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Dual-Link Data Resilient Edge-to-cloud Communication Framework for Agricultural Robots

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Why Reliable Links Matter

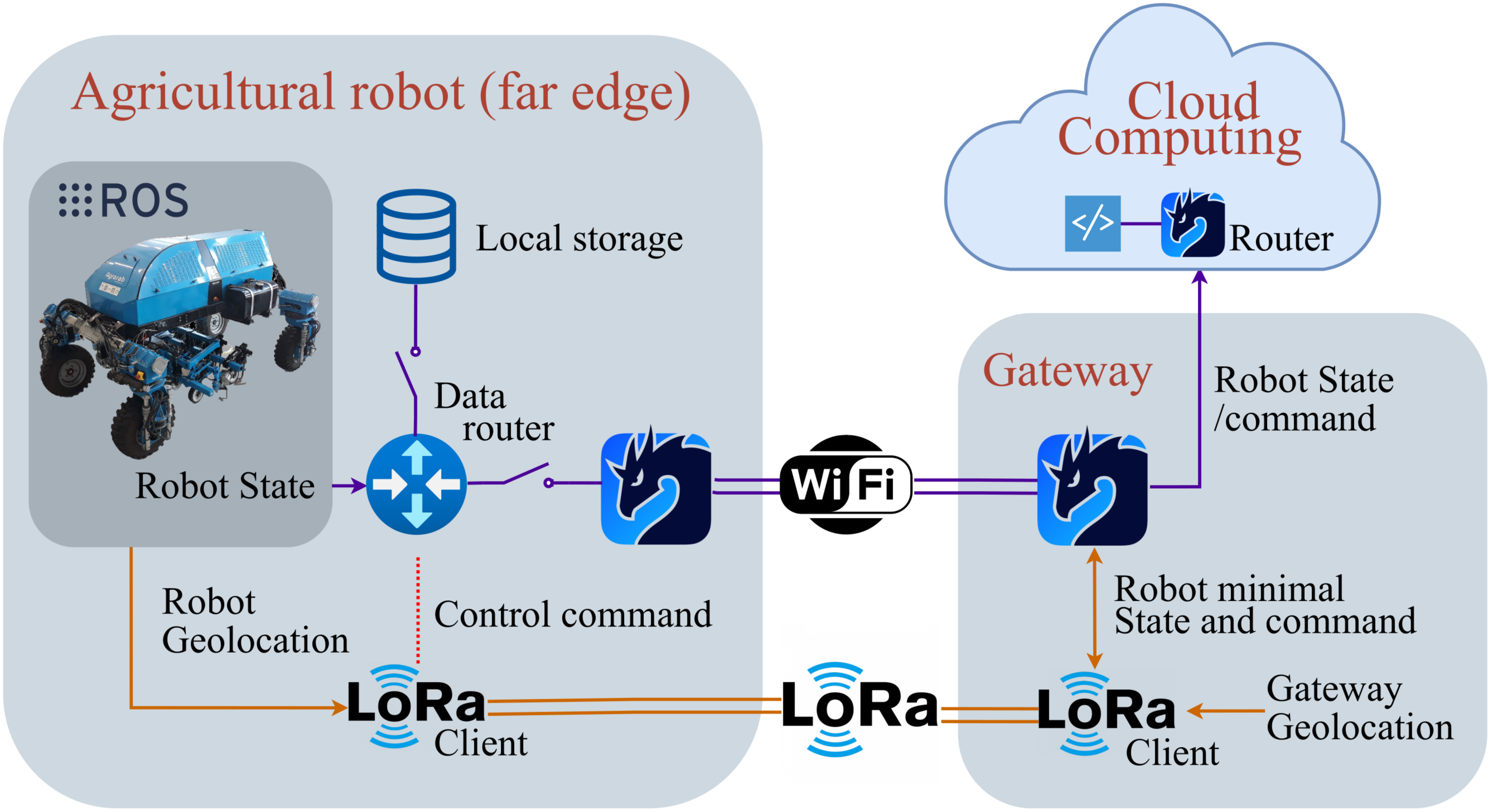
- Precision-farming robots generate **high-volume sensor data** but work in **connectivity-poor fields -** distant crop rows, orchards, vineyards.
- Existing links: **LPWAN = long range, tiny payload** vs **Wi-Fi = high payload, short range**.
- Mission-critical control **must never drop**; bulk data **must still reach** the cloud.
- Goal: **robust, high-throughput, low-latency comms** for one or many field robots.

