TARGET-X TRIALS BROCHURE

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DOI: 10.5281/zenodo.17175347

Published by TARGET-X Project
https://target-x.eu/

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Abbrevations

- IPT - FRAUNHOFER INSTITUTE FOR PRODUCTION TECHNOLOGY IPT
- EDD - ERICSSON GMBH
- RWTH AACHEN UNIVERSITY
  - WZL - Laboratory for Machine Tools and Production Engineering (WZL)
  - IP - Chair of Individualized Production
  - ACS - Institute for Automation of Complex Power Systems
- IDIADA - IDIADA AUTOMOTIVE TECHNOLOGY SA
- CCR - CONSTRUCTION ROBOTICS GMBH
- I2CAT - FUNDACIO PRIVADA I2CAT, INTERNET I INNOVACIO DIGITAL A CATALUNYA
- MARP - MARPOSS SOCIETA PER AZIONI
- MEE - MITSUBISHI ELECTRIC EUROPE BV
- MMS- MARPOSS MONITORING SOLUTIONS GMBH

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TARGET-X

TARGET-X is a project the European Commission co-funded from the HORIZON EUROPE programme. It is coordinated by FRAUNHOFER Gesellschaft Zur Forderung Der Angewandten Forschung Ev with the participation of 14 Consortium Partners from 6 countries (see details at https://target-x.eu).

The total TARGET-X budget of cascade funding (Financial Support to Third Parties - FSTP) is €6 000 000 of which up to €3 840 000 will be distributed under the 2nd TARGET-X Open Call: Testing or implementation of technologies oriented to use cases.

VISION

TARGET-X 's Vision is to strengthen important economic sectors in Europe by integrating 5G and 6G, accelerating the digital transformation.

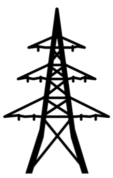
TARGET-X aims at that vision by providing testbeds for different verticals, developing new 5G/6G features, intuitive usage of 5G/6G and new business models. TARGET-X brings together information technology providers, operational technology providers and SMEs.

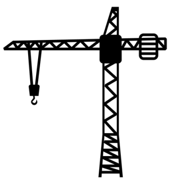
AMBITION

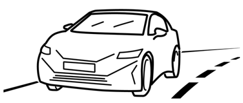
The main ambition of TARGET-X is to advance the state of the art of 5G technology with technical elements "beyond 5G", integrate those elements in testbeds operated in the project, and validate them in several use cases in four different verticals.

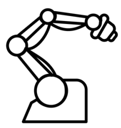
The fifth generation of wireless technology (5G) has arrived and is being rolled out globally. First industrial sectors such as manufacturing are testing the capabilities of 5G showing great potential for ubiquitous connectivity. With the sixth generation (6G), wireless communication will bring several industrial sectors new features, improved performance, and functional benefits.

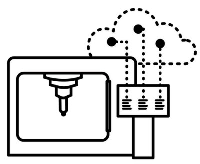
The TARGET-X project envisions accelerating the digital transformation of key verticals:


5G for energy monitoring


5G for construction


5G for automotive driving


5G for mobile robotics


5G for cloud native production

Using large-scale trials in multiple testbeds.

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TARGET-X

TESTBED DESCRIPTIONS

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MANUFACTURING

At the Fraunhofer Institute for Production Technology IPT a shopfloor of 2.700 m² is covered with a 5G indoor network as part of the 5G-Industry Campus Europe. Besides coverage at 3,7-3,8 GHz, an additional 3GPP Rel. 15 compliant indoor radio cell at mmWave spectrum is installed at 26,7-27,5 GHz. Additionally, a separate prototype system with URLLC functions is operated at the Fraunhofer IPT with an early implementation of TSN-over-5G, which will be extended within TARGET-X. The IPT trial site provides an ideal playground for testing 5G and 6G technology in a realistic environment. IPT possesses a comprehensive set of machine tools for manufacturing, including multiple milling machines, combined milling and turning centers, production metrology like coordinate measuring machines and optical sensors, injection molding, and embossing machines and laser material processing machines. In addition to the production and mobile communication equipment, the Fraunhofer IPT also has an on-premise Kubernetes Cluster from German Edge Cloud, a VMware vCenter Server, and a TSN testbed, which will be used for real-time communication and computation for cloud-in-the-loop applications. Furthermore, IPT owns extensive measurement and diagnostic equipment to perform performance and diagnostic measurements in the 5G and the production network.

Figure 1: Manufacturing Testbed

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ROBOTICS

Flexible Assembly Automation at the Laboratory for Machine Tools and Production Engineering (WZL) – RWTH Aachen University

The Sensing & Robotics department within the Chair of Intelligence in Quality Sensing at WZL provides a state-of-the-art trial site for testing and validating robotic systems in the context of flexible assembly automation. The facility features a fleet of mobile and semi-stationary robots built on a modular Robot Operating System 2 (ROS 2) architecture, operating within a $25 \times 5\,\mathrm{m}^2$ testbed equipped with high-precision large-scale metrology systems (laser trackers, motion capture) for benchmarking localization, calibration, and motion accuracy. The environment replicates realistic industrial setups, offering high configurability and scalability across more than 16 robotic testbed cells for a wide range of applications.

As part of the 5G-Industry Campus Europe, the site enables edge-controlled robotics through low-latency 5G and beyond connectivity. Computationally intensive tasks, such as Simultaneous Localization and Mapping (SLAM), AI-driven perception, and path and motion planning, are offloaded to edge servers, enabling real-time control with minimal onboard processing. In addition to traditional positioning technologies, WZL also hosts a 5G-based indoor localization system that leverages the existing radio infrastructure. High-bandwidth data from 3D LiDAR and camera streams is transmitted seamlessly from mobile robots to edge servers for further computation, supporting complex robotic operations in dynamic assembly scenarios. Simulation environments and digital twins complement physical experiments, enabling hybrid testing with real industrial components.

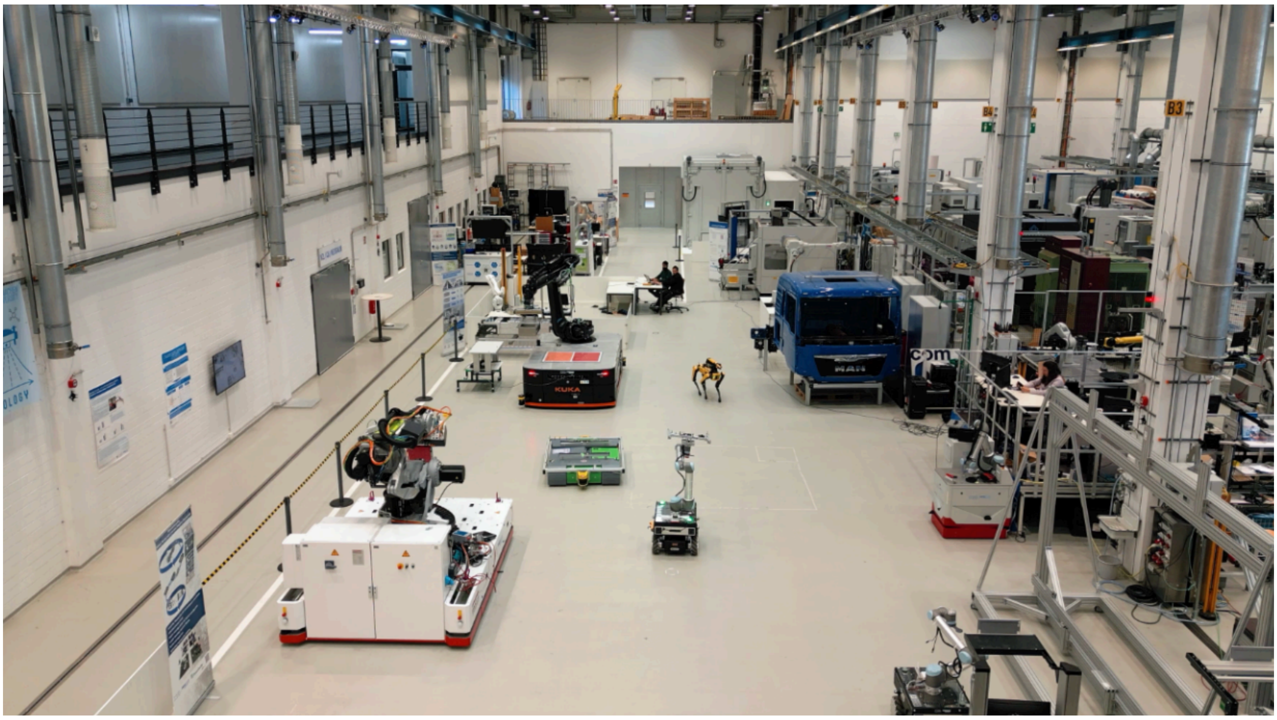

Figure 2: Robotics Testbed

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AUTOMOTIVE

5G for autonomous driving: Idiada Automotive 5G-Trial Site.

Applus IDIADA is a global partner to the automotive industry with over 30 years' experience in providing design, engineering, testing and homologation services. The company has more than 2,900 professionals and an international network of subsidiaries and branch offices in 22 countries, with headquarters located in Santa Oliva, Tarragona, Spain.

IDIADA HQ has 14 tracks with a technical center, 370 hectares covered by a confidential and secure environment, where a controlled and exclusive network with 2G, 3G, 4G and 5G NSA technologies is available. IDIADA, together with its partners, aims to boost the development and use of 5G networks in the automotive field through the following 3 use cases:

The feasibility of realizing the use cases using the best technologies will be evaluated and demonstrated throughout the project.

- Cooperative perception for Connected Automated Vehicles (CAVs)
- Digital Road Twin
- Predictive Quality of Service

Figure 3: Automotive Testbed

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ENERGY

The Automation of Complex Power Systems (ACS) Institute at E.ON Energy Research Center (ERC) belongs to RWTH Aachen University. The main target of research at E.ON ERC is energy efficiency, energy savings and sustainable energy supplies. The project TARGET-X Energy vertical is handled by the RWTH-ACS Institute, which involves deploying measurement devices for low voltage and current.

To achieve the goal of Energy Monitoring and Consumption Awareness use case, a plug-and-play, weather-proof and outdoor-capable measurement box called Meter-X is designed and used in the Energy Vertical. Further edgePMU devices are developed and deployed for the grid measurement trial sites at different locations within the Melaten Campus. The goal is to derive a better understanding of the local grid voltage and the impact of the local 5G network on the measurement quality.

For the energy awareness use case, Meter-X measurement devices are deployed at the Reference Construction Site of the Center Construction Robotics (CCR) and Laboratory for Machine Tools and Production Engineering (WZL) on Campus Melaten in Aachen, Germany. For the monitoring use case, Meter-X and 5G edgePMU devices are deployed at the energy testbed at the RWTH-ACS building, Aachen, Germany.

The energy monitoring setups are used to sample data at these different sites and are connected to the existing 5G-Industry Campus Europe infrastructure. This allowed for an evaluation across various verticals, increasing energy awareness and grid monitoring capabilities in the fields of construction, manufacturing, and energy.

Figure 4: Energy

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CONSTRUCTION

Reference Construction Site

Operated by the Center Construction Robotics on RWTH Aachen University's Campus Melaten, the Reference Construction Site is Europe's first 5G-enabled, large-scale construction testbed. Since its establishment in 2020, it has served as a dynamic living laboratory, driving innovation at the intersection of digitalization, robotics, and the circular economy in the construction sector.

The site provides a unique, real-world environment for testing, implementing, and evaluating cutting-edge processes, concepts, and products. Research here focuses on automating construction machinery, integrating robotics into construction workflows, and developing robust digital twins of construction processes. It also pioneers new approaches to working, teaching, and communication, fostering interdisciplinary collaboration across national and European projects.

Connected to the 5G-Industry Campus Europe, the Reference Construction Site leverages advanced 5G technology to enable real-time communication and seamless data fusion from distributed sensors. This infrastructure empowers researchers and industry partners to explore innovative applications such as autonomous machinery operation, modular construction and deconstruction, on-site 3D printing, and human-robot collaboration in dynamic, unstructured environments and human-cyberphysical systems. By harnessing 5G, the testbed accelerates the automation of construction processes while ensuring the development of advanced safety concepts to protect workers in increasingly automated environments.

With its 4,000 m^2 experimental area, the Reference Construction Site offers a scalable platform for transforming construction practices—making them more efficient, connected, and sustainable for the future.

Figure 5: Construction Testbed

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TARGET-X

USE-CASE DESCRIPTIONS

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USE-CASE	5G-enabled Wireless Sensor Platform for Industrial Manufacturing
NAME OF RESPONSIBLE CONSORTIUM PARTNER	IPT
OTHER CONSORTIUM PARTNERS INVOLVED	MMS, MEE

OVERVIEW

In many manufacturing industries, it is necessary to monitor the condition of the workpiece and track it. This monitoring enables the industry to implement quality control and checks, enhance efficiency, and improve productivity through advanced techniques such as predictive maintenance, advanced control loops to prevent defects, and digital twins. Typically, to monitor the condition of the workpiece, the parameters that affect the workpiece are monitored using wired sensors connected to the workpiece.

Within TARGET-X, a wireless sensor platform for industrial manufacturing using 5G/6G technologies, such as Reduced Capability (RedCap), has been developed. The wireless sensor platform complies with industrial requirements such as low latency and high reliability, making it more suitable for wireless communication for real-time applications. With the localization features, the 5G/6G not only handles data transfer but also provides information such as the device and machine positions, along with accurate timestamps, for the fusion of sensor and network data. In combination with the Asset Administration Shell (AAS), this data can be stored and accessed efficiently for flexible monitoring and control of production. Two use cases have been evaluated within TARGET-X: Environmental Condition Monitoring and Track and Tracing of Workpieces.

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ARCHITECTURE

For each use case, specific software modules are developed and integrated. To capture various parameters (temperature, pressure, acceleration, orientation, power, etc.), the wireless sensor platforms employ internal and optional external sensors. Collected data is transmitted via 5G to the cloud. The condition-monitoring module extracts features from sensor streams, the track-and-trace module computes positions, the data visualization provides interactive dashboards, and the digital-twin module creates virtual replicas of machines. The AAS in the cloud holds all data models required for interoperability and interpretation. Figure 6 shows the architecture and integration concept.

