

Dual-Mode Telemetry for Industrial Monitoring: Data Integrity between USB and LoRaWAN in Critical Infrastructure

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Abstract:

Expansion joints are safety-critical components in thermal power plants, petrochemical facilities and district-heating networks. The traditional inspection routine for these components is invasive, time-consuming and has limited diagnostic capability. The Smart Kit provides an alternative way to monitor expansion joints by turning the joint itself into a sensor node and continuously streaming its thermal load profile to a cloud backend, where artificial-intelligence-based (AI-based) assessment methods may use the data. The node supports two transmission paths: a wired USB link, which acts as a deterministic reference, and a wireless LoRaWAN link, intended for the actual industrial deployment. Both paths share the same firmware, the same data structure, and the same backend schema in InfluxDB, so that any difference between the two streams may be attributed to the communication layer. Tests in a lab environment and on a turbine test rig show that a properly sized LoRaWAN network, with two gateways and 15 nodes at Spreading Factor 7 (SF7) in the EU868 band, reaches a Packet Delivery Ratio (PDR) of 99.4 % and stays within sensor accuracy limits when compared to the USB reference.

Keywords: Industrial IoT, LoRaWAN, data integrity, predictive maintenance, condition monitoring

Introduction

Expansion joints are mechanical components used in gas turbine power plants, petrochemical processing units, district-heating networks, and heat-recovery steam generators (HRSGs). Their role is to absorb thermal expansion, mechanical vibration and pressure fluctuations, so that this stress is not transferred to the rigid piping next to them [1], [2]. The operating conditions are harsh. During a turbine start-up or load change, the temperature inside the piping may change by several hundred Kelvin within minutes. Over many such cycles, the fabric or bellows of the joint slowly suffer thermo-mechanical fatigue. An industrial expansion joint is in fact a composite assembly of steel and fabric components. While the fabric layers carry the main thermal insulation and sealing function, the surrounding steel frame is exposed to the same cyclic loads and is therefore equally susceptible to fatigue damage.

The shift towards renewable energy has made this worse. Thermal power stations are now used as flexible backup capacity, which means more cold and warm starts and faster load ramps than they were originally designed for [3]. Expansion joints sit in inconvenient places inside the plant and are normally inspected only on a fixed schedule, often with handheld thermometers. Damage such as fabric fatigue, seam cracks, insulation loss, or local overheating may build up between two inspections without anyone noticing. When the joint finally fails, the whole plant typically has to be shut down [4], [5].

One way to reduce this gap is to add sensor-based continuous monitoring. For such an Industrial IoT (IIoT) system to actually replace today's inspection routine, two things need to work at the same time. First, the communication technology has to fit the physical reality of the plant, such as distances, obstructions and the cost of cabling. Second, the data arriving at the backend has to be correct, regardless of which transmission path it took. Continuous monitoring

cannot prevent every failure mode. A sudden mechanical event, such as a broken steel frame, may still force an immediate shutdown irrespective of the available sensor data. The intended benefit is rather to detect the gradual mechanisms early enough to schedule maintenance before such a critical state is reached.

The **Smart Kit** is a dual-mode monitoring system developed inside a collaborative research project funded by the German Federal Government under the 7th Energy Research Programme. The project partners are TU Darmstadt, Hochschule Darmstadt, TU Dresden, and the industrial partner DEKOMTE de Temple. The work reported here focuses on the sensor and communication subsystem. It covers the hardware and firmware of the sensor nodes, a comparison between a wired USB channel and a wireless LoRaWAN channel built on the same firmware and data schema, and field validation on a turbine test rig under nominal and fault-induced conditions. The machine-learning side of the project is handled by TU Darmstadt and is out of scope here.

Failure mechanisms in expansion joints

The main ways an industrial expansion joint can fail are thermo-mechanical fatigue from repeated start-ups and shutdowns, forced vibration from turbulent flow, from the turbine movement itself or pressure surges, chemical attack by acidic or corrosive flue gases, and overstraining from misalignment during installation [4], [5]. If these mechanisms are not picked up early, they progress to fabric rupture, bellows deformation, broken seams, insulation failure, or flue-gas leakage, and any of these usually means a full plant shutdown. Fixed inspection intervals are too coarse to catch the early signs, which is the practical motivation for continuous monitoring.

