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## Motivation & Problem Statement

- Industrial gas leaks waste 20–30% of compressed gas, creating major energy and operating costs
- Manual inspections and handheld acoustic cameras are intermittent, labor-intensive, and difficult to scale across large facilities
- GASLEAD provides continuous, non-invasive monitoring for compressed air pipelines



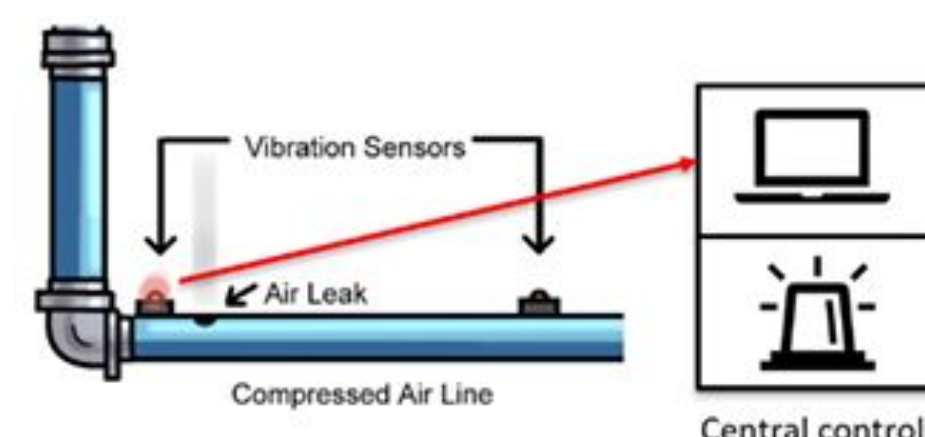
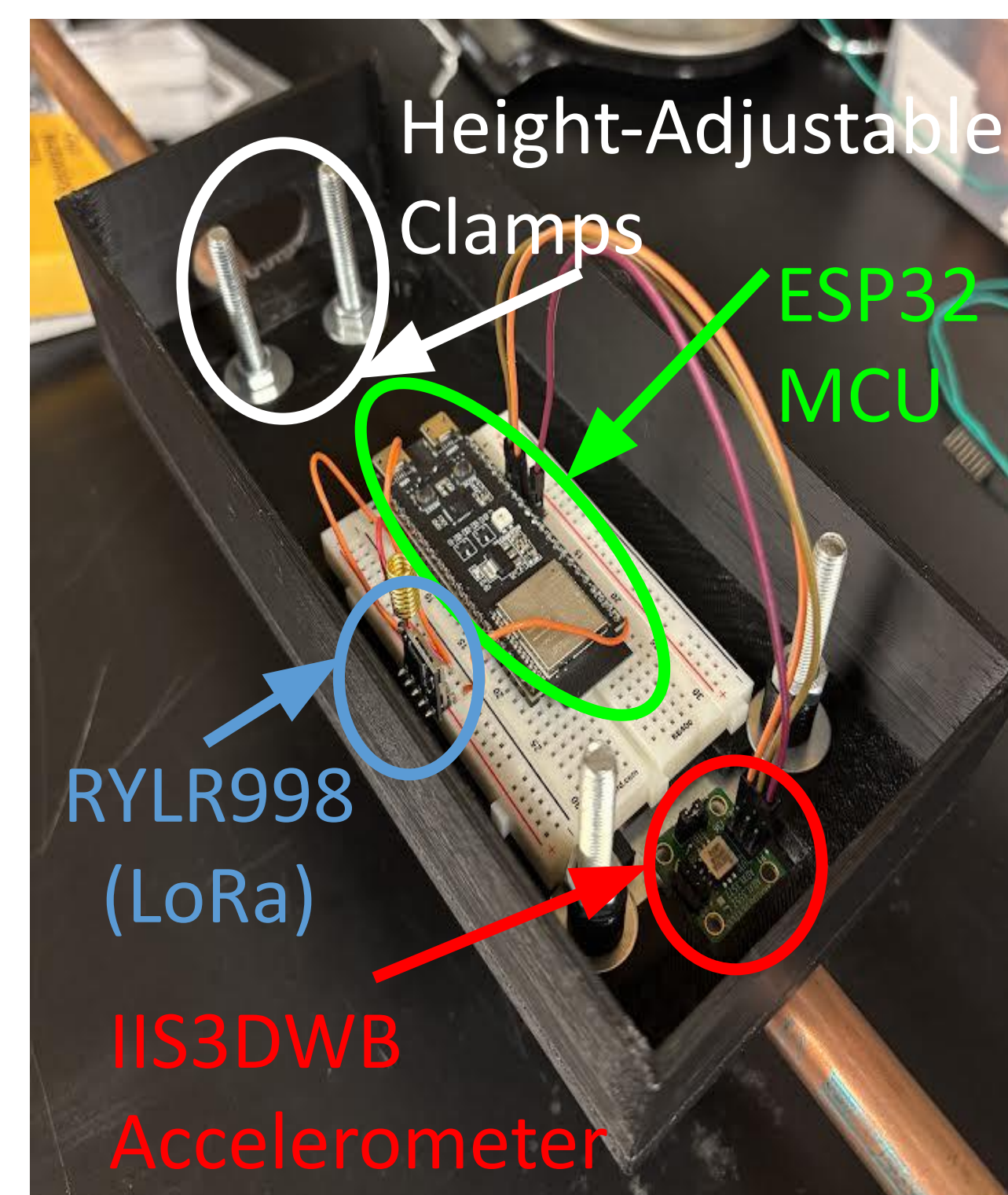
## Requirements