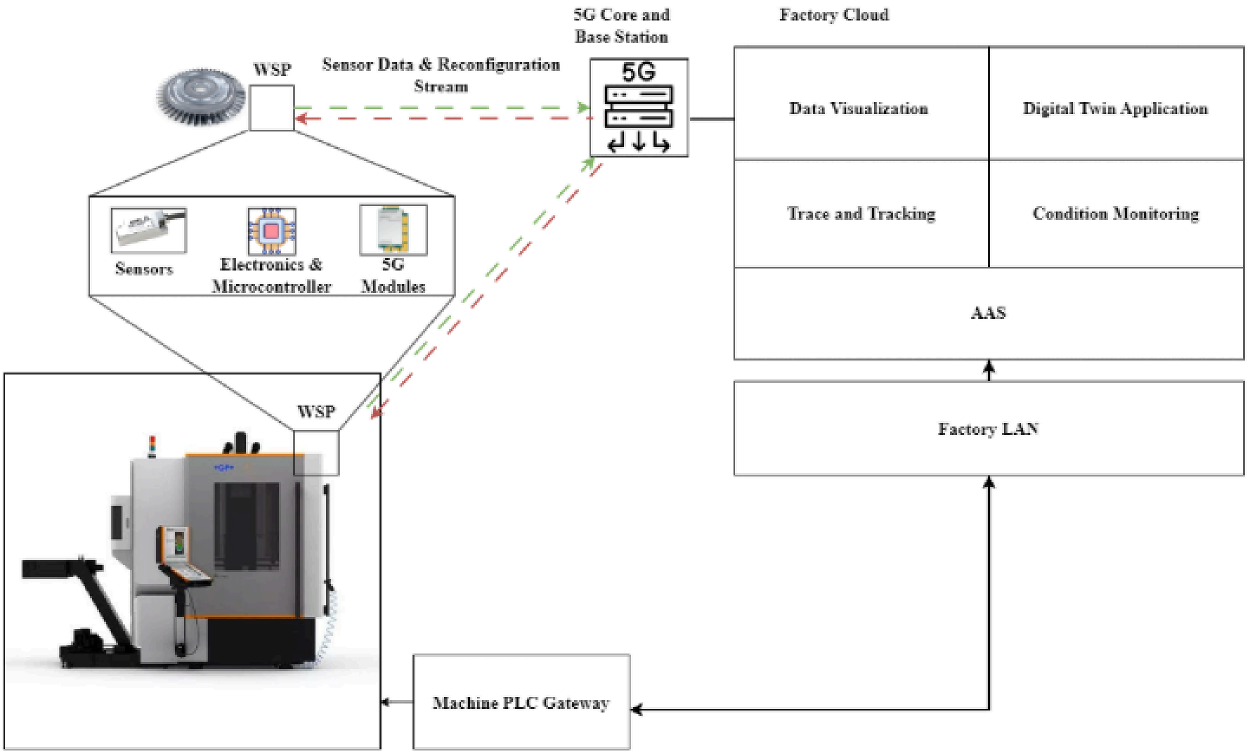

Figure 6: Architecture of the wireless sensor platform.

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TRIAL

Within TARGET-X, the wireless sensor platform has been validated for two use cases:

Environmental Condition Monitoring: During machine operation, the process data is monitored, and the logs are collected from different measurement devices. These are then compared to measure the accuracy of the developed system, with the state of the art, and then identify the latency on certain current peaks observed and their impact. In addition, the developed sensor platform provides the flexibility of improved data quality by dynamically increasing the sampling frequency, and the increased data rate is handled by the 5G network.

Track and Tracing of Workpieces: Incorrect milling parameters or worn tools can cause chatter, resulting in poor surface quality of the workpiece. To test the wireless sensor platform, milling tests were carried out with a Chiron FZ08S machining center. In a first test, a constant feed rate was used, but the spindle speed varied. In a second test, a constant spindle speed was used, but the feed rate varied. A thin ball cutter was used for the milling tool, which is prone to chatter.

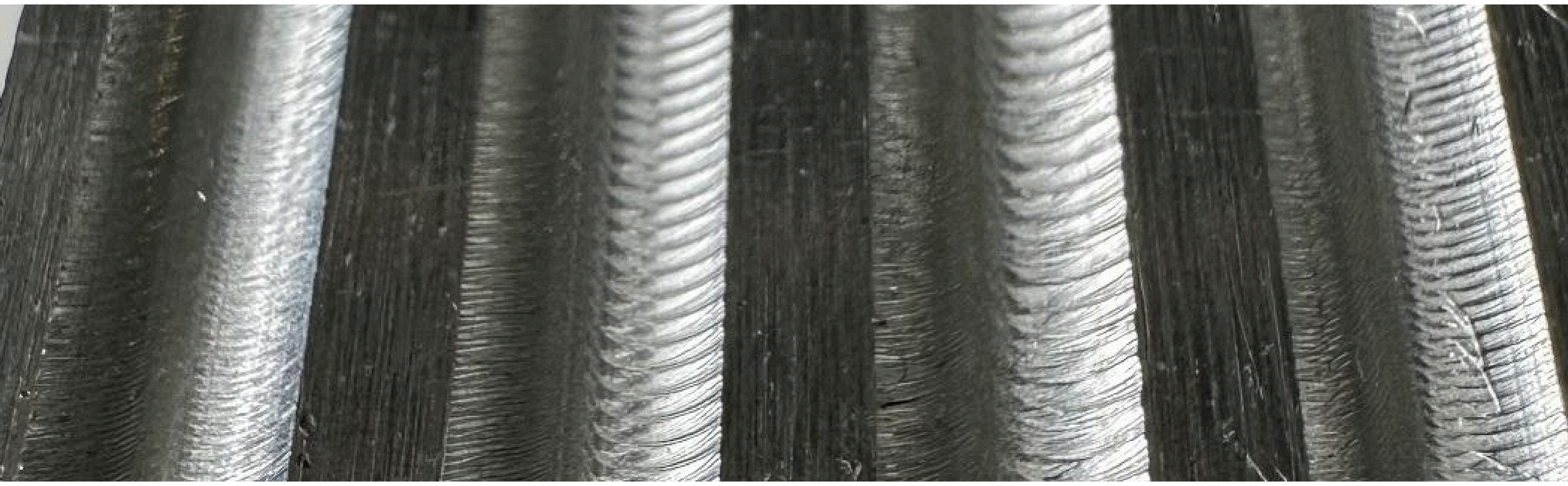

Figure 7: Surface of the workpiece with and without chatter.

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RESULTS

Within the TARGET-X trials, the high relevance of wireless sensor systems, the fast integration, and the high resolution of sensor data coming from 5G-enabled sensors could be validated and demonstrated. The wireless sensor platform proved to be a cost-effective solution for measuring high-frequency vibrations instead of industrial ADCs in combination with powerful processing hardware.

Further, the findings underscore the potential of RedCap to enhance the development of energy-efficient wireless sensors, particularly within the context of 5G/6G technologies in manufacturing. The balance between power consumption and performance metrics, such as latency and throughput, will be crucial for future innovations in this rapidly evolving field.

Figure 8: Interactive dashboard for the visualization of the energy consumption.

5G EMPOWERMENT

For industrial 5G sensor systems, energy efficiency and compactness are highly important. By comparing RedCap and emBB modules, TARGET-X demonstrated that RedCap's streamlined design dramatically lowers power draw without compromising responsiveness, allowing battery-powered sensors to run longer in smaller housings. This extended autonomy and reduced need for charging cuts maintenance effort, downtime, and operational costs. Latency remains on par under typical loads, ensuring timely data delivery for monitoring and control. Although applications demanding peak throughput may still rely on full-feature modules, RedCap strikes an optimal balance between energy conservation and performance. This makes it an ideal choice for sustainable, cost-effective IIoT deployments, supporting mobile, flexible sensing across the factory floor.

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6G SNS

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USE-CASE	Real-time communication using 5G and TSN
NAME OF RESPONSIBLE CONSORTIUM PARTNER	IPT
OTHER CONSORTIUM PARTNERS INVOLVED	EDD, MEE

OVERVIEW

Machine tool processes such as milling and turning are very complex to handle, especially for high-quality workpieces. Small changes in the parameters or wear of the work tool can cause a significant decrease in workpiece quality and can cause rejects. Therefore, the workpiece needs to be verified frequently at a metrology laboratory for quality assurance of the product. This is costly in terms of measuring machines, the time of the measuring expert, and the time that the process needs to stop for quality assurance. An alternative is an inline quality control and assurance system inside the machine. The data of the workpiece, work tool, and the machine itself can be monitored and used to determine if the process is running as planned.

Deterministic communication services such as Time-Sensitive Networking (TSN) are slowly establishing themselves in the industrial domain for wired communication. They offer more flexibility and interoperability due to compliance with the OSI Reference Model, and with 5G/6G. Using 5G/6G as a wireless bridge in such a real-time capable network enables placing sensors inside the machine directly on the workpiece, monitoring the process behaviour, without interfering with the degrees of freedom needed for the process. The goal of the condition monitoring using 5G/6G PLC to remote communication use case is to validate if 5G can be used for wireless real-time sensing during machining processes.

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ARCHITECTURE

The validation focus is placed on real-time capabilities essential for modern industrial applications that use deterministic fieldbus protocols such as CC-Link IE TSN. In Figure 9, the overall architecture of the implementation is shown. The architecture can be separated into three different subsystems:

- The OT hardware for sensor data acquisition and control tasks.
- The real-time wired communication network consisting of TSN switches and Layer 2 to Layer 3 tunnels.
- The wireless communication network consisting of the 5G system, 5G-UEs, and a local breakout.

Key features that have been validated within TARGET-X are layer 2 support, time synchronization over the air, traffic shaping, and FRER for high reliability.

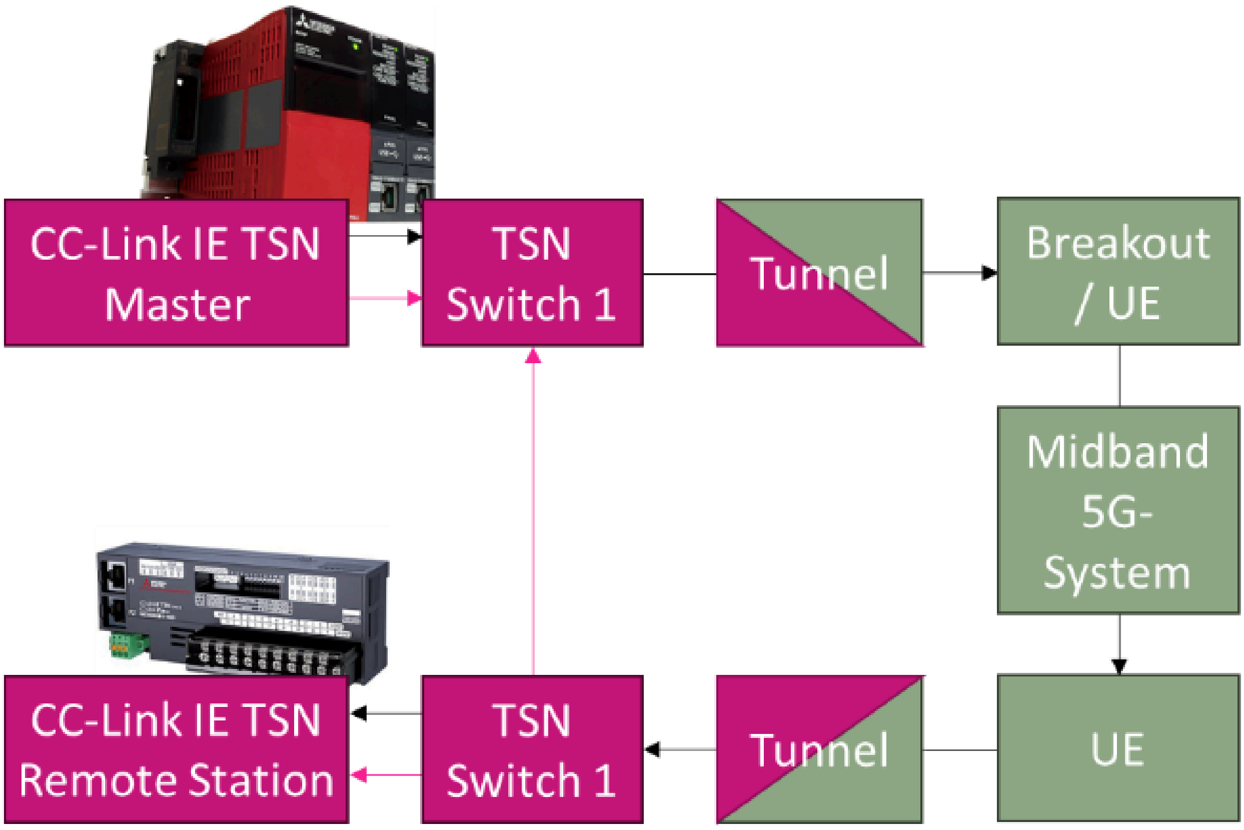

Figure 9: Overall architecture of the quality assurance system for machining.

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TRIAL

Within the TARGET-X trials, the goal was to leverage and validate CC-Link IE TSN Class B communication over a 5G network. The trials focused on two aspects:

Time-sensitive communication: For the trial, TARGET-X aimed at validating 5G and TSN using off-the-shelf OT hardware for data acquisition and control. For the network, a TSN network with L2–L3 tunnels with an integrated 5G network has been set up. As communication protocol, CC-Link IE TSN has been used. Key TSN features include 802.1Qbv traffic shaping and 802.1CB FRER.

High reliability communication: At the Fraunhofer IPT shop floor within the 5G-Industry Campus Europe, five FRER configurations across four distinct 5G systems (midband, mmWave, URLLC) were evaluated under realistic industrial conditions characterized by dense machinery and metal enclosures. The trials tested redundant transmissions using single and multiple UEs to assess FRER's reliability advantages in harsh factory settings.

RESULTS

Within the TARGET-X trials, the goal was to leverage and validate CC-Link IE TSN Class B communication over a 5G network. The trials focused on two aspects:

Time-sensitive communication: To achieve deterministic communication, IEEE 802.1 Qbv and IEEE 802.1 AS were used for traffic shaping and scheduling. During the trials, it could be shown that the varying latency of the 5G communication could be bounded, except for higher latency spikes. Due to the high requirements of industrial fieldbus protocols, those spikes caused CC-Link IE TSN to terminate the session and start reconnecting to the remote device. This behaviour underlines the high need for deterministic and highly reliable communication.

High reliability communication: To achieve high reliability, TARGET-X implemented IEEE 802.1CB, also referred to as "Frame Replication and Elimination for Reliability" (FRER). The validation showed the capability to meet the stringent requirements of industrial fieldbus communication, achieving less than 10 ms latency for 99.99% of packets. However, the validation also showed the introduced challenges when using FRER, including increased hardware costs due to the need for additional infrastructure, heightened network complexity, and greater bandwidth usage.

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5G EMPOWERMENT

While 5G communication without TSN provides fast communication, spikes with high latency up to 40 ms and more are not uncommon. Such spikes can create issues for industrial fieldbus communication, which relies on a stable communication pipeline. As shown in the trials, the PLC responds to such spikes by terminating the existing communication session, thereby ensuring the integrity and reliability of the data transmission. After disconnecting, the PLC tries to reconnect, hoping for a more stable connection. This process takes time, during which the process either stops or runs without the control signals of the PLC.

The combination of 5G with different TSN features, such as IEEE 802.1 Qbv - Enhancements for Scheduled Traffic and IEEE 802.1CB – Frame Replication and Elimination for Reliability, enables the implementation of a wireless communication pipeline with bounded latency and very low jitter. During TARGET-X, a reliable communication with a latency below 10ms for 99.99% of the messages without spikes has been achieved. Such a performance allows a smooth operation of the PLC without reconnection or downtimes.

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USE-CASE	Edge-Controlled Automation with Mobile Manipulation
NAME OF RESPONSIBLE CONSORTIUM PARTNER	RWTH-WZL
OTHER CONSORTIUM PARTNERS INVOLVED	EDD

OVERVIEW

The Edge-Controlled Automation with Mobile Manipulation use case at RWTH Aachen University's WZL testbed demonstrates how 5G supports mobile robotics for flexible (dis)assembly in modern manufacturing.