Losing information risks crop damage, data loss, and safety incidents.

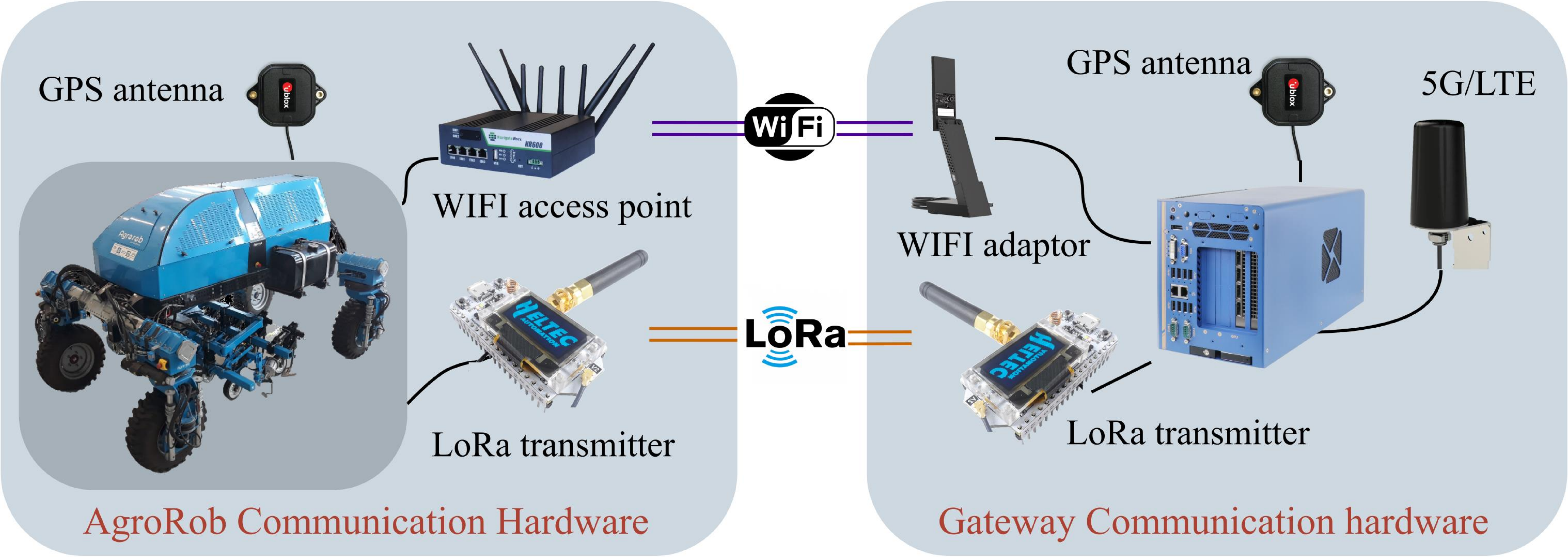
Our Contributions

- Dual-link framework that runs control over LoRa radio and bulk data over Wi-Fi/Zenoh.
- Smart data router on the robot that decides when to stream and when to log locally.
- Machine-learning detector that spots a weak Wi-Fi link seconds before it drops.
- Field proof: under 100 ms Wi-Fi latency up to 240 m; LoRa reliable beyond 350 m.
- Built-in scalability for fleets of robots using standard ROS 2 namespaces.