Communication technology selection

An IIoT system for distributed asset monitoring has to balance range, power consumption, data rate and cabling cost. USB is deterministic, lossless and has very low latency, which makes it a good reference channel for laboratory work, but it needs a physical cable to every node and is therefore not realistic for joints distributed across a plant. LoRaWAN is the opposite: its chirp-spread-spectrum physical layer (PHY) reaches several kilometres at sub-milliwatt standby power, which fits sparse telemetry in large facilities where running cables is either too expensive or simply impossible [6], [7].

LoRaWAN comes with restrictions a wired link does not have. The EU868 sub-bands impose duty-cycle limits of about 1 %, the Medium

Access Control (MAC) layer is a probabilistic ALOHA scheme that loses packets when node density rises, and the end-to-end latency depends on what the gateway is doing at the time [8], [9]. To still get usable data out of such a link, the system has to add explicit data-integrity measures: time stamps applied at the sensor, gap detection, and an encoding that does not depend on the transport layer.

Predictive maintenance algorithms, such as unsupervised anomaly detectors (e.g. Isolation Forest), recurrent models such as Long Short-Term Memory (LSTM) networks, or survival models used to estimate remaining useful life, essentially depend on the quality of the input data. Missing time stamps, transmission distortions, or artefacts that depend on the communication protocol all reduce model accuracy and may cause either false alarms or missed detections [10], [15]. Therefore, the communication subsystem and the analytics subsystem cannot be designed in isolation.

Three-layer architecture overview

The Smart Kit is organised in three layers. The **sensor layer** is made up of battery-powered nodes that are mounted directly on the flange of an expansion joint and read a small set of temperature, humidity and pressure sensors. The **communication layer** offers two transmission paths in parallel: a wired USB link used for lab calibration and as a ground truth, and a LoRaWAN link used in the actual deployment. The **application layer** is open source. It consists of a ChirpStack network server, an InfluxDB 2.x time-series database and a Grafana dashboard for visualisation.

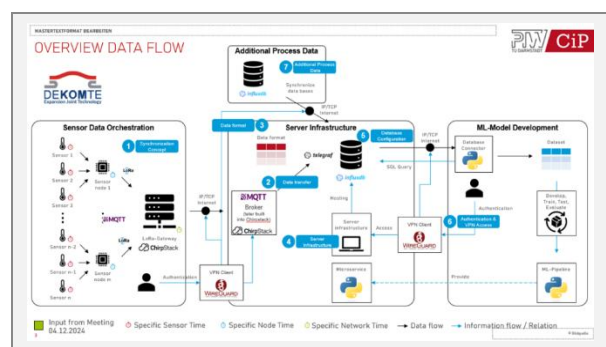


Fig. 1. High-level Smart Kit architecture: data flow from the sensor nodes to the cloud backend via USB and LoRaWAN.

Sensor node hardware

The node is built around an Adafruit Feather RP2040 board with an integrated RFM95W LoRa transceiver. The RP2040 is a dual-core ARM Cortex-M0+ microcontroller and the RFM95W operates at 868 MHz with +20 dBm

transmit power and -137 dBm receiver sensitivity. The sensors are listed in Tab. 1. An Adafruit PCA9548A I²C multiplexer is added between the microcontroller and the sensors so that several devices with the same default I²C address can coexist on the same bus. All components run from a single 3.3 V rail. Between two transmissions the node enters deep sleep and draws around 45 μ A, which gives an estimated battery life of more than 18 months on a 2000 mAh Li-Po cell.

Tab. 1: Sensor subsystem and prognostic role.