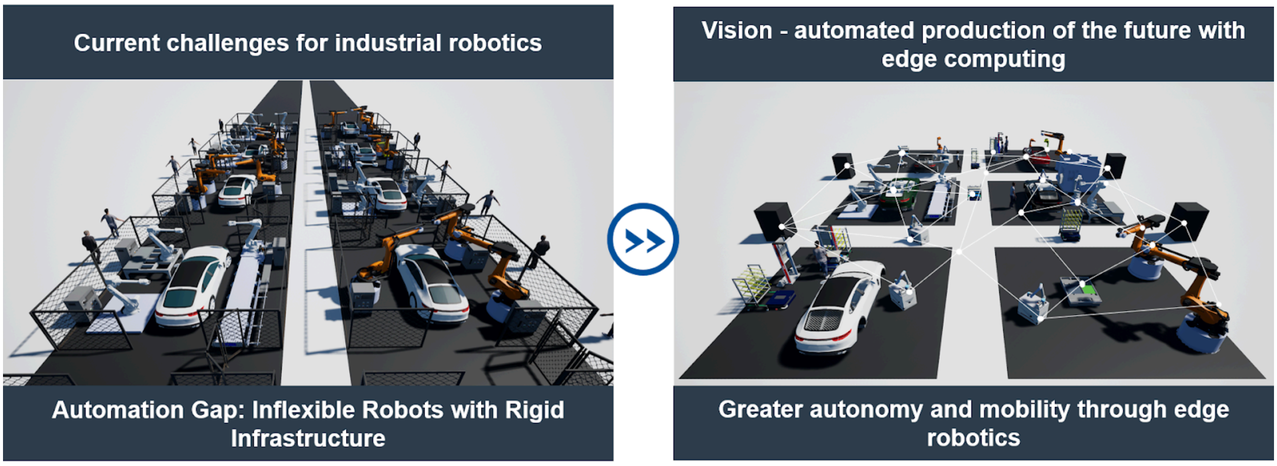

Figure 10: Illustration of the transition towards flexible assembly systems with edge computing capabilities.

The scenario addresses the removal of EV battery modules, with a mobile manipulator performing Simultaneous Localization and Mapping (SLAM), navigation (path planning optimization), object detection, motion planning of the manipulator, grasping, and placement tasks coordinated by an edge server. A Robot Operating System (ROS) 2-based state machine manages the process, while 5G ensures reliable, low-latency communication between robot and edge. The concept illustrates how fleets of robots could operate across multiple stations in parallel, with 5G providing the uplink capacity, reliability, and configurability needed for dense and dynamic factory settings. Trials with RWTH-WZL and Ericsson focused on selected navigation steps of this workflow to analyse communication demands, highlighting the scalability potential of 5G-enabled automation.

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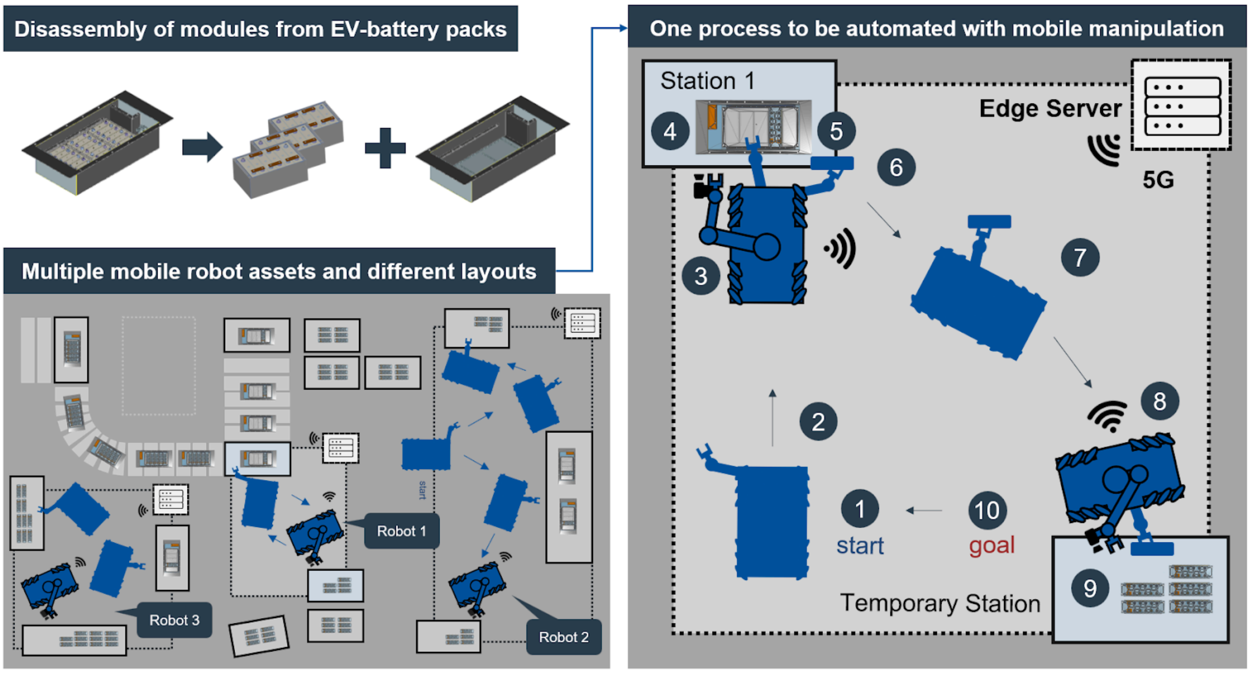

Figure 11: Edge-controlled automation with mobile manipulation for the disassembly of battery modules from EV-battery packs. Multiple robots for multiple assembly process (bottom left), process steps to be automated (right).

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ARCHITECTURE

The system integrates an RB-Kairos+ mobile platform with a UR10 robotic arm, equipped with 2D & 3D LiDARs, a depth camera, and IMU sensors, connected to a high-performance edge server via private 5G at the 5G-Industry Campus Europe. The edge executes localization, navigation, perception, motion planning, and digital twin simulation (Isaac-Sim), while ROS 2 with DDS/Zenoh provides middleware support. Software is deployed via Docker and CI/CD pipelines for modularity and fast updates. In realistic shop-floor conditions with dense equipment and wireless coexistence, uplink requirements reached ~142 Mbit/s at <20 ms latency. To mitigate this, LiDAR data was reduced, filtered, and compressed, lowering the uplink from ~127 Mbit/s to ~37 Mbit/s with minimal loss of accuracy. A non-intrusive monitoring pipeline (ROS 2 diagnostics, iPerf3, Wireshark/tshark) provided multi-layer visibility into system performance. This setup illustrates both the communication demands of edge-controlled robotics and the role of 5G in meeting them.

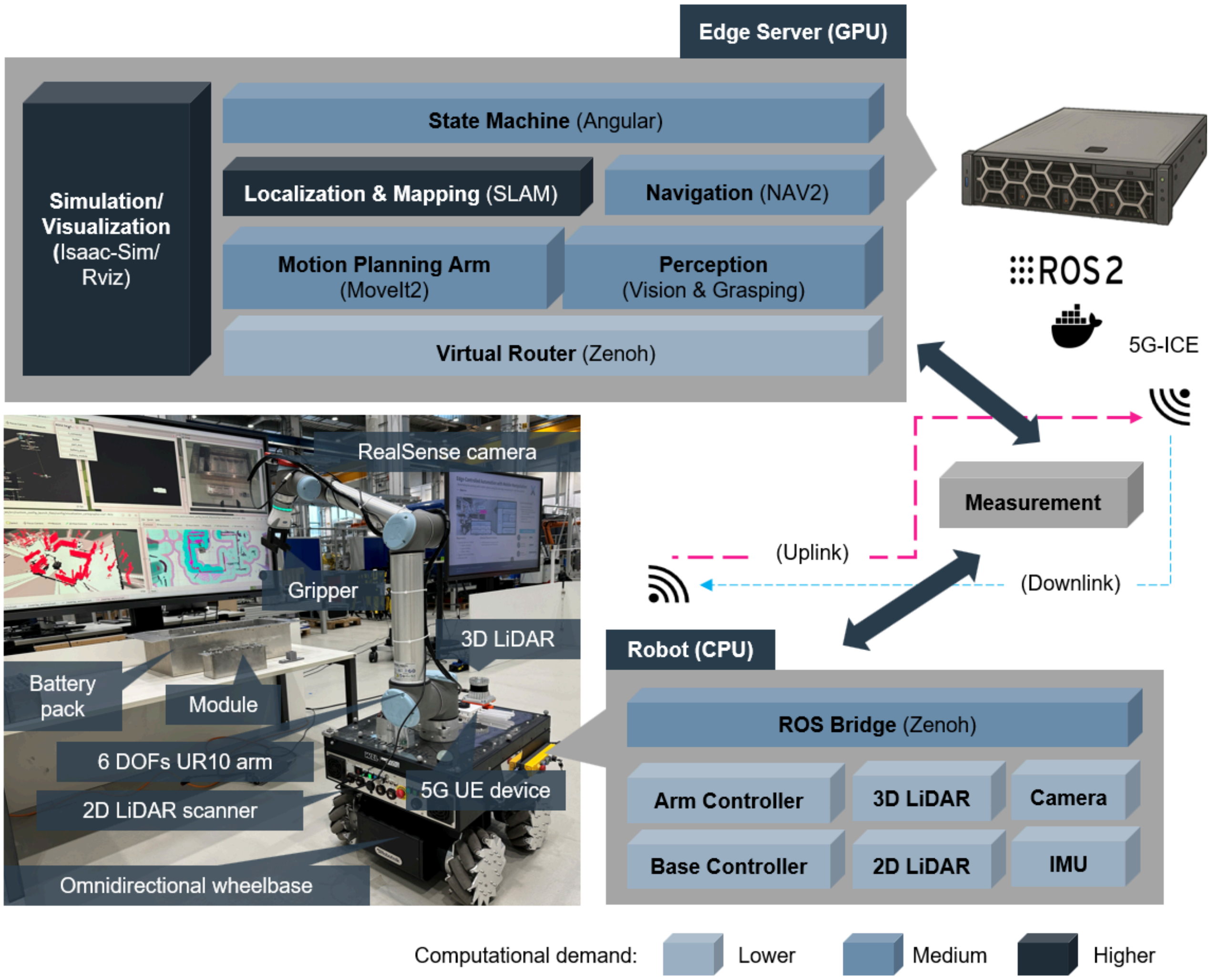

Figure 12: Hardware and ROS 2-based software architecture of the edge-controlled mobile automation use case. Hardware components of the robot are shown in the bottom left; edge and onboard software components are color-coded by computational demand. Monitoring pipeline is also illustrated.

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TRIAL

The use case was deployed at the WZL testbed using the private 5G NSA network of the 5G-ICE. A mobile manipulator executed a workflow for disassembling EV battery modules, including localization with SLAM, navigation, scanning, grasping, and placement, coordinated by an edge server. The environment reproduced dense factory conditions with reflective surfaces and coexisting wireless infrastructures, enabling controlled evaluation of communication and robotic performance.

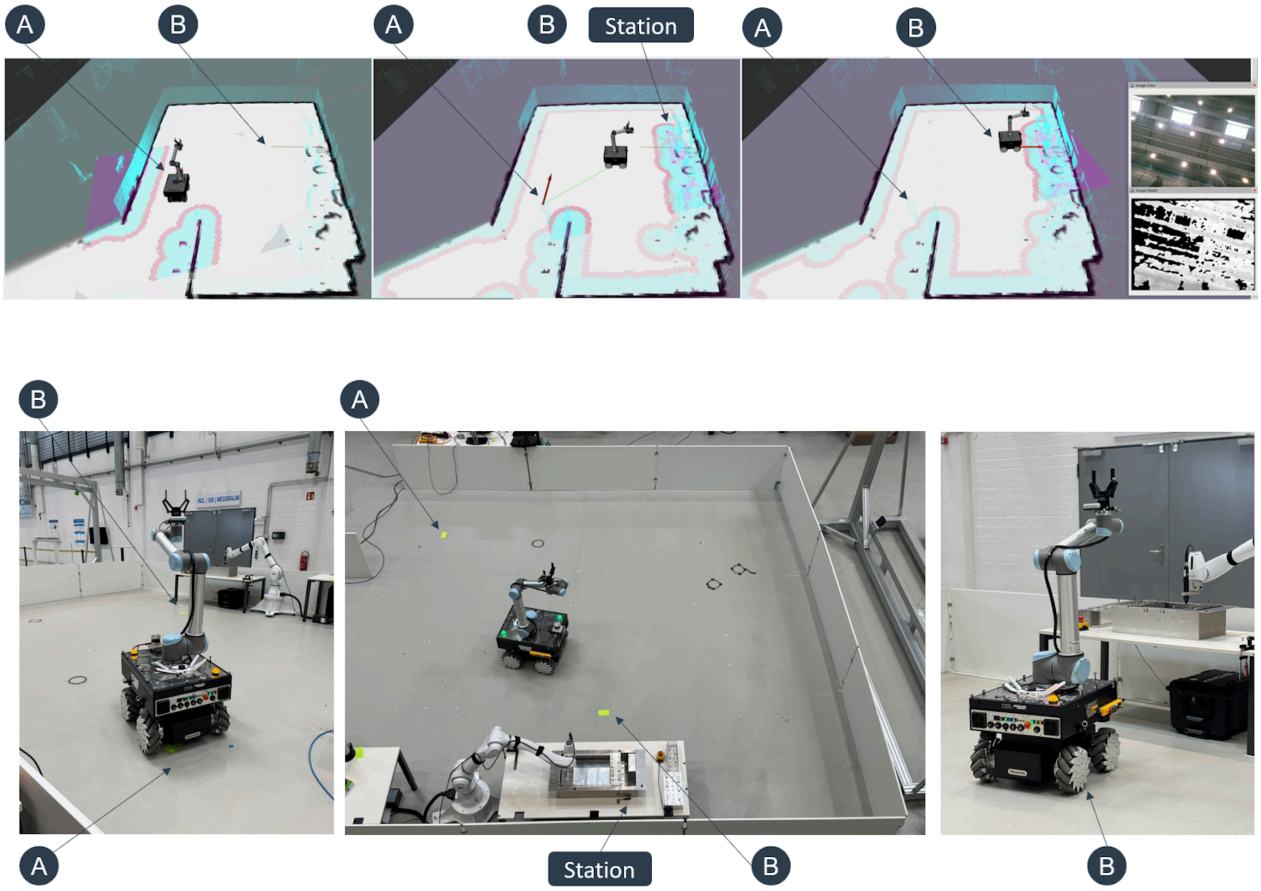

Figure 13: Edge-executed software stack for cloud-based localization and navigation (top). Operator-defined positions A and B are configured via the GUI interface. Photographs of the A–B–A navigation trials conducted at the WZL Testbed (bottom).

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RESULTS

Validation of A–B–A navigation cycles showed stable real-time operation under 5G. Uplink averaged ~37 Mbps with bursts during re-planning, while downlink averaged ~1.7 Mbps with minimal variance, ensuring reliable control. A ROS 2 topic monitor confirmed low latency and stable bandwidth, showing that 5G supported safe, collision-free navigation. Results highlight uplink optimization strategies and confirm 5G's suitability for latency-sensitive robotic control.