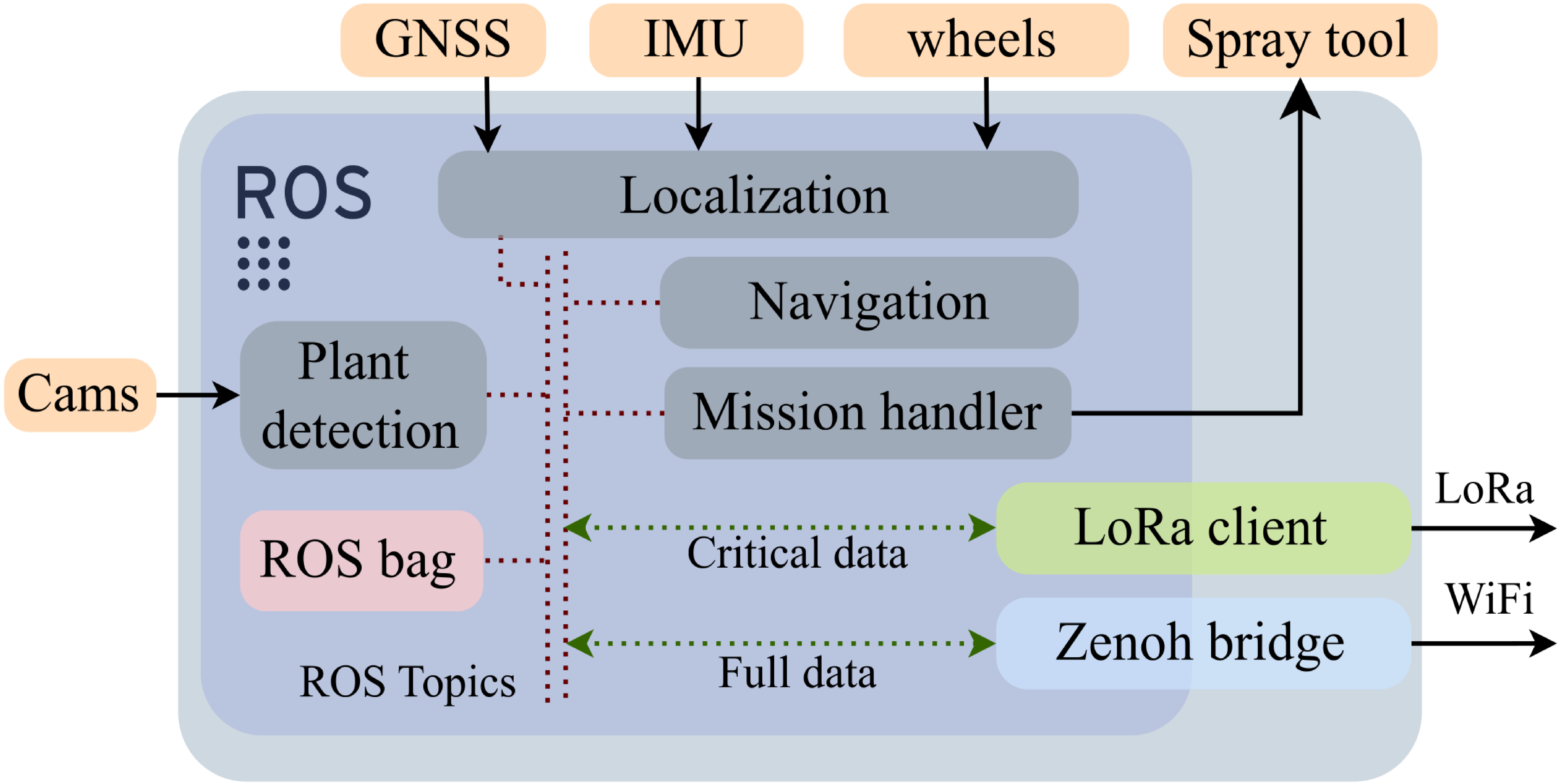
System Architecture



System Hardware



Data Flow


GNSS
IMU
wheels
Spray tool
ROS
Localization
Navigation
Plant detection
Cams
Mission handler
LoRa
LoRa client
Critical data
ROS bag
WiFi
Zenoh bridge
Full data
ROS Topics

Data Router Logic

- **Inputs**: robot–gateway distance + heartbeat delay trend.
- If Wi-Fi looks healthy → **Transfer Mode**: stream live data to gateway.
- If Wi-Fi degrades or distance is too large → **Storage Mode**: stop streaming, start local ROS-bag recording.
- Target ≥ 1 s overlap so nothing falls through the cracks; achieved 0.8 s in tests.