Sensor	Parameter	Prognostic role
BME280	Ambient T / RH / P	Environmental baseline
MCP9808	Surface temperature	Joint flange thermal load
MCP9601 + K-type TC	Hotspot temperature	Localised overheating

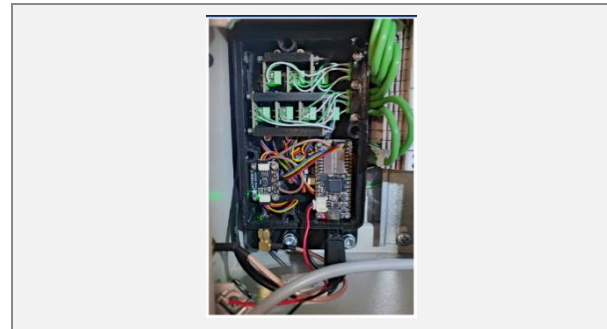
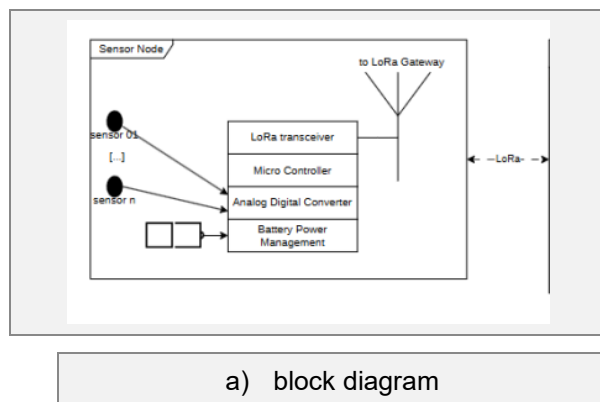
Sensor specifications:

BME280 ± 0.5 °C / ± 3 % RH / ± 1 hPa;

MCP9808 ± 0.5 °C at 0.0625 °C resolution;

MCP9601 with K-type thermocouple, up to 1473 K at ± 2 °C [14].

The whole assembly is placed in an IP65 polycarbonate enclosure with a breathable membrane so that the inside does not build up pressure when the temperature changes. The printed circuit board (PCB) is conformally coated against condensation. The MCP9808 breakout is thermally bonded to an external probe with a copper strap, and a thermal block between the probe feedthrough and the main board keeps the heat from leaking back into the electronics.



b) assembled node inside the IP65 enclosure

Fig. 2. Sensor node: (a) block diagram with RP2040, RFM95W, I²C multiplexer and sensor breakouts; (b) assembled node inside the IP65 enclosure.

The LoRaWAN gateway is a Raspberry Pi 3B+ with a Seeed Studio WM1302 concentrator (Semtech SX1302, 8 channels), mounted at about 4 m height and connected to a 5 dBi dipole antenna. ChirpStack is installed on the same device and handles device management, payload decryption and Message Queuing Telemetry Transport (MQTT) forwarding to the application layer.

Common acquisition core for USB and LoRaWAN

The firmware is written in CircuitPython 8.2.0. The acquisition core (sensor sampling, value encoding, data-structure definitions) does not depend on which transport path is used: the same code produces a USB record and a LoRaWAN uplink with the same content. Both end up under the same schema in InfluxDB, which is what makes a direct quantitative comparison of the two channels possible. The USB side is implemented as a Communications Device Class (CDC) virtual serial port with a simple delimited text format, chosen so that it can be parsed by hand if needed. A watchdog and pre-configured fallback values keep the node sending data even when one of the I²C sensors temporarily fails to respond.

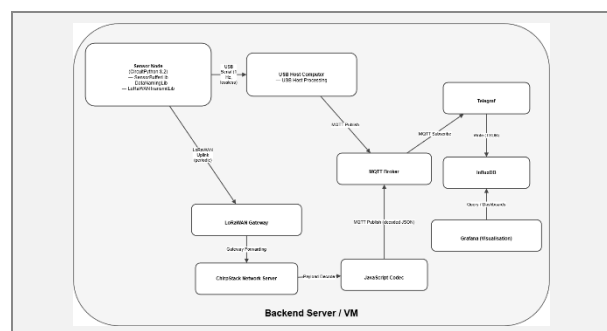


Fig. 3. Dual-path software architecture. The USB and LoRaWAN streams are acquired independently but written to a common schema in the backend.