- GASLEAD provides a clamp-on, wireless vibration sensor network
- Autonomously detects and localizes gas leaks in industrial piping
- Non-invasive, avoids pipe modification or operational downtime

Criteria	Goal
Detection frequency range	0–5 kHz
Detection latency	10–30 seconds
Installation method	Clamp-on, non-invasive
Wireless communication	LoRa, battery-powered

## System Architecture

- IIS3DWB MEMS Accelerometer – 3-axis digital sensor designed for industrial condition monitoring
- ESP32-S3 MCU – On device FFT and feature extraction
- RYLR998 LoRa Module (868/915 MHz) – long-range, low-power wireless transmission to gateway
- Clamp – Height adjustable clamp accommodates variable pipe diameters
- PLA Enclosure – minimal vibration absorption.



## Accelerometer Vibration Sensing

- MEMS accelerometers capture structural vibrations in the 80–400 Hz band, measuring the pipe wall's resonant response to a gas leak
- A 1024-point FFT with Hann windowing extracts the frequency-domain power spectrum from each sample window, isolating target band features for anomaly detection
- Hardware cost and environmental noise tolerance motivates low-frequency harmonic detection over direct ultrasonic sensing

Found 20 peaks above threshold:  
 Candidate f0=4007.2 Hz → 3 harmonics found  
 Candidate f0=4131.3 Hz → 3 harmonics found  
 Candidate f0=4387.2 Hz → 4 harmonics found  
 Candidate f0=7278.9 Hz → 2 harmonics found