Predicting Wi-Fi Link Failure Proactively

- **Data fed every 2 s**: last 64 heartbeat gaps ⟨robot ⇄ gateway⟩ + current range.
- **Offline learning**: XGBoost regression trains on 3 285 normal samples to model expected timing behaviour.
- **Online scoring**: residuals clustered with K-Means ($k = 20$); high distance ⇒ anomaly.
- **Accuracy** on field logs:
  - Precision 0.95
  - Recall 0.97

Experiments

In our experiments we measured:

- Communication Latency
- Packet Loss
- Network Coverage
- Data Overlap

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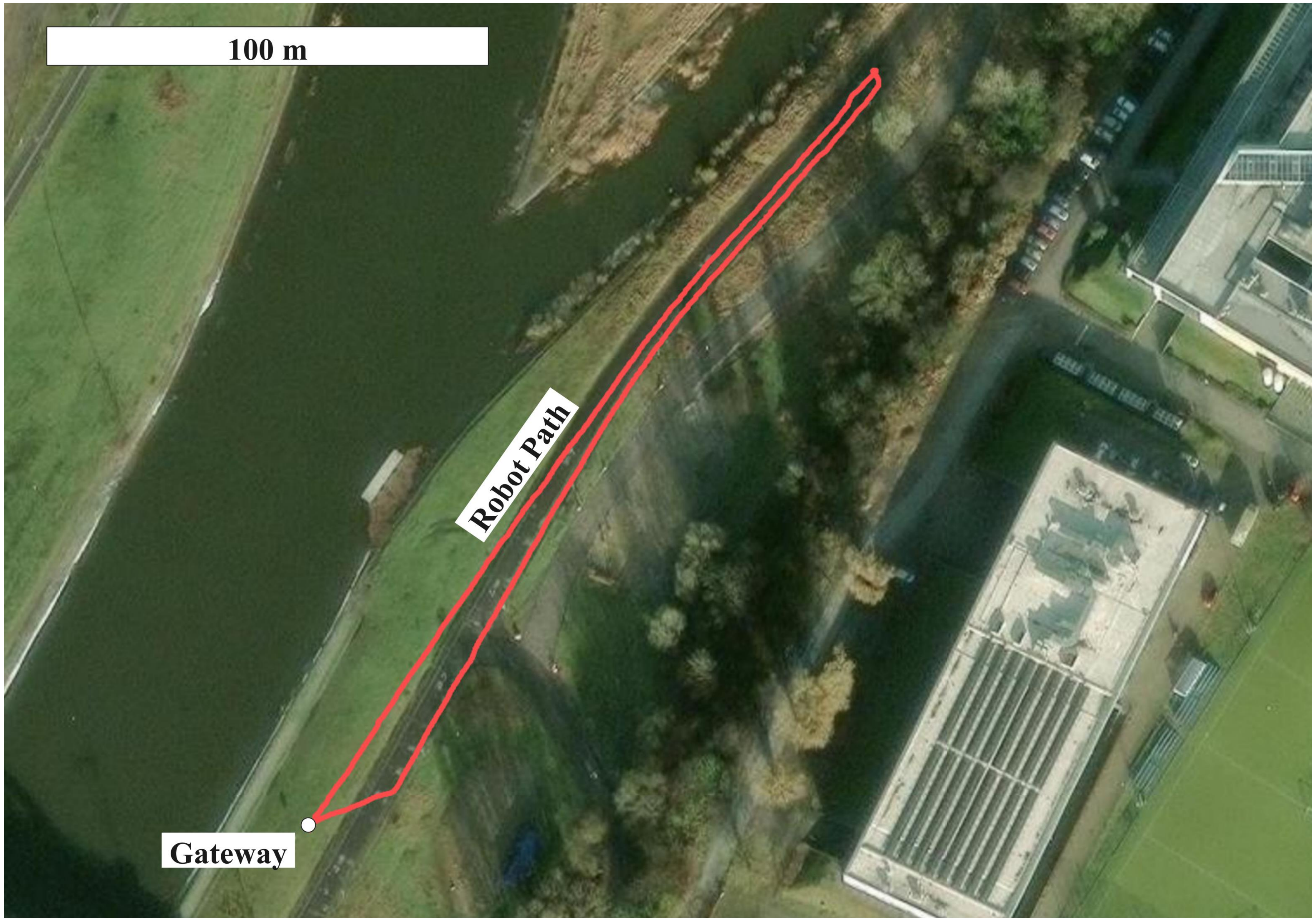
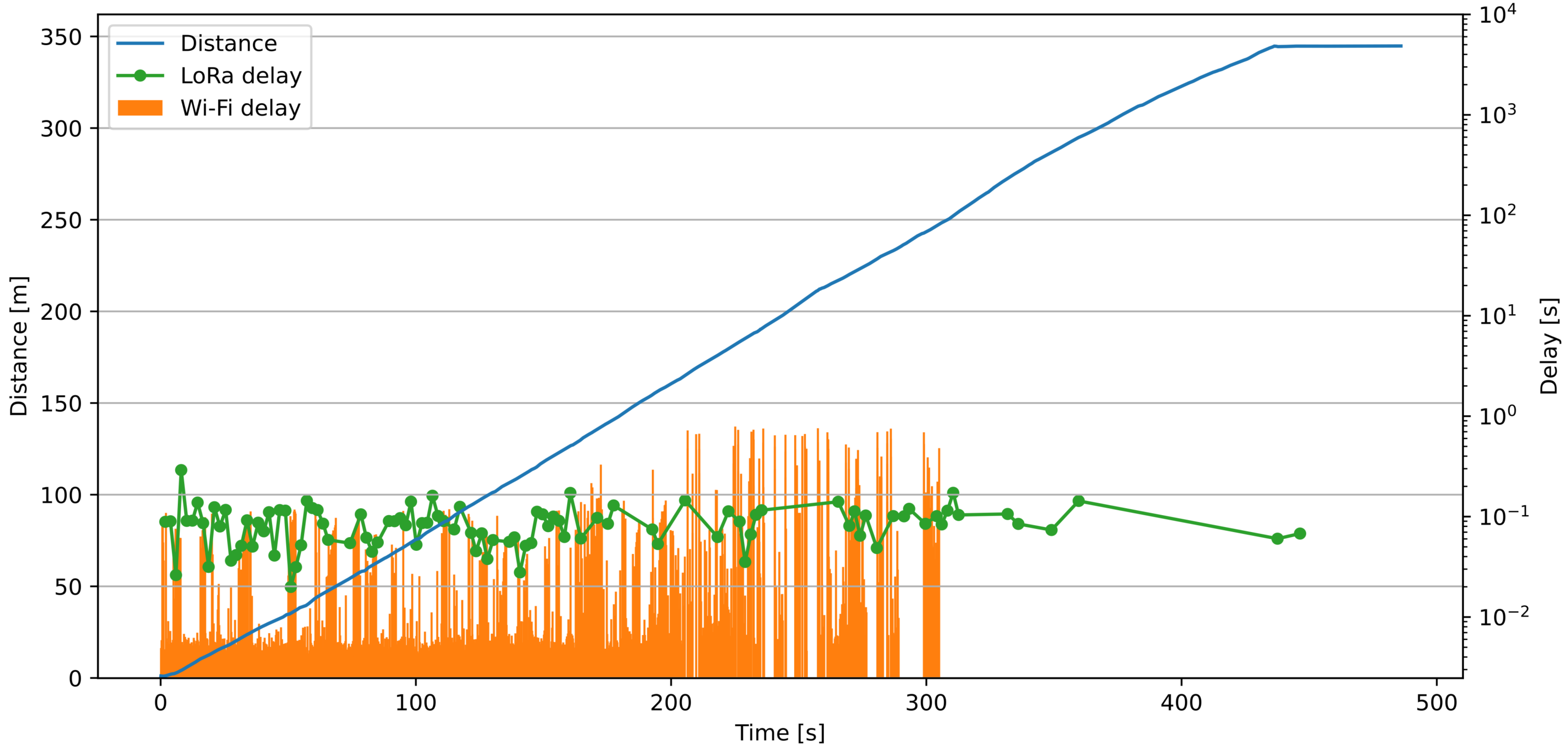
Field-Test