LoRaWAN payload encoding

On EU868 with Spreading Factor 7 the usable payload is around 51 bytes per uplink. To stay safely below this limit, ten sensor values (one internal temperature, one ambient pressure, one relative humidity and seven K-type thermocouple readings) are packed into a 24-byte integer. Each value occupies 14 bits, with 4 extra bits used as a sensor identifier. The corresponding maximum quantisation error for a temperature reading is below 0.04 °C, which is well inside the ± 0.5 °C accuracy of the MCP9808. Because the field widths and the order of the sensors are fixed, the same encoding can be inverted at the application layer without any loss.

Uplink frame counters are written to the microcontroller's non-volatile memory so that they survive power cycles and resets. Without this, ChirpStack would silently drop uplinks whose counter is lower than expected. For the experimental phase the nodes were configured with Activation by Personalisation (ABP) rather than OTAA (Over-the-Air Activation), mainly to avoid the join-procedure delay and to keep the session parameters fixed across reboots [11]. Time stamps are applied on the node at the moment of sampling on both paths and the two clocks are aligned at the start of an experiment, which is what allows a paired comparison between USB and LoRaWAN samples later on.

Both streams are consumed over MQTT and pre-processed by Telegraf, which parses the payloads, adds metadata, normalises the time stamps and writes the result into InfluxDB. Two buckets are used: a high-resolution bucket with a 30-day retention for anomaly analysis, and a one-year bucket with downsampled values for longer-term trends. A Grafana dashboard then shows the two transmission paths next to each other in real time.

Test environment and methodology

The lab tests were carried out in a hall of about 40 m by 25 m. The room is large enough to place obstacles between the nodes and the gateway, so that the radio environment is closer to that of an actual industrial plant floor than to that of an empty office. All nodes operated on the EU868 band at SF7 with a fixed reporting interval of 300 s, which is in line with what a periodic condition-monitoring application would use. Three scenarios were run, each for 24 h, with one USB-connected node placed next to the wireless nodes to act as the ground-truth reference:

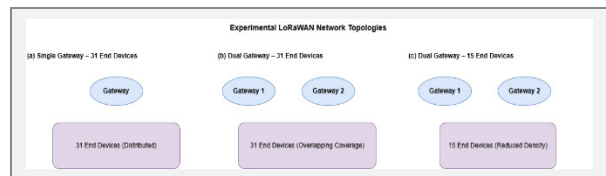
Scenario A (congested baseline): 1 gateway, 31 end devices.

Scenario B (scalability test): 2 gateways, 31 end devices.

Scenario C (target performance): 2 gateways, 15 end devices.



a) Laboratory experimental setup



b) Three network topologies

Fig. 4. (a) Laboratory experimental setup; (b) the three network topologies used in Scenarios A, B and C.

Data integrity between USB and LoRaWAN

For Scenario C, paired USB and LoRaWAN samples coming from the same dual-mode node were compared on a per-time-stamp basis so that any observed difference can only come from the communication layer. The result of this comparison is summarised in Tab. 2.

Tab. 2: Data-integrity error: USB vs. LoRaWAN (Sc. C).

Metric	Temp.	RH	Press.
Max abs. error	< 0.5 °C	< 3 % RH	< 1 hPa
Quant. error	< 0.04 °C	< 0.02 %	< 0.05 hPa
Sys. bias	None	None	None
Drift	None	None	None

In every case the deviation between the two paths stays within the sensor's own accuracy limits. No systematic bias was observed, no drift

over time, and no artefact that could be traced to the 14-bit packing scheme. The theoretical quantisation error of that scheme is below 0.04 °C, which is more than an order of magnitude smaller than the ± 0.5 °C accuracy of the MCP9808. Fig. 5 illustrates this on three hours of surface-temperature data taken under Scenario C: the USB trace is essentially flat as expected from a deterministic reference, and the LoRaWAN trace follows the same trend with a small amount of random variation on top.

