of traffic across multiple Pis.
  - Stations automatically switch gateways when a connection times out, ensuring robust, self-healing communication.
- **Cloud Microservices Infrastructure**
  - Containerized architecture using Docker: includes API backend, PostgreSQL for storage, Redis for real-time data, and ThingsBoard for live dashboards.
  - Interactive map powered by Redis displays real-time station data and mobility.
  - Integrated AI via the **Gemma model** synthesizes sensor readings into human-readable summaries of current as well as forecasted conditions.
  - Deployed on CIRRUS for scalable, community-replicable infrastructure.

Key Technical Features and Tools



- **Thingsboard**
  - Real-time sensor dashboards and live telemetry visualization
  - Automatic station registration with metadata and status tracking
  - Customizable charts, maps, and widgets for community-friendly displays
  - Multi-station views for comparative environmental monitoring
  - Built-in rule engine for alerts and automation
  - Web-based interface accessible without programming skills
- **Real time Station Map**
  - Displays all active sensor stations on an interactive map
  - Supports heterogeneous nodes with varying sensor setups
  - Visualizes mobile deployments using live GPS data
  - Shows forecasted conditions per station using integrated AI
  - Converts real-time and forecast data into human-readable summaries
  - WebSocket-powered for low-latency, scalable client updates
  - Online stations shown in green, offline ones in red for quick status checks

NCAR BOULDER MESONET

- Testbed Sites(Fixed deployment):
  - 3 fixed stations deployed at Mesa Lab
  - Two gateways on Tower A and Tower B for redundancy
  - Station and gateway pairs at Center Green and Foothills Lab
- Mobile deployment:
  - A robotic dog equipped with sensors and custom 3D-printed mounts acts as a mobile station
- Key Field Observations:
  - Multi-hop routing allowed stations out of direct range to reach a gateway via nearby nodes
  - Ping/pong load balancing enabled stations to dynamically select the optimal gateway
  - Demonstrated fault tolerance and adaptability in real-world deployment

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