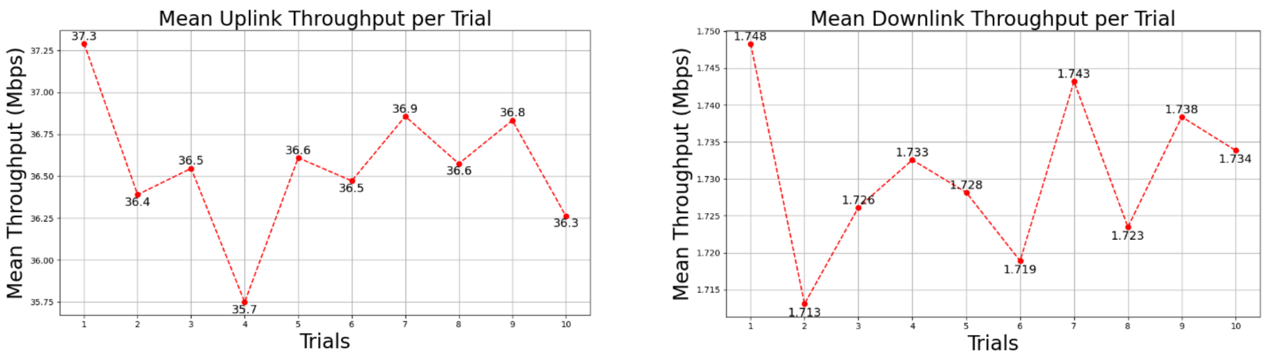

Figure 14: Mean application-level throughput across 10 trials. Uplink traffic is shown on the left, downlink traffic on the right

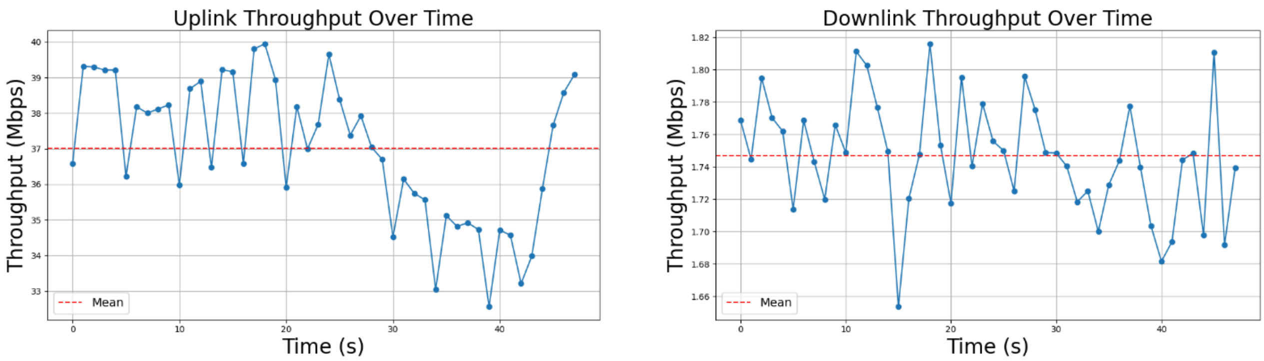

Figure 15: Uplink (left) and Downlink (right) throughput over time during Trial 9 of the A–B–A navigation task.

5G EMPOWERMENT

5G enables real-time robotic edge control with low latency, reliable uplink, and secure on-premises data handling. Its flexibility and scalability allow many robots to operate simultaneously, each with significant uplink needs. Network capacity can be adapted to demand (e.g., through TDD configuration), ensuring reliable performance even in dense factory environments. This positions 5G as a key enabler of large-scale, safe, and flexible automation.

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USE-CASE	Cooperative perception
NAME OF RESPONSIBLE CONSORTIUM PARTNER	IDIADA
OTHER CONSORTIUM PARTNERS INVOLVED	i2CAT

OVERVIEW

This use case has two scenarios: (1) a zero-visibility intersection between vehicles, and (2) a stationary vehicle blocking a moving one. In both, infrastructure provides road layout and static details, while vehicles share Cooperative Awareness Messages (CAM) and Collective Perception Messages (CPM) to build a full view of the environment. All vehicles send CAM/CPM to the infrastructure, which forwards them to others. CAMs describe a vehicle's state, while CPMs use perception systems (lidar, radar, cameras). In Scenario 1, CPMs cannot detect the hidden car, but in Scenario 2, the stationary vehicle can be identified through CAM or CPM, enhancing safety through better awareness and anticipation.

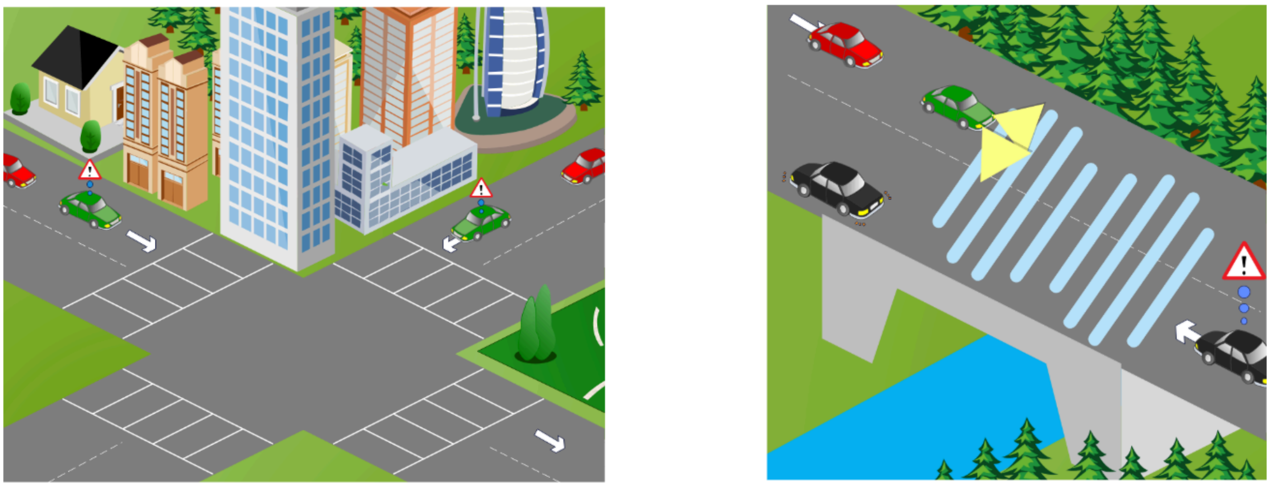

Figure 16: Use-case scenario.

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ARCHITECTURE

The high-level architecture, represented in the Figure below, shows a general overview of the architecture, where CAMs and CPMs messages from the CAVRide, and only CAMs from the connected vehicle, are sent to the C-ITS platform. Each car has a 5G router that allows connectivity to the C-ITS platform, a GNSS/GPS system with RTK corrections that gives a high-precision location, and a computer to run the vehicle C-ITS client.

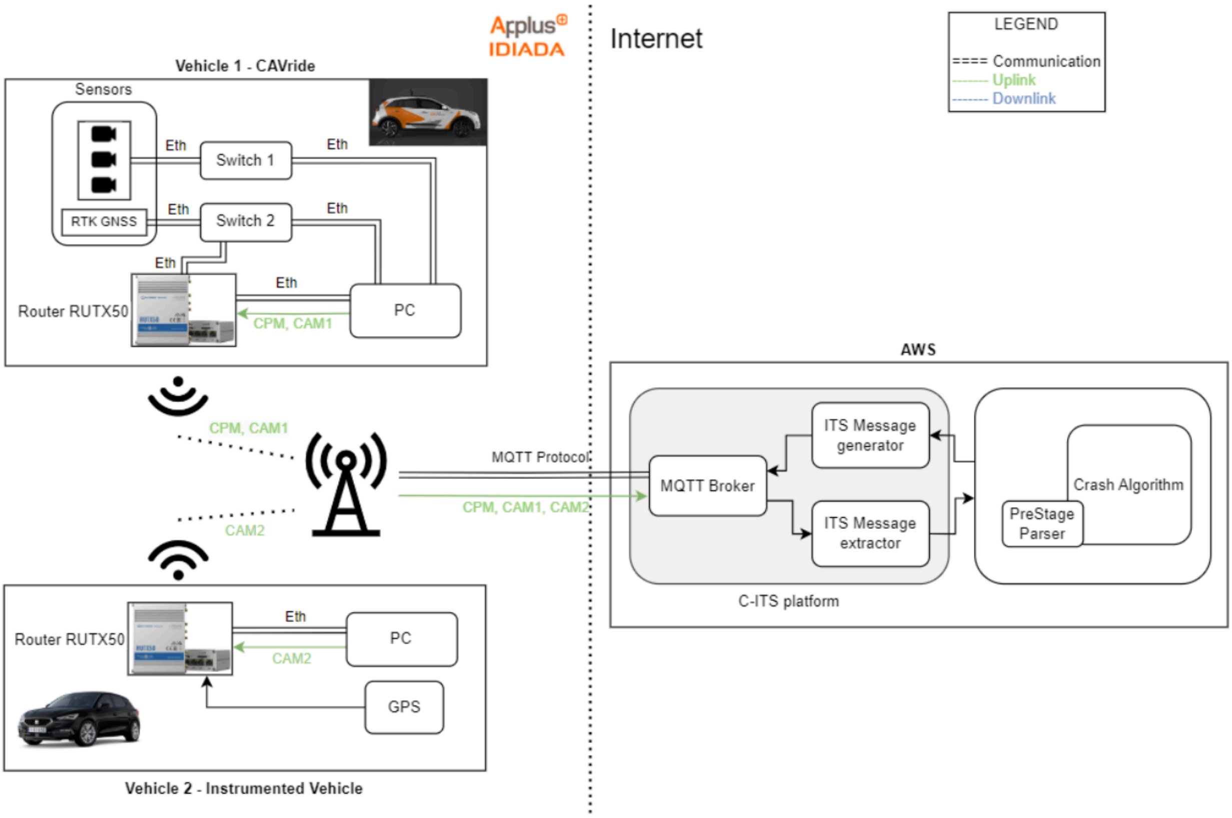

Figure 17.

TRIAL

In the TARGET-X trials, the objective was to assess message reliability and one-way latency of CAM, DENM, and CPM messages. The assessment was done using either 4G or 5G, and by hosting the ITS either in an edge computing system directly connected to the UPF or in the cloud. For each case, 15 runs were performed, and the KPIs were collected. In scenario 1, the speed was 30 kmph, and in scenario 2, it was 50 kmph.

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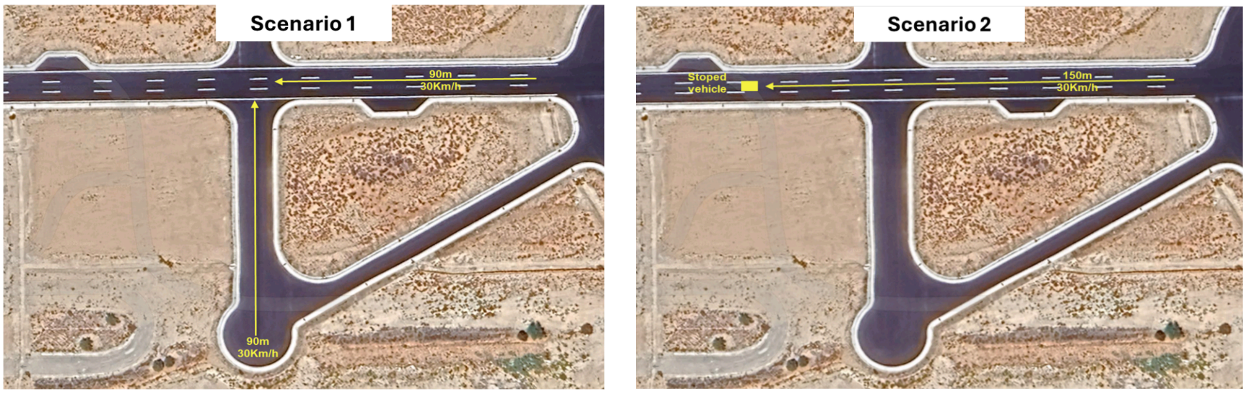

Figure 18: Automotive Scenarios

RESULTS

Within the TARGET-X trials, the goal was to validate the one-way latency and the reliability of the CPM, DENM, and CAM messages. The results showed that using 5G enhances the performance of the system, especially in terms of latency, which can be decreased by up to 25%. Also, using an edge system instead of the cloud can decrease the latency by 65% depending on the location of the cloud.

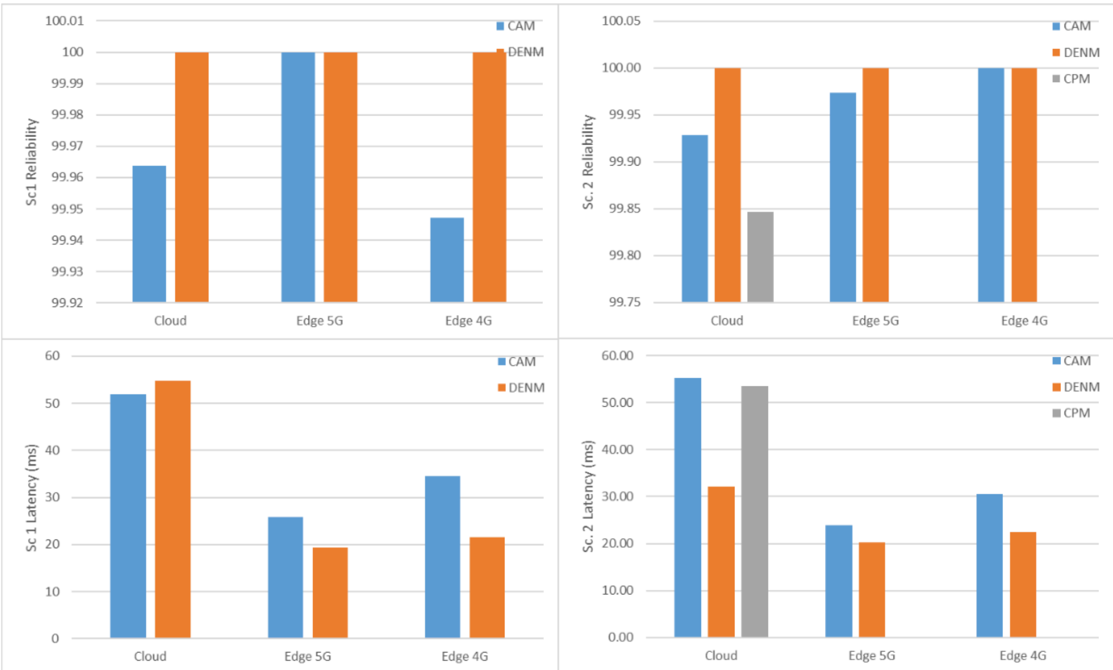

Figure 19.

5G EMPOWERMENT

The use of 5G/6G can reduce the latency of the message by up to 25%, which is important in this use case as it gives the driver a larger window of time to take decision.