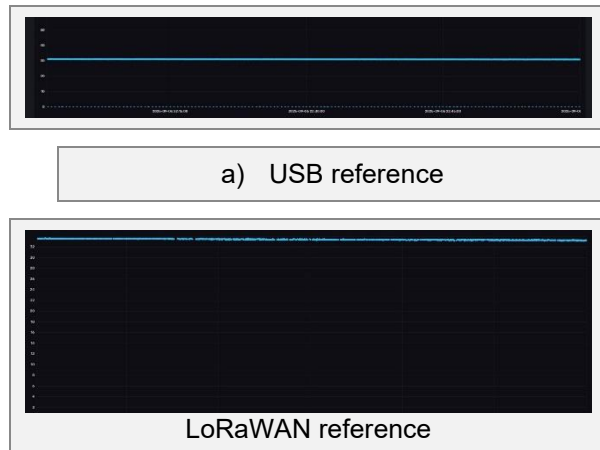


Fig. 5. Three-hour comparison: (a) USB reference; (b) LoRaWAN, showing the same trend with minor stochastic variation.

Packet delivery ratio and network congestion

The PDR results are shown in Tab. 3. In Scenario A the single gateway serving 31 nodes ended up with a mean PDR of only 68.2 %, and the gaps in the frame-counter sequence confirmed that the cause was collisions in the ALOHA-based MAC. Adding a second gateway (Scenario B) raised PDR to 91.5 % thanks to spatial receiver diversity, but the network was still effectively at capacity. Bringing the number of nodes down to 15 while keeping the two gateways (Scenario C) gave a PDR of 99.4 % with fully monotonic frame counters, which for the periodic monitoring use case is functionally equivalent to a wired link.

Tab. 3: Packet Delivery Ratio (PDR) across scenarios.

S c.	Config.	PDR	Observation
A	1 GW, 31 nodes	68.2 %	Contention
B	2 GW, 31 nodes	91.5 %	Spatial div.
C	2 GW, 15 nodes	99.4 %	Wire-equiv.

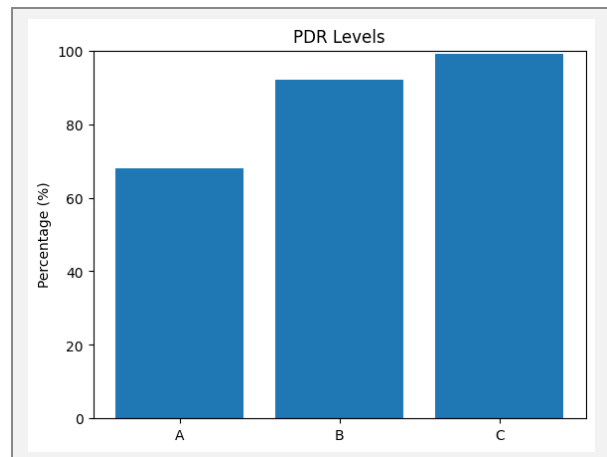


Fig. 6. Packet Delivery Ratio across Scenarios A, B and C.

End-to-end latency

End-to-end latency is measured here as the difference between the time stamp applied at the sensor and the time stamp written into InfluxDB. It therefore includes everything in between: the LoRa air time, the gateway forwarding, MQTT, Telegraf and the InfluxDB write itself. Tab. 4 lists the mean latency for the reference path and for the three LoRaWAN scenarios.

Tab. 4: End-to-end latency: USB vs. LoRaWAN scenarios.

Path	Latency	Overhead
USB reference	2.3 s	0.3 s
LoRaWAN, Sc. A	9.1 s	1.1 s
LoRaWAN, Sc. B	8.8 s	0.8 s
LoRaWAN, Sc. C	8.4 s	0.4 s

The USB path has an average pipeline overhead of 0.3 s with very low variance, as expected from a deterministic serial link. The LoRaWAN path is slower and more variable, dropping from 9.1 s in Scenario A to 8.4 s in Scenario C as the congestion decreases. For an application where the underlying physical change unfolds over minutes to hours, a latency in the 8 to 10 s range is not a limitation. Across all scenarios the order of the packets and the time stamps on them were preserved.