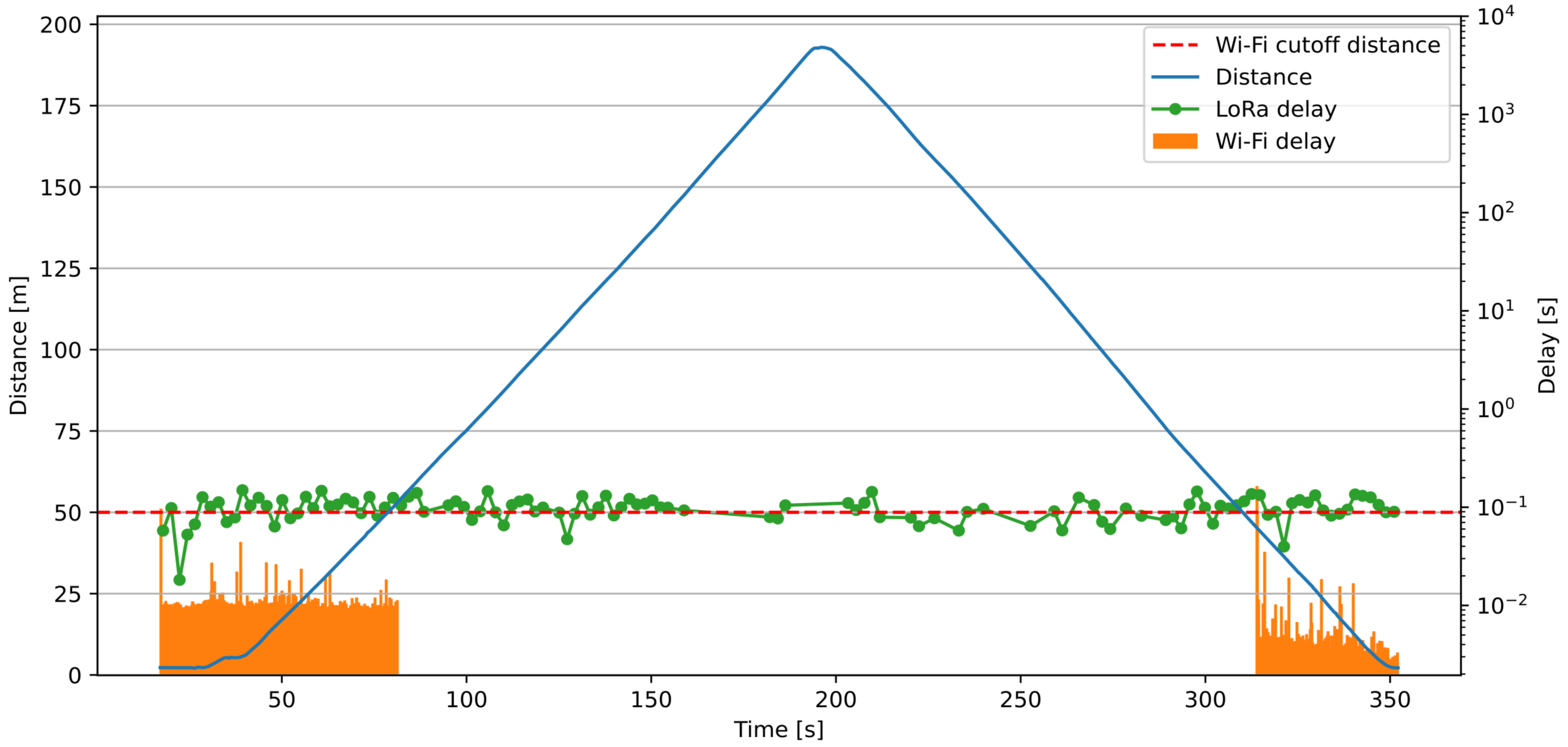


Results: WiFi and LoRa delay

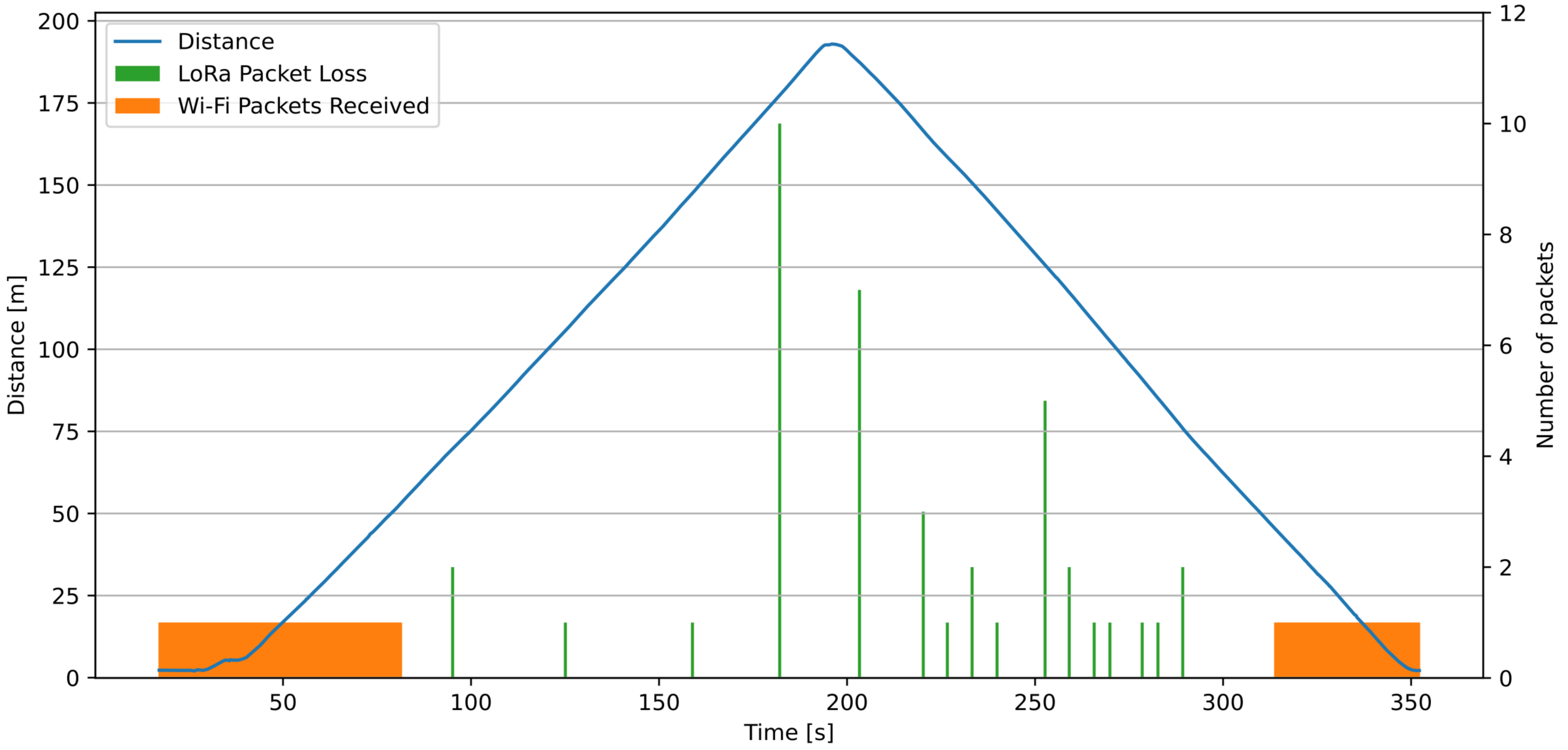


WiFi and LoRa packet delays as the robot moves away from the gateway. As the robot recedes from the gateway, packet transmission delays increase; the Wi-Fi link fails beyond approximately 300 m, whereas the LoRa channel continues to deliver low-bandwidth data with an almost constant latency.