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USE-CASE	Automotive Digital Twin
NAME OF RESPONSIBLE CONSORTIUM PARTNER	IDIADA
OTHER CONSORTIUM PARTNERS INVOLVED	i2CAT

OVERVIEW

The Digital Twin bridges the physical and digital worlds by integrating real-world data into simulations and vice versa. The TARGET-X Digital Twin focuses on capturing V2X data exchanged between Intelligent Transport Systems (ITS) stations within a road segment or scenario. This data can then support simulations with advanced elements (e.g., autonomous vehicles) or real-world testing through Vehicle-in-the-Loop (ViL) validation.

The use case aims to replicate Scenario 1 from the cooperative perception case, where two vehicles are approaching an intersection with zero visibility and should be aware of this situation through the exchange of information via the ITS. In the Digital Twin, a virtual object (e.g., a vehicle) is introduced into the system and displayed in the Human-Machine Interface (HMI), prompting the system to react exactly as it would if a real vehicle were present.

ARCHITECTURE

The figure below shows the architecture for replay functionality, built on a database, Recorder, and Replayer. The Recorder processes incoming C-ITS messages (e.g., CAM, DENM, CPM) from the ITS Platform, storing metadata such as type, timestamps, topic, and retention. The Replayer retrieves saved messages, updates time-based fields, and redistributes them via 5G to vehicles. This allows simulations and Vehicle-in-the-Loop (ViL) tests, making vehicles perceive virtual events from stored scenarios as real. The Recorder connects to the external MQTT broker, receiving all ITS messages from Geomessaging.

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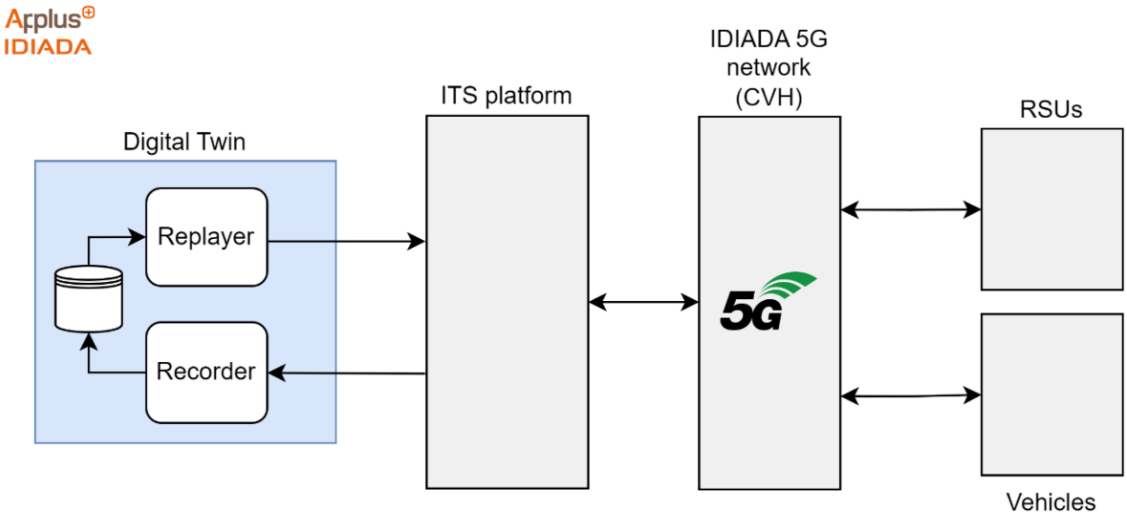

Figure 20: Architecture for replay functionality.

TRIAL

In the TARGET-X trials, the objective was to assess replay reliability in the digital twin to support validation of cooperative perception strategies. By recording one of the two vehicles in UC1 at the intersection, the system can replay the scenario and place the "vehicle in the loop," allowing repetition with modified parameters such as speed. This enables testing at higher speeds while eliminating risk.

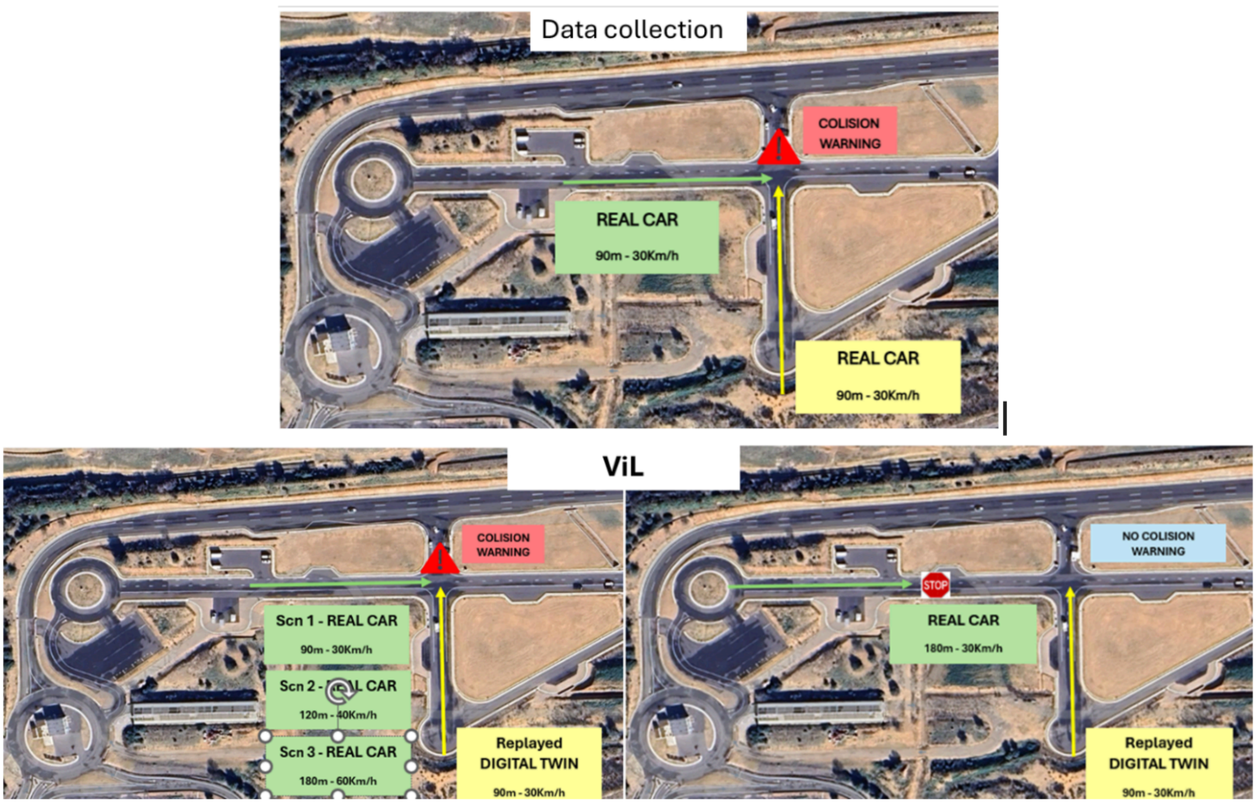

Figure 21: Data collection and ViL.

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RESULTS

Within the TARGET-X trials, the goal was to validate the replay reliability over 17 replays. In each replay, over 38000 messages were exchanged as a replica of the original use case. The difference in the one-way latency was measured for each message, and the average of these deviations was computed. An average of 2 ms was observed with a standard deviation of 1.5 ms.

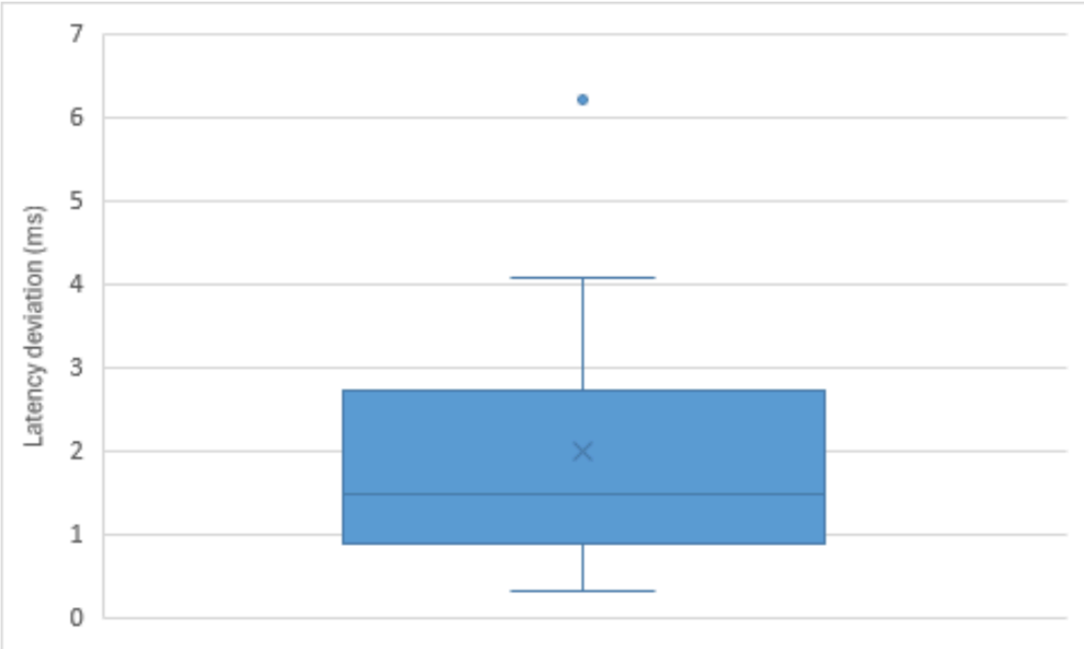

Figure 22.

5G EMPOWERMENT

The use case allows the assessment of the performance of different cooperative perception policies and architecture under different mobile technologies (45/5G/6G) and driving environment (different vehicle speeds) without risking the safety of the drivers.

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USE-CASE	Predictive QoS for Tele-Operated Driving
NAME OF RESPONSIBLE CONSORTIUM PARTNER	IDIADA
OTHER CONSORTIUM PARTNERS INVOLVED	i2CAT

OVERVIEW

The use case aims to (1) assess Tele-Operated Driving (ToD) performance over 5G and (2) show the value of accessing network performance data via advanced 5G features like exposure APIs to prevent sudden braking. Without such insight, a Tele-Operated Vehicle (ToV) may stop unexpectedly if network issues arise, requiring manual recovery. TARGET-X solves this by providing network information through an exposure interface and a prediction function that alerts the remote driver in advance, enabling timely braking or rerouting decisions and avoiding unsafe or disruptive stops.

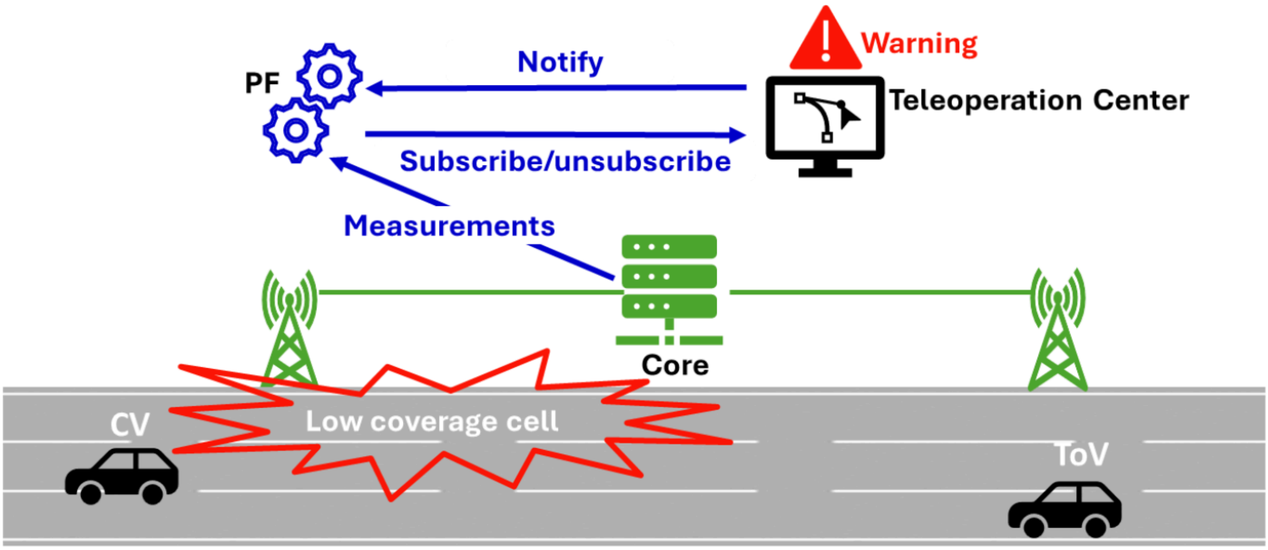

Figure 23.

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ARCHITECTURE

The functional architecture spans three blocks–mobile network, Tele-operated Vehicle (ToV), and Tele-operation Centre (ToC)–and three layers: communication, ToD, and intelligence. The communication layer uses 5G infrastructure, a ToD Application Server at the edge for secure registration/authentication, and a ToV modem for connectivity. The ToD layer includes the operator app in the ToC (remote driving, HMI, controls) and the in-vehicle interface (sensors, event detection, command execution). The intelligence layer hosts the Prediction Function (PF) in the network and a PF client in the ToC to process warnings and assist the driver. As standard APIs lack the required granularity, TARGET-X developed a custom PF.

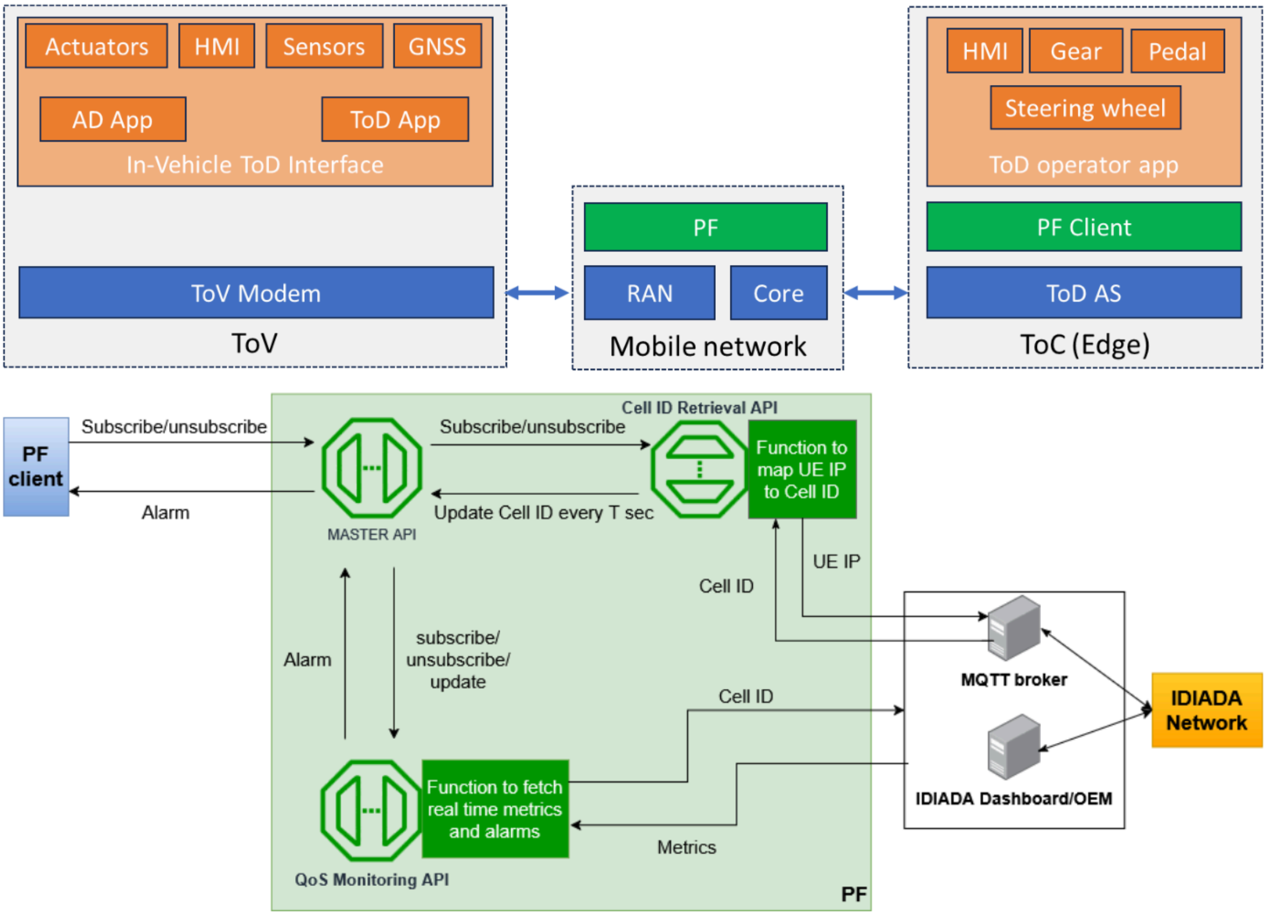

Figure 24.