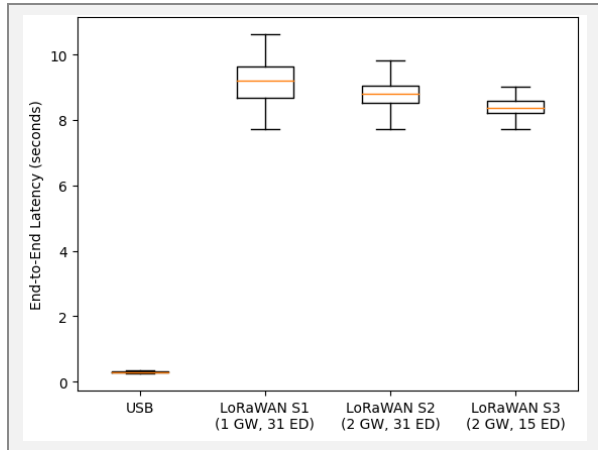


Fig. 7. End-to-end latency: USB reference (narrow, close to zero) compared to LoRaWAN Scenarios A, B and C.

Practical deployment guidelines

A few points are worth noting when sizing a LoRaWAN-based monitoring network for this kind of application. A single gateway can comfortably serve about 15 to 20 nodes at SF7 with a 300 s reporting interval; pushing past that figure brings PDR well below 99 %. The most effective way to scale up is to add more gateways, rather than to raise the transmit power or move to a faster data rate, since most of the loss comes from collisions, and not from link budget. Furthermore, frame counters and microsecond-accurate time stamps need to be kept at all times. They are what allows the operator to tell apart a quiet sensor from a lost packet.

Field validation on a turbine test rig

After the lab tests the Smart Kit was deployed on a turbine test rig between September 2025 and February 2026. The rig itself is already instrumented with K-type thermocouples and pressure transducers, and the Smart Kit nodes were added next to that existing instrumentation using the same hardware and firmware as in the lab. Out of the full test campaign, seven runs were selected for detailed analysis. They cover nominal operation (baseline step tests at 450 kW electrical output of the Kawasaki gas turbine), induced faults (insulation cover insertion and unilateral air leakage), the same faults at the higher load of 650 kW, and one multi-day fault-progression test [12].

The reference step tests at 450 kW produced the temperature response expected from the geometry of the rig and gave a stable baseline envelope against which the later fault signatures could be compared. The sensor response also lined up in time with the control-system events

on the rig, confirming that the time stamping shown in the lab works correctly in the field.

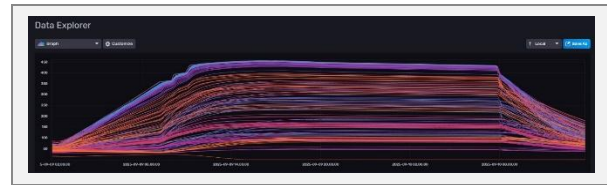


Fig. 8. Baseline step test at 450 kW: temperature and power profiles during nominal operation.

Fault signatures

The first fault scenario consisted of inserting an insulation cover fully and was repeated at 450 kW and 650 kW. In both cases the temperature deviation relative to the baseline was clear and repeatable. The shape and amplitude of the signature did not degrade when the load was raised from 450 kW to 650 kW, which is the result we wanted: a higher thermal load is not turning the diagnostic signal into noise.

A second, longer test was carried out over two consecutive days to see whether the system can also follow a fault that changes slowly. On the first day the rig was run at 650 kW with the cover in place and the fault condition stayed stable through the night. On the second day the cover was withdrawn step by step on an hourly schedule (07:30, 08:30, 09:30, 10:30, 11:30 and 12:30). Each step produces a small plateau in the temperature record, and all six plateaus are visible in the data. That is exactly the kind of gradual transition a trend-based anomaly detector would have to work with.

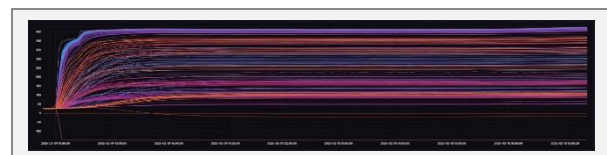


Fig. 9. Dynamic fault-progression test over two consecutive days: stable fault state during the night, then stepwise thermal recovery as the cover is withdrawn.

The third scenario was unilateral air leakage. Because the leak is on one side of the joint, the temperature pattern across the sensor positions becomes asymmetric. This asymmetry is a useful and repeatable indicator of which side of the joint the leak is on. The effect is consistent across both load levels and is more pronounced at 650 kW, so the spatial resolution of the system is preserved under the heavier thermal load.