Results: 50-meter distance threshold



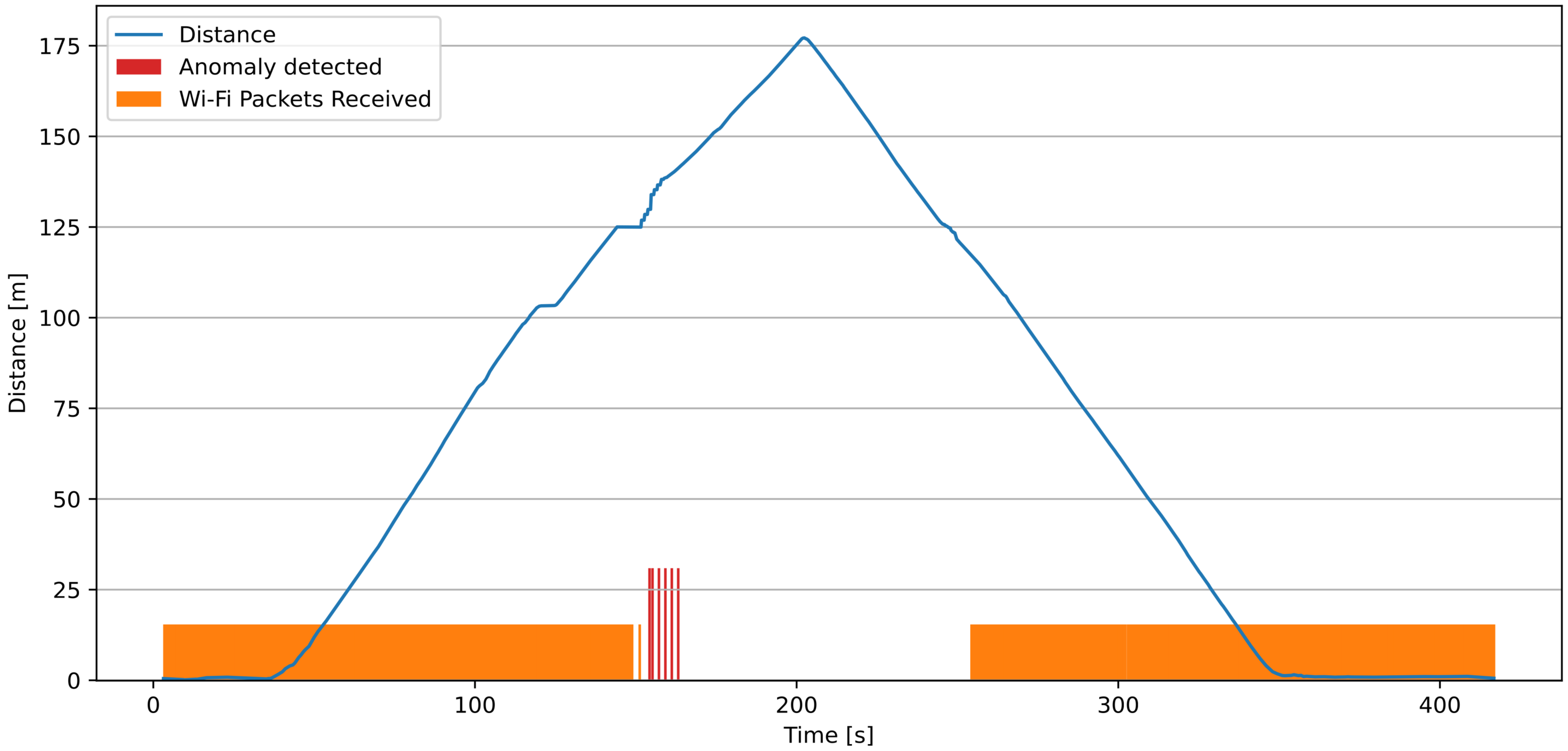
A) WiFi and LoRa packet delays



B) WiFi Received packets and LoRa packet lost

A) WiFi and LoRa packet delays, and B) WiFi received packets and LoRa packet loss as the robot moves away from and gets close to the gateway, switching between Transfer and Storage Modes at a 50-meter distance threshold.

Results: Anomaly Detection



Anomaly detection system recognizes issues with Wi-Fi data transfer, particularly as the distance between the robot and the gateway increases and signal quality begins to degrade.

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Conclusions

- **Hybrid LoRa + Wi-Fi scheme**: LoRa carries vital control/status; Wi-Fi/Zenoh off-loads high-volume sensor data.
- Field trials confirm **robust control** beyond 350 m and sub-100 ms bulk-data links within 240 m.
- **Architecture already multi-robot-ready**: ROS 2 namespaces isolate streams; single Zenoh bridge ingests all; LoRa multicast fans out commands.
- **Next steps:** stress-test heterogeneous fleets; optimise hot-standby Zenoh; study high-density LoRa multicast; integrate automated cloud sync under EU ICOS meta-OS.

Thank You!

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