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TRIAL

In the TARGET-X trials, the objective was to assess the latency of the commands, the throughput, and the jitter of the videos. The assessment was done using either 4G or 5G, and by connecting the remote system either to a 4G/5G modem (scenarios 1-3) or directly to the core network (scenario 4). For each case, 15 runs were performed, and the KPIs were collected. Scenario 4 is similar to scenario 1- Step one, but the remote system is directly connected to the core network.

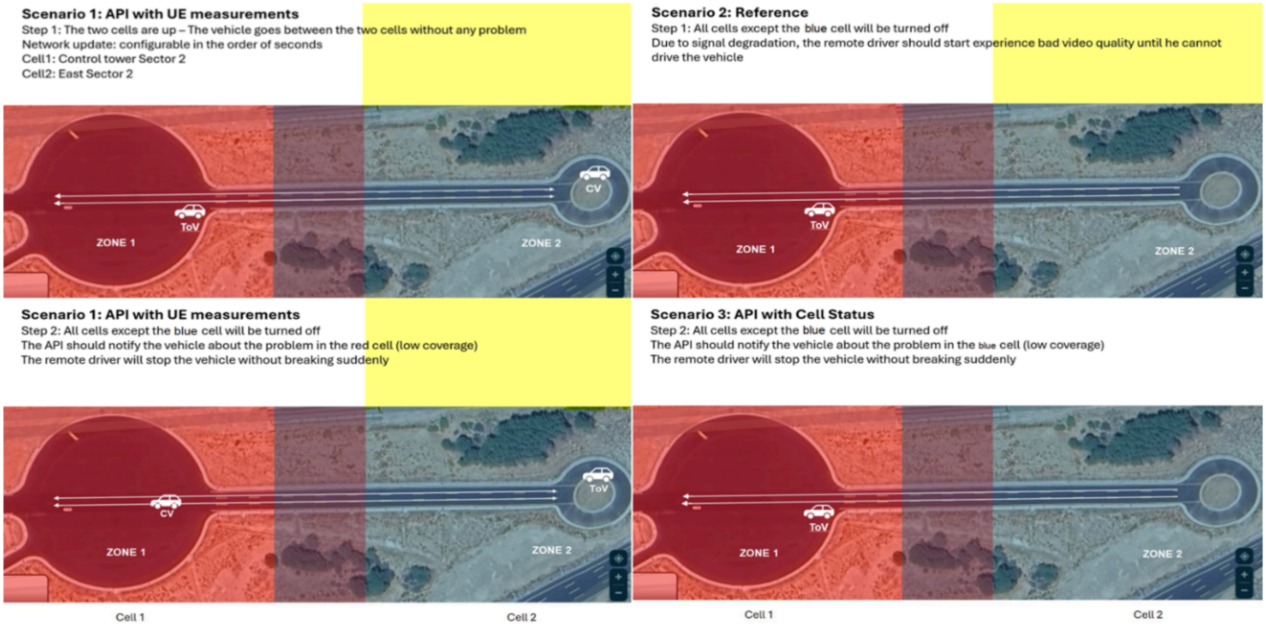

Figure 25.

RESULTS

Within the TARGET-X trials, the goal was to validate that the remote driver will be notified before the quality of the video and commands starts to decrease. The results show how the quality of driving will deteriorate if no warning is received by the remote driver (Scenario 2). Also, it shows a reduction by 48% and 18% in the command latency and video jitter when 5G is used instead of 4G.

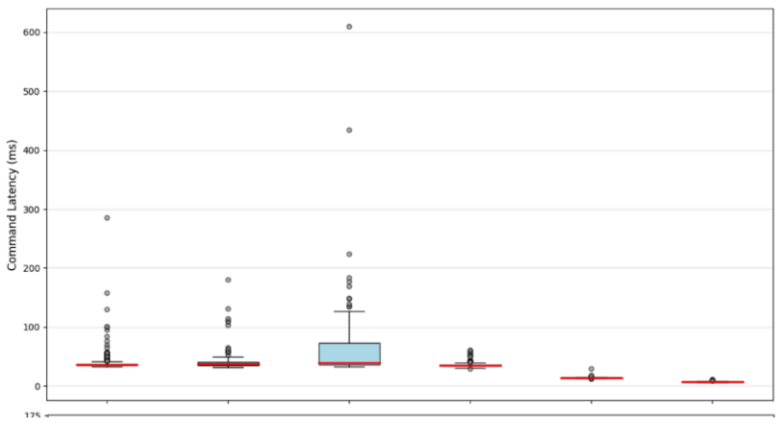

Figure 26.

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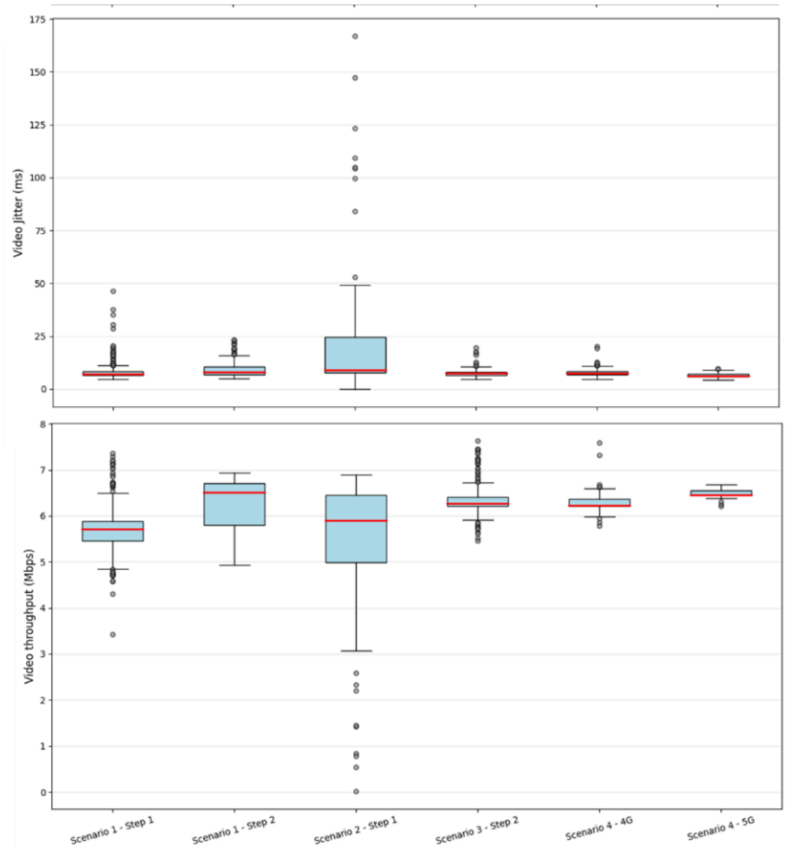

Figure 27.

5G EMPOWERMENT

The use of network exposure APIs enabling the interaction between the network and the application enhances the quality of experience of tele-operated driving by avoiding being stuck in areas without enough network coverage to remotely drive the vehicle.

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USE-CASE	Energy Monitoring and Energy Consumption Awareness
NAME OF RESPONSIBLE CONSORTIUM PARTNER	RWTH-ACS
OTHER CONSORTIUM PARTNERS INVOLVED	CCR, RWTH-IP, RWTH-WZL

OVERVIEW

As a part of the TARGET-X project, the 5G Energy vertical is focused on the Energy Monitoring and Energy Consumption Awareness use-case. The objective of this use case is to focus on monitoring in a low-voltage grid, where monitoring has traditionally been limited. With the increase in usage of variable energy sources at the low voltage level, energy consumption awareness and understanding have become very important for stable power grid operation. To achieve these goals, 5G-enabled software and hardware were used in the trial.

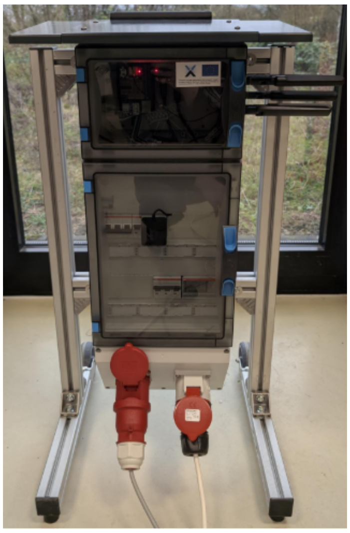

Figure 28.

Measurement devices are deployed at three test sites. For the energy awareness case, the devices are deployed at the construction, robotics, and energy testbed in Aachen, Germany. For the monitoring case, the setup Meter-X and 5G edgePMU is deployed at the energy testbed at the RWTH-ACS building, Aachen, Germany.

Considering the reduction of the environmental footprint in the construction industry, consumers need awareness about their energy usage patterns. To achieve this, a device named Meter-X, as shown in Figures 28 and 29, was designed and proposed, which provides a plug-and-play solution for the metering of the power consumption of machinery without internal sensors. It is an outdoor-capable measurement box that can be connected in line with the device under test. In the case of the construction site, that could, for example, be a crane.

Figure 29.

As Robotics plays a critical role in modern manufacturing by improving productivity and greater adaptability. The Meter-X device is used in the WZL robotics testbed using a Kinova robot to monitor its energy consumption to evaluate how different factors impacted efficiency, revealing that dynamic variables like payload weight and motion patterns significantly influenced both energy usage and mechanical wear.

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ARCHITECTURE

The TARGET-X project energy trial architecture, as shown in Figure 30, combines 5G, robot control, energy analytics, edge cloud, edgePMU, and Meter-X devices for increasing Energy Monitoring and Energy Consumption Awareness in Construction, Manufacturing, Robotics, and Energy verticals. The 5G network is used for the connection and communication between the physical hardware and the Edge server. The robot control system 2 is used to manage communication with the robot's drivers. The Meter-X device is used for mobile deployments and long-term energy metering, especially for energy awareness use cases. It performs inline measurements directly within the device. While edgePMU is specifically developed for grid monitoring applications in the project. It supports flexible sensor connections via analogue inputs, essential for measuring high voltages and currents beyond direct sensing capabilities. The ABB device is used for the metering application and to provide validated energy metering.

The Meter-X and 5G edgePMU are Raspberry Pi-based hardware that use open-source software named VILLASnode for the handling and analytics of energy measurements.

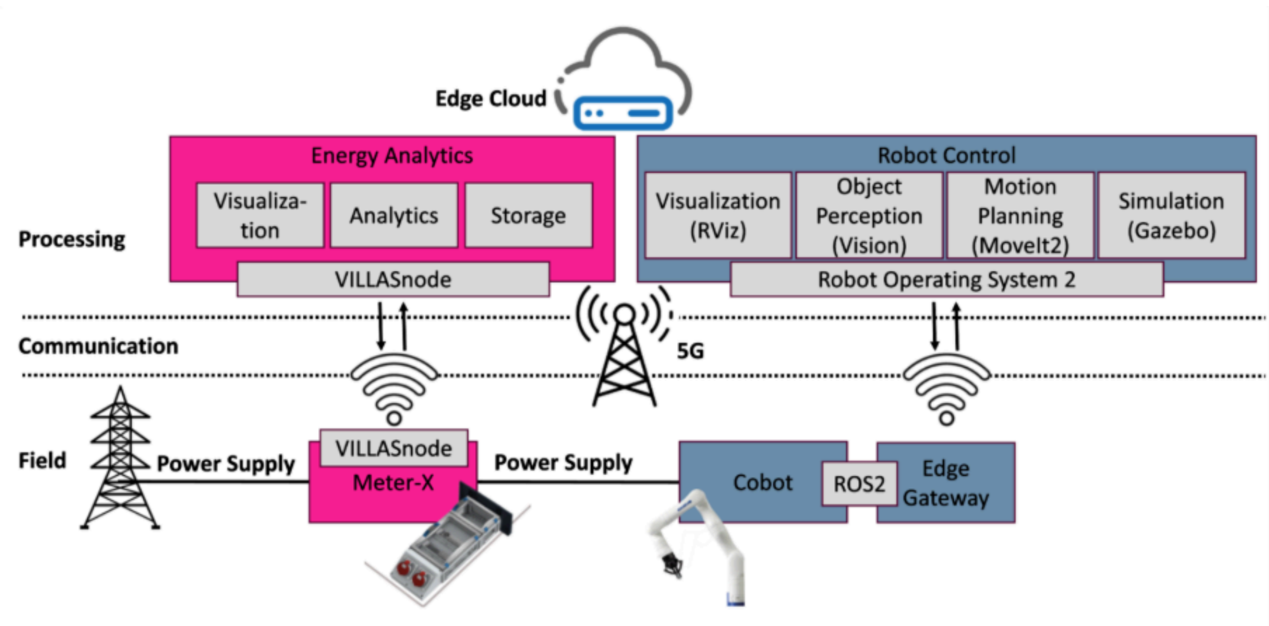

Figure 30: Architectural goal of the project.

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Figure 31: Demonstration with Kinova robot of energy consumption.

Figure 32: Power consumption for different weights. (1) four weights (2) only the fixture no additional weights

The energy testbed features two device types: Meter-X devices across three rooms and one 5G edgePMU at ACS-RWTH. For energy awareness, power consumption is tracked, while voltage and phase angles are measured for grid monitoring. In the construction testbed, the Meter-X monitors a material hoist, and in the robotics testbed, it tracks power usage with a robot arm, comparing energy consumption for different weights to enhance energy awareness.

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TRIAL

Figure 33: Hardware deployment in energy testbed. Mechanical workshop ACS-RWTH (left), electronics lab ACS-RWTH (center) and server room ACS-RWTH (right).