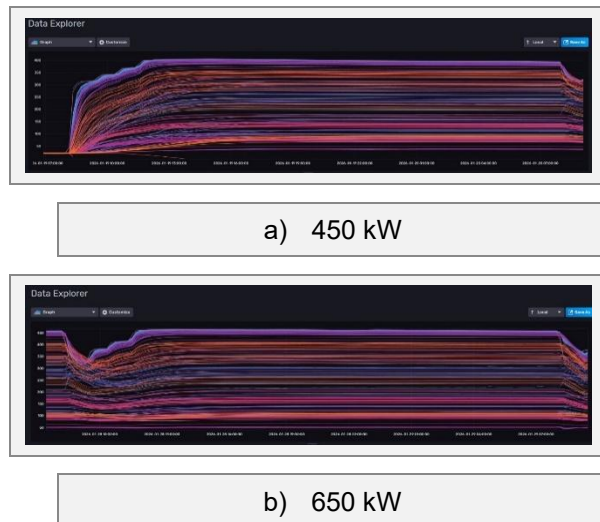


Fig. 10. Leakage-induced spatial temperature asymmetry at (a) 450 kW and (b) 650 kW.

During the whole field campaign there were no data dropouts, no time-stamp irregularities and no other artefacts that could be traced to the communication path, including during load changes and during the induced faults. The reliability seen in the lab therefore carried over to a real industrial environment with temperature gradients, mechanical vibration and electromagnetic noise.

Discussion

The lab results and the field campaign suggest that a properly sized LoRaWAN deployment can carry the data of an industrial condition-monitoring system without acting as a bottleneck. The main observation is that the dominant cause of lost packets in a large wireless deployment is essentially congestion in the shared MAC, and not random bit errors on the radio channel. Congestion can be mitigated by adding gateways and by keeping the number of nodes per gateway low [13].

Because the USB and LoRaWAN paths share the same firmware, the same encoding and the same backend schema, the difference between the two is essentially limited to whatever happens on the link itself. The data that the application layer sees is statistically the same in both cases. This matters for the machine-learning side of the project: the model should not have to learn to ignore artefacts introduced by the transport layer rather than by the physical process [10], [15].

The field tests show that three different fault categories, such as insulation loss, slow fault progression and unilateral leakage, leave a usable signature in the data, without any of these signatures being washed out by communication

issues. This supports the broader claim of the project, that the Smart Kit can act as the data-acquisition layer for AI-based predictive maintenance on expansion joints.

There are several limitations to keep in mind. The nodes used here are still based on development boards rather than dedicated PCBs. Vibration and strain sensing are not included yet. The test campaign, although it covers several months, does not cover a full seasonal cycle on a real plant. Furthermore, the predictive-maintenance algorithms themselves are developed by partner institutions and are not part of this work.

Future work

The next steps involve longer in-situ deployments, the integration of vibration and strain sensors, and adaptive LoRaWAN parameter management such as automatic adjustment of the spreading factor or the reporting interval based on link quality. The data pipeline described here may then be coupled more closely to the diagnostic models developed by the project partners. Furthermore, the validated Smart Kit may be used as a template for monitoring other safety-critical components in thermal power plants.

Conclusion

This paper presented the Smart Kit, a monitoring system for industrial expansion joints. It uses a wired USB channel as a reference and a wireless LoRaWAN channel for the actual deployment. Both channels share the same firmware and the same backend schema. The lab experiments and the turbine-test-rig campaign give four main results.

The two transmission paths produce data that agrees within sensor accuracy. No systematic bias, no drift, and no protocol-specific artefact was observed. A two-gateway configuration with fifteen nodes reaches a PDR of 99.4 % at SF7 with a 300 s reporting interval, which for the application considered here is essentially equivalent to a wired link. The system records three different fault categories, such as cover-insertion insulation loss, slow fault progression, and unilateral leakage asymmetry, clearly and without communication losses. Furthermore, the resulting sensor-to-cloud pipeline is in a state where it may serve as the data layer for an AI-based predictive-maintenance system.

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