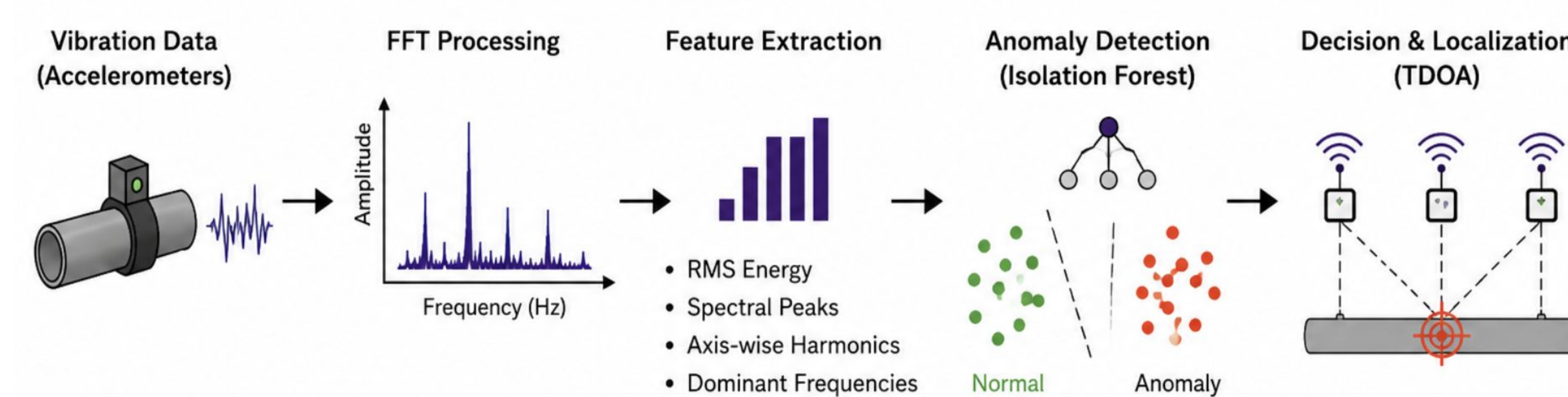
▲ GAS LEAK DETECTED!

Fundamental frequency: 4387.2 Hz  
 Harmonics confirmed: 4

Harmonic 1: 4375.0 Hz (magnitude: 300)  
 Harmonic 2: 8945.3 Hz (magnitude: 567)  
 Harmonic 3: 13242.2 Hz (magnitude: 310)  
 Harmonic 4: 17851.6 Hz (magnitude: 1359)

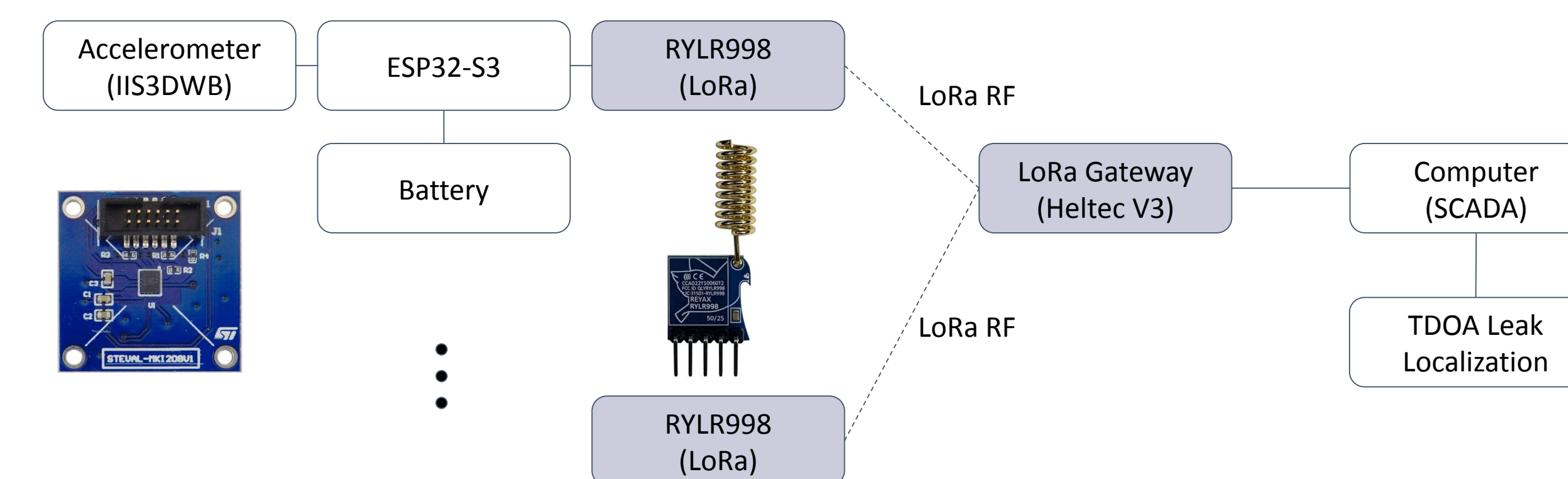
## ML Anomaly Detection Model

- 18-dimensional feature vector per window: RMS, spectral peaks, harmonic magnitudes, and axis-wise FFT across X, Y, Z axes
- Isolation Forest trained on 51,691 no-leak windows; flags windows where anomaly score > threshold
- 3-of-5 voting across consecutive windows reduces false positives from transient vibration spikes
- On-device inference on ESP32-S3 — features computed locally, only alerts transmitted over LoRa