Figure 34: Mounted 5G edgePMU in electronics lab ACS-RWTH(left), Second design iteration of Meter-X connected to the material hoist on the construction testbed (right)

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USE-CASE	Robotic deconstruction prototype system
NAME OF RESPONSIBLE CONSORTIUM PARTNER	RWTH-IP
OTHER CONSORTIUM PARTNERS INVOLVED	CCR

OVERVIEW

The TARGET-X project explores the application of 5G technology across various industries, including construction. This trial focuses on a robotic deconstruction prototype that integrates Extended Reality (XR) technology for adaptive planning and execution.

The aim is to show how 5G-enabled robotic deconstruction can boost efficiency, precision, and safety in dismantling building structures, thus promoting a circular economy. By reducing human exposure to hazardous environments and proximity to heavy machinery, the risk of accidents is greatly minimised. Plans are also in place to apply the developed technologies to other construction site processes.

The trial took place at the Reference Construction Site in Aachen, Germany, using the ReStage Structure, a multi-material demonstrator. Mobile robots from KUKA and INNOK carried out the deconstruction, supported by 5G URLLC communication for real-time coordination between machines, operators, and edge servers.

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ARCHITECTURE

The TARGET-X trial architecture (see figure 35) integrates 5G, robotics, and XR technologies to improve the efficiency and safety of deconstruction. A 5G non-standalone (5G NSA) network connects all components, enabling real-time data exchange. A customised KUKA KR 70 R2100 robot, equipped with a specialised end effector, carries out the deconstruction through machine-to-machine (M2M) communication. Communication between the user device, the robot, and the edge server is facilitated using ROS and MQTT protocols. Exchanged data includes the robot's joint states and force-torque sensors' readings, trajectory planning inputs from the user device, and additional exteroceptive sensor data for environment perception.

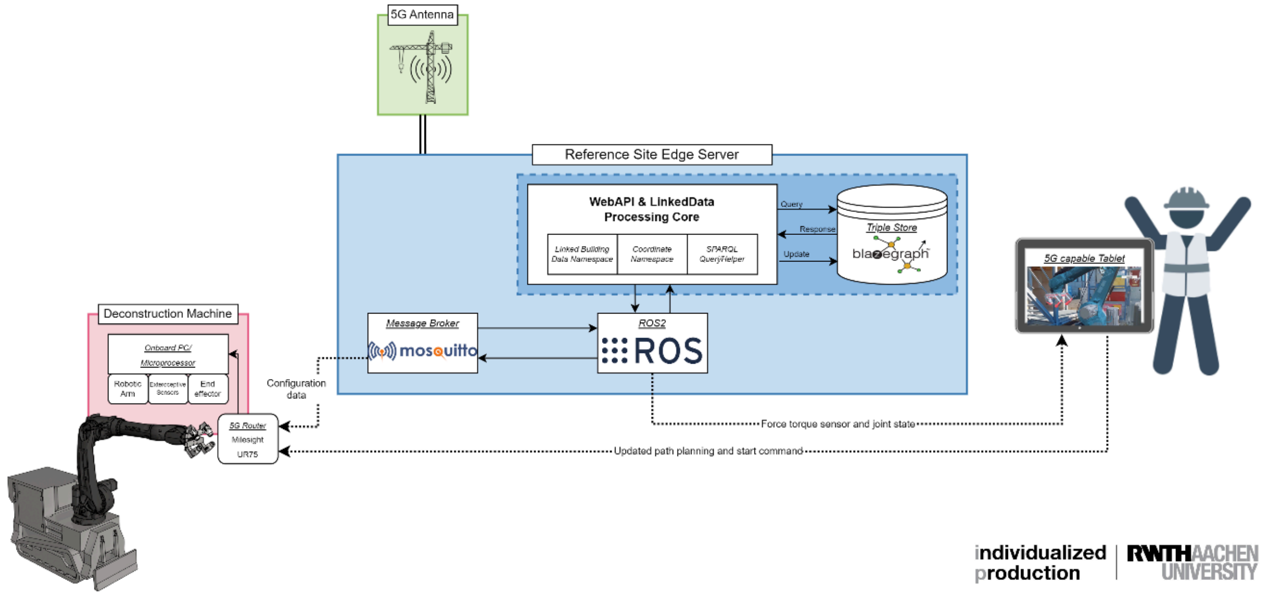

Figure 35: Overview showing the data exchange between the devices and edge server (https://doi.org/10.5281/zenodo.14615798).

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TRIAL

The trial was conducted at the Reference Construction Site in Aachen, operated by Construction Robotics GmbH, where a 5G network was established using antennas mounted on a tower crane. The KUKA robot was configured with XR-based positioning, while a mobile safety robot, equipped with LiDAR and AI detection, ensuring secure operations (see figure 36). An edge server handled data, processing, and command execution, enhancing automation, precision, and real-time monitoring.

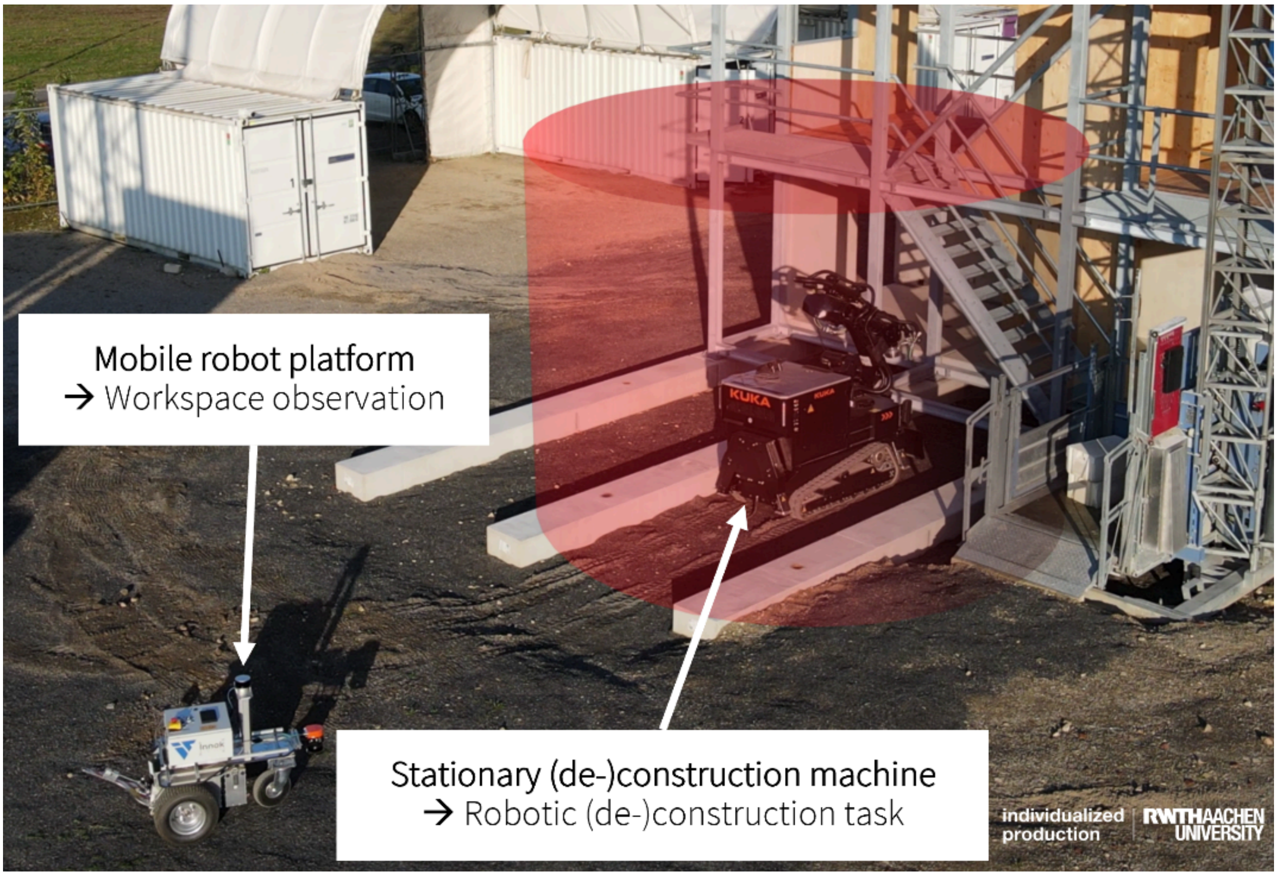

Figure 36: Overall deconstruction setup on the Reference Construction Site, Aachen (https://doi.org/10.5281/zenodo.14755973)

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RESULTS

This trial successfully demonstrated the feasibility and benefits of 5G-enabled robotic deconstruction.

- Remote-controlled deconstruction via 5G reduces accident risk by allowing operators to work at a safe distance from heavy machinery.
- 5G is the core enabler, ensuring reliable two-way communication, transmitting control commands to machines, and returning data for real-time monitoring and evaluation.
- The project's "Financial support for third parties" programme supported early 5G trials by industry partners across diverse construction use cases. In total, 27 companies received funding.

Video: https://doi.org/10.5281/zenodo.14755973

5G EMPOWERMENT

5G offers several key advantages to the trial by delivering the bandwidth required to stream point cloud data for real-time safety analysis, enabling detailed monitoring of the deconstruction area. Its low latency ensures fast, precise robot control, supporting smooth operation of robotic systems. In addition, low-latency machine-to-machine (M2M) communications enhances coordination among all components, ensuring efficient and safe task execution with minimal delay.

5G Advanced and 6G are expected to introduce greater flexibility through support for multiple Quality of Service (QoS) flows. Moreover, integrated localisation and, in the future, Integrated Sensing and Communication (ISAC) capabilities could replace some of the scanning equipment currently used for construction digitalisation.

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TARGET-X

FSTP PROJECT DESCRIPTIONS

1ST AND 2ND SUPPORT PROGRAMME

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PROJECT NAME (ACRONYM)	DEMETER (DEMETER)
NAME OF BENEFICIARIES	WEGO SRL MINERVAS S.R.L.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	i2CAT

OVERVIEW

The Demeter project aims to integrate MinervaS's digital twin and driver evaluation technology into the Volvero car-sharing platform, enhancing driver awareness on safety, sustainability, costs, and environmental impact. The project involves MinervaS (technology provider) and wego srl (Volvero platform) as main partners.

The pilot (TRL6) was conducted in Vicenza (May 2024) using a Lancia Ypsilon, focusing on live data acquisition, user experience, and feedback to drivers, with dynamic scoring and reward mechanisms. The final trial is scheduled at IDIADA (Sept 2024), testing under real 5G conditions. Key milestones: integration of MinervaS and Volvero apps, compliance with GDPR, and definition of safety KPIs. Achievements include a functional prototype, real-world driver scoring, and dynamic incentives for improved behavior.

ARCHITECTURE

The Demeter architecture connects vehicle, smartphone, and cloud layers to deliver real-time driver feedback. Data is collected from the vehicle via an OBD-II dongle and transmitted to the driver's smartphone through Bluetooth. The MinervaS app processes this data and sends it to the cloud using 4G/5G. In the cloud, a digital twin is maintained and analyzed for driver behavior and safety KPIs. The Volvero platform receives feedback and delivers interactive scorecards and suggestions to users. The architecture is scalable and secure, supporting GDPR-compliant data flows and enabling advanced analytics for safety and sustainability

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TRIAL

The main trial deployment took place at IDIADA (September 2024), using a passenger vehicle equipped with an OBD-II dongle and smartphones (iPhone 14 Pro, Xiaomi 13 DS, Samsung Galaxy) over 5G. MinervaS and Volvero apps enabled real-time data collection, driver feedback, and gamification, focusing on 5G performance and safety KPIs.

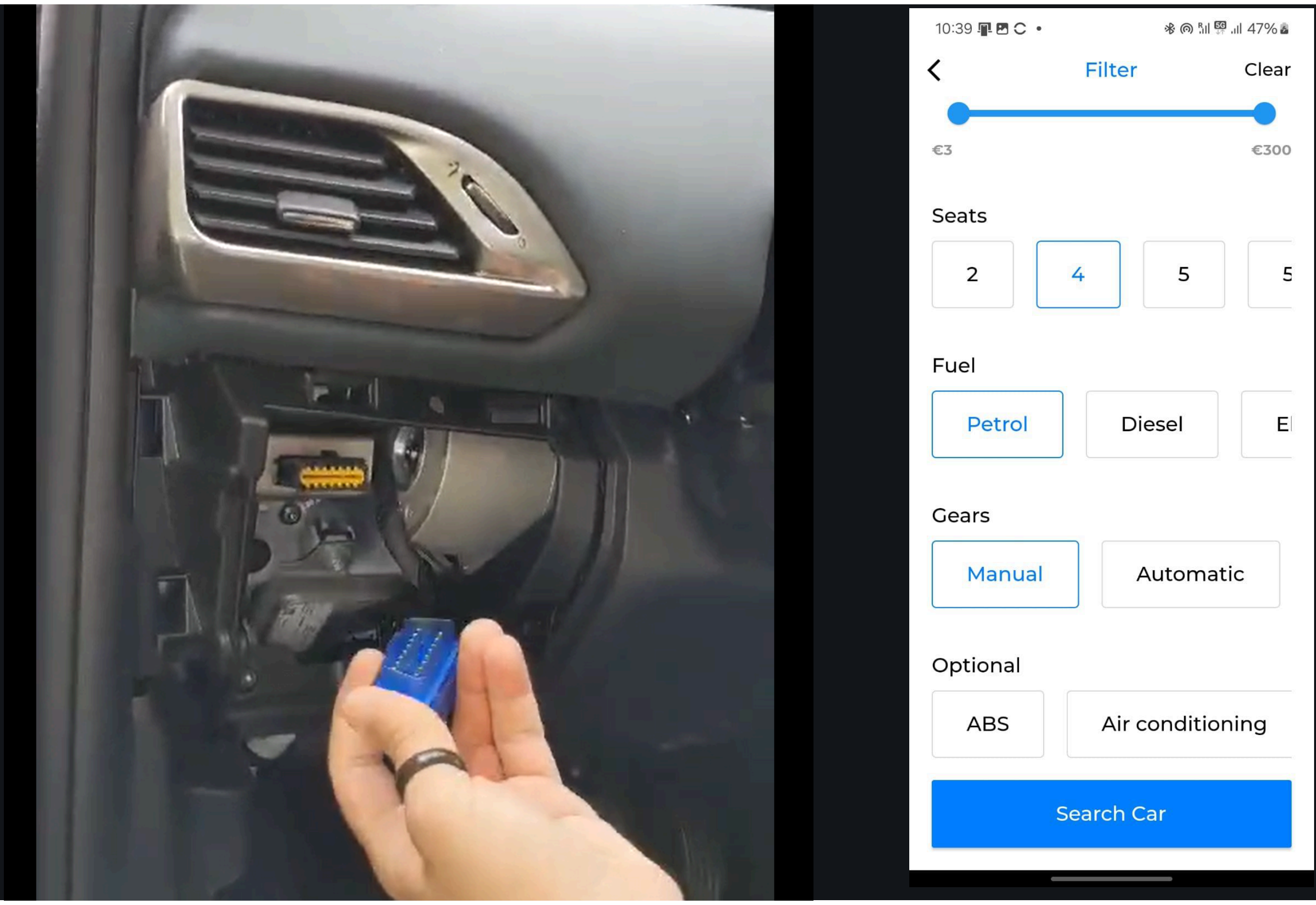

Figure 37: OOBD dongle installation, app screenshots, photo of vehicle setup in Vicenza.