## LoRa Communication

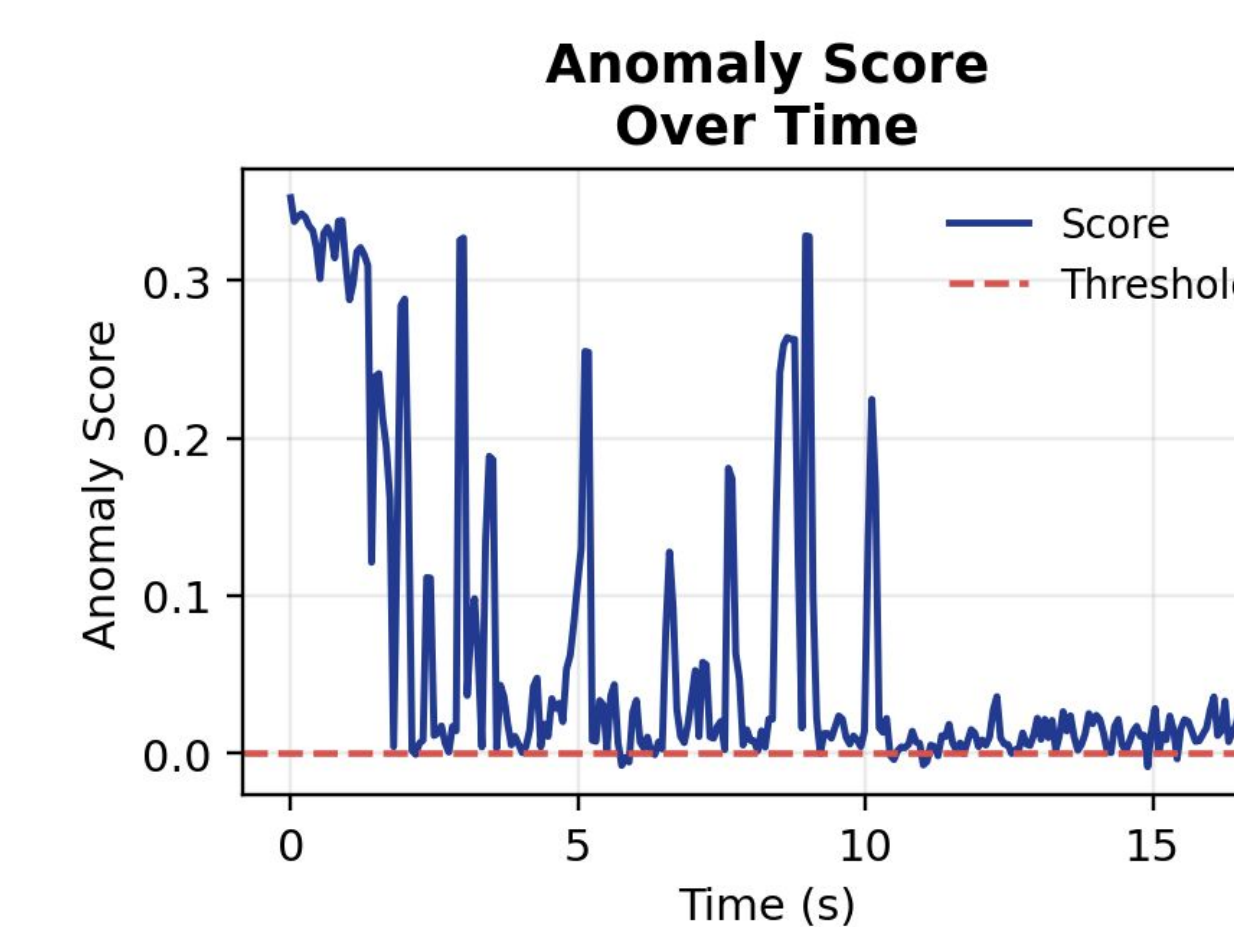
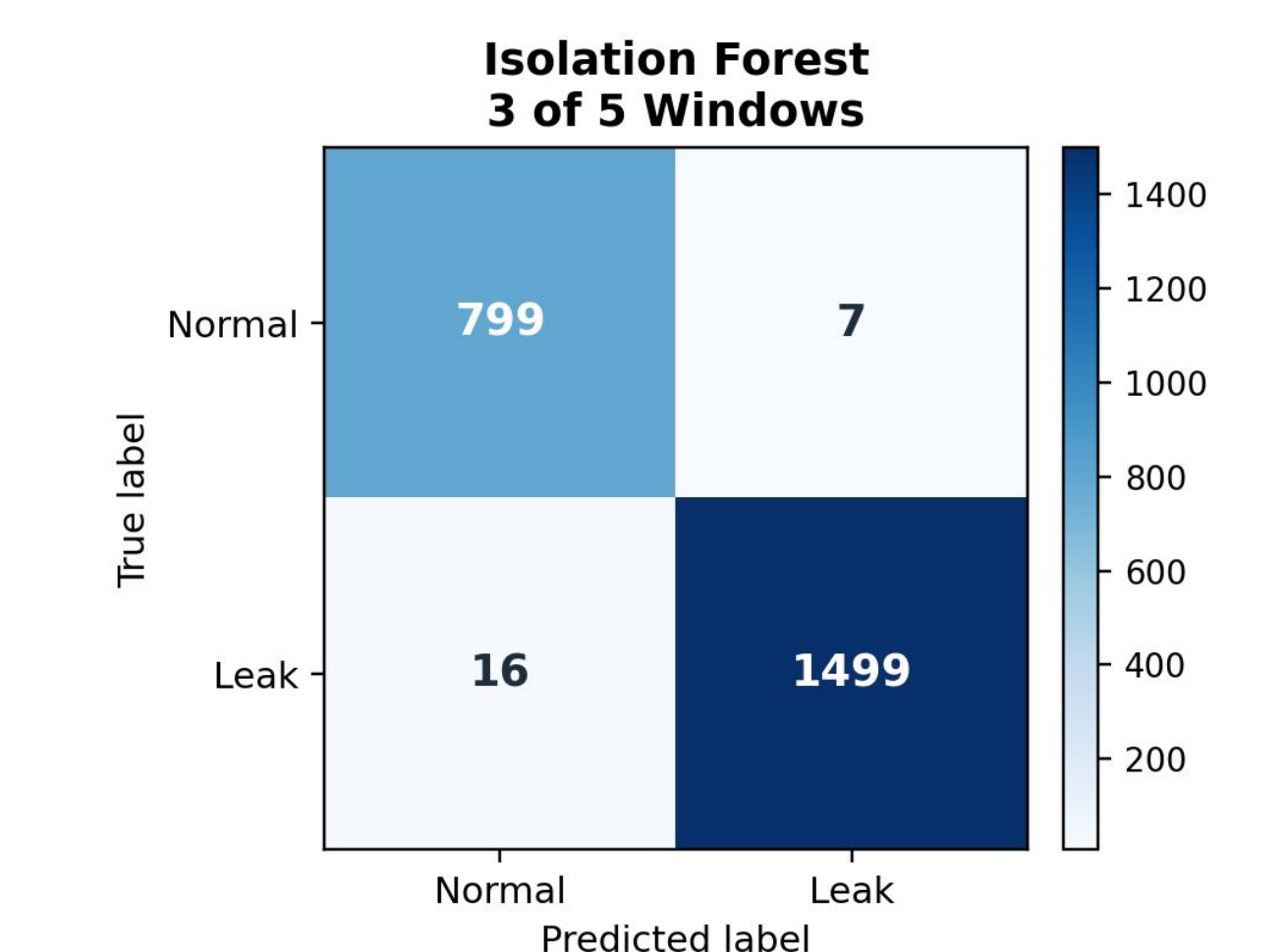
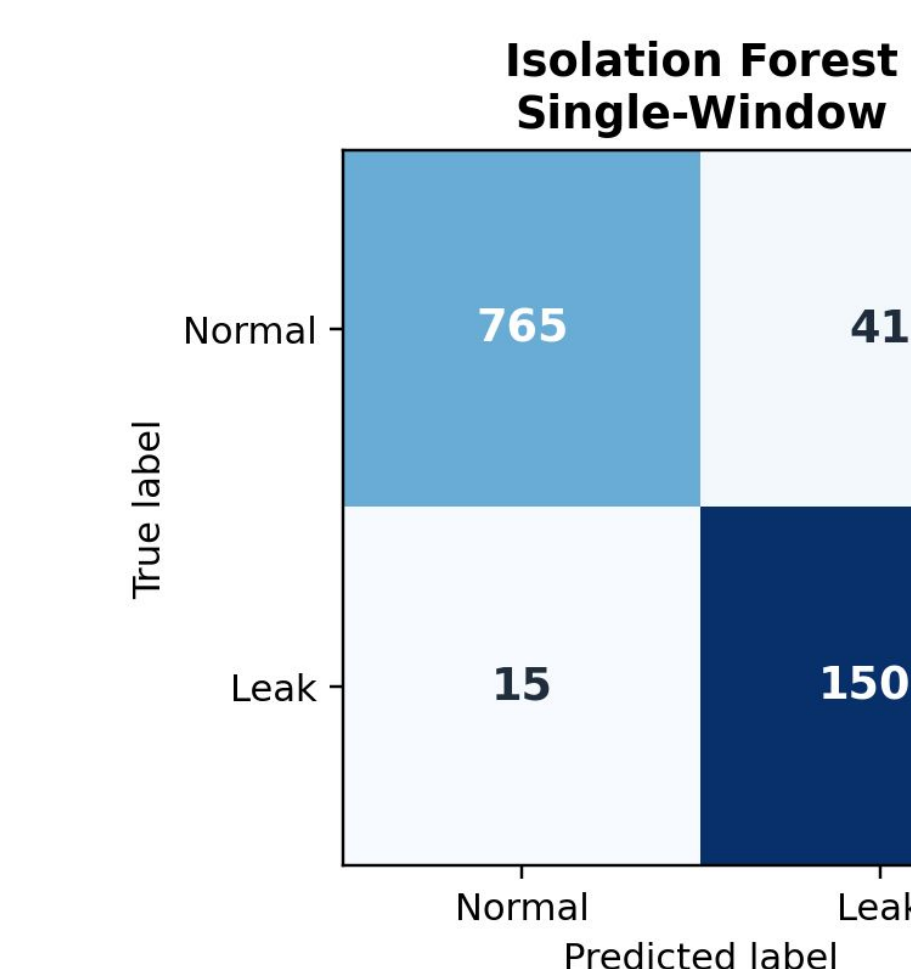
- LoRa provides a low-power wireless link suitable for noisy industrial environments
- Nodes transmit processed features instead of raw data to reduce communication load
- Multi-node anomaly confirmation improves robustness against factory background vibration
- Gateway aggregates node alerts for SCADA visualization and TDOA localization



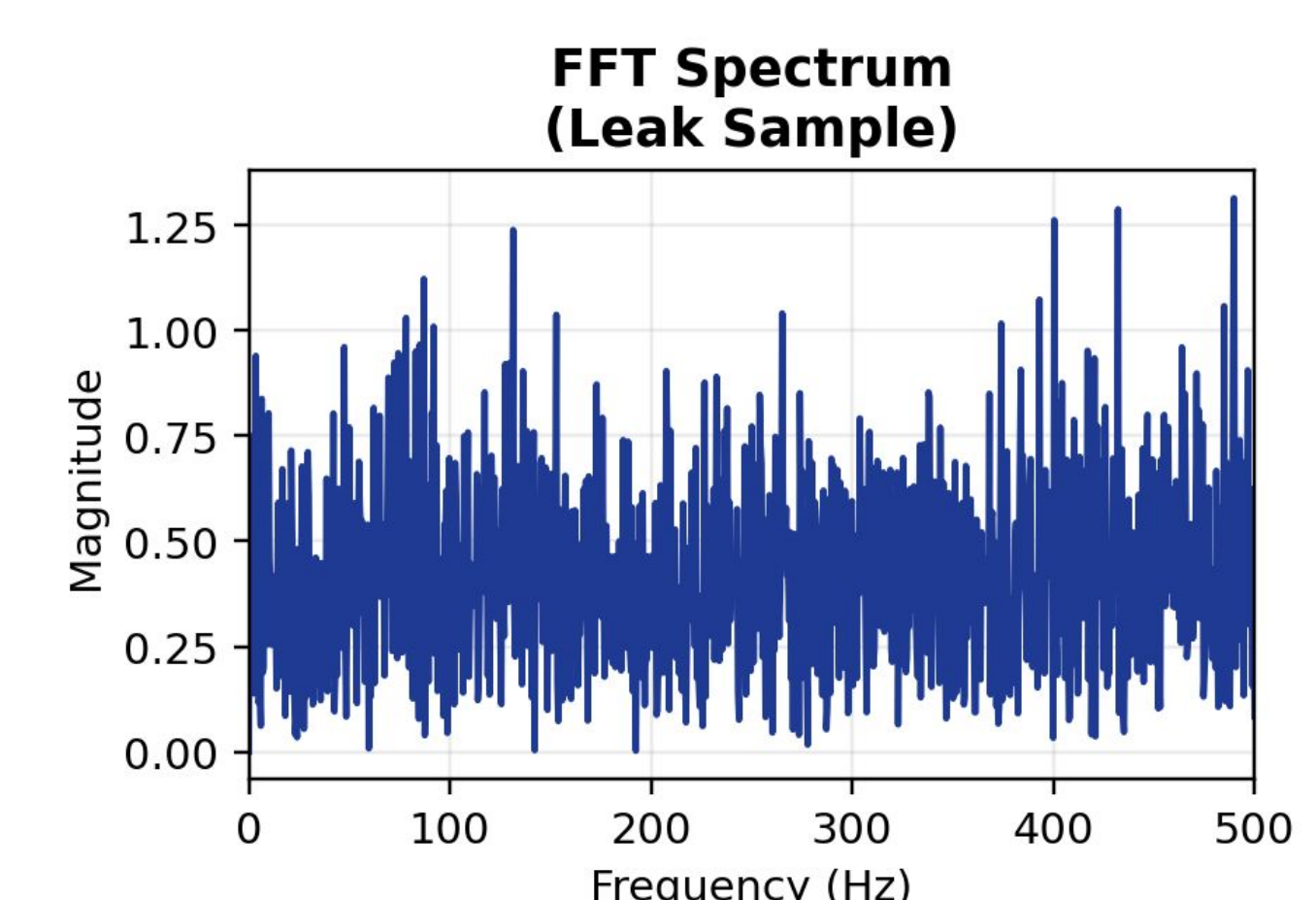
## Results & Conclusion

Metric	Result
Single-window accuracy	97.6 %
3-of-5 window accuracy	99.0 %
Normal recall	99.1 %
Anomaly recall	98.9 %

- Training data: 51,691 non-leak samples (806 windows)
- Test data: 97,517 leak samples (1,515 windows)
- Sampling rate: ~1 kHz



Score > 0 is more anomaly-like, Score < 0 is more normal-like



FFT shows vibration energy across frequency, current data covers the 0–500 Hz structural vibration band

- Isolation Forest achieved strong leak detection on collected vibration recordings
- Multi-window voting reduced false alarms while maintaining high leak recall
- The results support the feasibility of GASLEAD's vibration-based sensing approach

## Future Work

- Expand to a multi-node network and implement TDOA localization to identify leak location.
- Integrate real-time volumetric leak rate estimation and translate directly to dollars lost.
- Implement adaptive duty cycling across all power-consuming subsystems to achieve 1+ year battery life.
- Expand on-site normal data collection and develop site-specific baseline calibration