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RESULTS

Demeter enabled real-time driver feedback and gamification on the Volvero platform, fostering safer and more sustainable driving. Key achievements: TRL6 prototype, dynamic driver scoring, GDPR-compliant data handling, and integration with Volvero for rewards. Business KPIs: improved user retention, dynamic pricing, and enhanced safety scores.

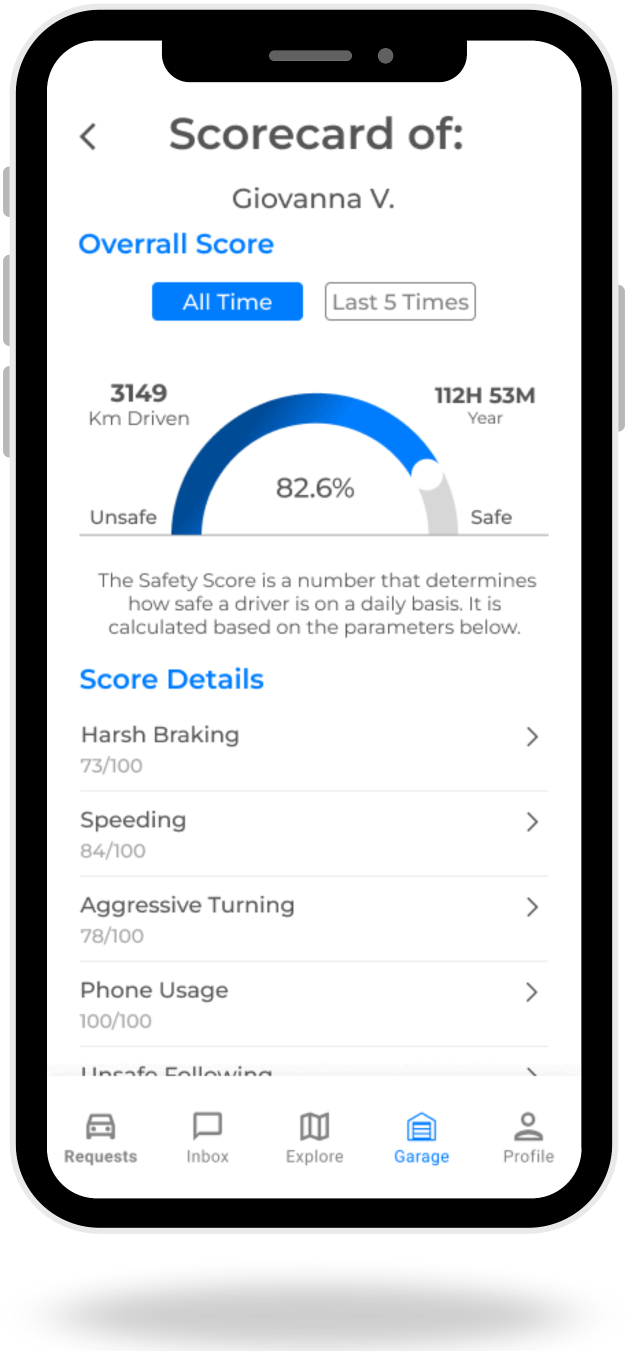

Figure 38.

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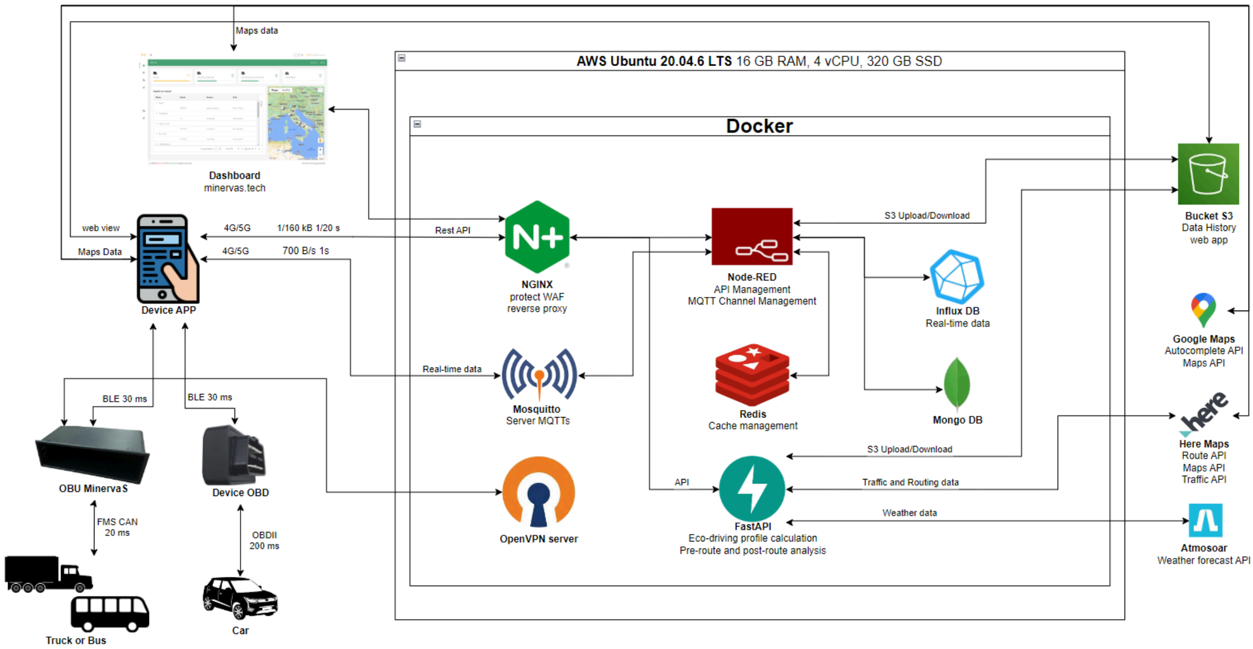

Figure 39.

Links: https://volvero.com/en/demeter/ ; https://www.minervas.it/demeter/

5G EMPOWERMENT

5G enables ultra-low latency and high bandwidth, supporting instant feedback, adaptive navigation, and advanced safety analytics for Demeter users. Compared to 4G, 5G allows dynamic driver guidance, secure cloud integration, and scalable mobility services, empowering new car-sharing business models that previous networks couldn't enable.

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PROJECT NAME (ACRONYM)	VEHICULAR VIDEO STREAMING FOR REALTIME MONITORING (V-STREAM)
NAME OF BENEFICIARY	PI.PE GmbH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 02/09/2024
LIST OF INVOLVED PARTNERS	i2CAT

OVERVIEW

V-STREAM (Vehicular Video Streaming for Realtime Monitoring) was a TARGET-X Call 1 project enabling pi.pe GmbH (https://pi.pe) to test and demonstrate its secure, ultra-low-latency "watchdog" software solution for remote vehicle supervision under challenging network conditions.

Autonomous shuttles and robo-taxis only meet their business case without an onboard driver, yet safety, regulation, and passenger assurance require human oversight. Jurisdictions such as Germany and California already mandate remote supervision.

V-STREAM combined live video, audio, and telematics in an encrypted |pipe| connection over LTE/5G, with no intermediary cloud server. It was validated first in 5G lab tests and then at varying speeds at the IDIADA proving ground - and was soon after implemented for driver monitoring/coaching in professional motorsports and is now being commercialised there by an eponymous subsidiary, V-Stream.Camera (https://v-stream.camera).

V-STREAM CAMERA

Figure 40.

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ARCHITECTURE

V-STREAM integrates |pipe|'s embedded "watchdog" software into a self-contained network camera, entirely independent of the vehicle's own driving systems. The unit streams live video, audio, and telematics directly to the remote supervisor's browser over LTE/5G via an end-to-end encrypted ultra-low-latency |pipe| connection, with no intermediary cloud server. This WebRTC transport layer is optimised for high mobility, jitter, and packet loss, ensuring continuous connectivity and an optimal video image even under very challenging network conditions.

For trials at the IDIADA proving ground, the camera was mounted in a standard electric passenger vehicle, enabling controlled evaluation of performance over the same circuit/network at constant speeds, from 30kph to 160kph.

Figure 41: V-Stream Camera mounted in a professional race car (copyright: V-Stream.Camera UG).

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TRIAL

V-STREAM trials began in a 5G lab, where the V-STREAM camera with embedded |pipe| software was tested under controlled 5G conditions, including induced congestion and attenuation, and measuring glass-to-glass latency, also observing the effects of switching to 4G. Each scenario was run twice – with |pipe| active and inactive – to provide clear A/B results.

This comparative approach was then applied at the IDIADA proving ground in Spain, mounting the V-STREAM camera in a standard electric passenger car and driving for a fixed time period at constant speeds of 30, 50, 80, 100, 130, and then 160kph. These high-mobility tests evaluated live streaming performance in controlled driving conditions. No photography or video filming was allowed at IDIADA, so we have no images to show from those test sessions.

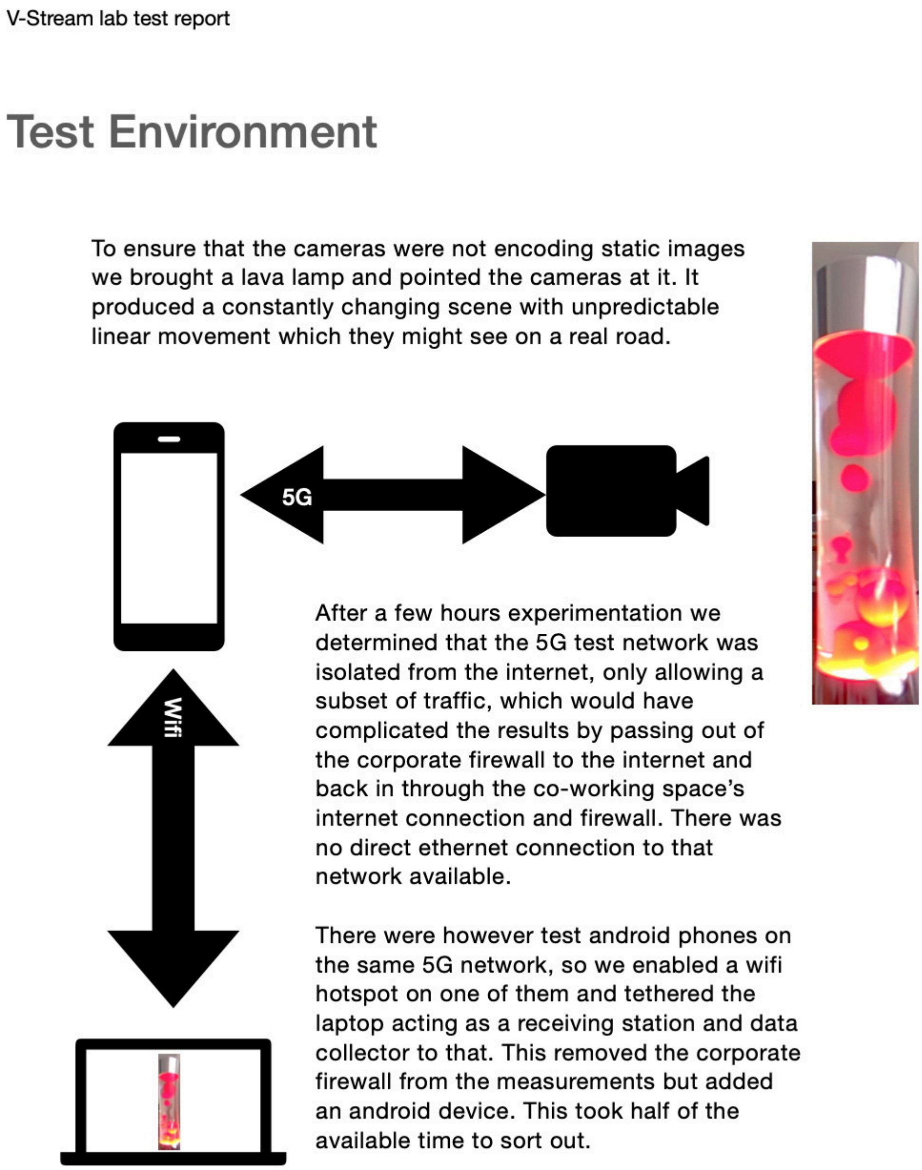

Figure 42: V-Stream Lab Test Report.

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RESULTS

The IDIADA proving ground trials provided a direct A/B comparison of streaming performance with |pipe| active vs. |pipe| inactive, under identical conditions.

Across six fixed-speed runs (30, 50, 80, 100, 130, and 160kph) lasting five minutes each time, the streaming video froze 40× less often when running the |pipe| software than the no-|pipe| baseline, and remained usable even at the highest speeds tested.

Both modes showed degradation as speed increased, but |pipe| maintained smooth, usable video throughout, even at very high speed. Full IDIADA test results are shown in the table here.

Results

Km/h	Min	freeze %	comp	hops	cells	Rtt ms	Mbit/s
nopipe							
30	5	18.28	635	4	4	37	5.0
50	5	23.37	600	5	5	41	5.0
80	5	26.02	609	9	9	42	5.0
100	5	31.62	572	10	10	39	5.0
130	5	33.60	573	14	10	43	5.0
160	6	32.42	596	18	10	43	5.0
all	32	29.67	578	55	15	41	5.0
|pipe|							
30	4	0.00	1023	4	4	36	1.0
50	5	0.09	916	7	6	40	2.9
80	5	0.14	837	8	8	42	3.9
100	5	2.91	893	9	9	39	3.7
130	5	0.52	916	13	9	41	4.0
160	5	0.63	938	16	10	40	3.6
all	30	0.73	917	53	16	40	3.2

Figure 43: V-Stream Lab Test Results.

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5G EMPOWERMENT

V-STREAM proved that |pipe|'s embedded "watchdog" software unlocks LTE/5G for secure, real-time remote vehicle supervision - meeting Call 1 Topic 22 goals.

In IDIADA tests, the same 5G camera without |pipe| froze repeatedly, while with |pipe| it stayed smooth even at 160kph.

The solution was later validated with Berlin-based stage 4 AV partner MOTOR Ai (TARGET-X Call 2 project VISTA) and in professional motorsport, proving its effectiveness at over 250kph:

https://www.youtube.com/watch?v=7CZSzowGd-A

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PROJECT NAME (ACRONYM)	DEVELOPING AND TESTING TOKENME 5G PRIVATE NETWORK (TOKENME 5G PRIVATE NETWORK)
NAME OF BENEFICIARIES	TOKENME B.V.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	CCR

OVERVIEW

Private 5G networks offer some interesting advantages for our system in two ways: firstly, they can give coverage to an entire building site. These sites are often in remote locations that do not have public network coverage (yet). With just one to three base stations, we expect to cover a whole site, which offers a simplification in our infrastructure compared to the 9 or more LoRaWAN gateways we currently use. A private 5G network gives us full control over the network configuration. Many of the power-saving features of LTE-M can be requested by the UEs, but public networks may not always support these features or may not allow the requested configuration values. In particular, the network has a fixed RCC inactivity timer that forces the UE to stay connected to the network for an extended period after each data transfer. Having the ability to set this duration to as small a value as possible in the core network can give a significant power reduction to our devices.

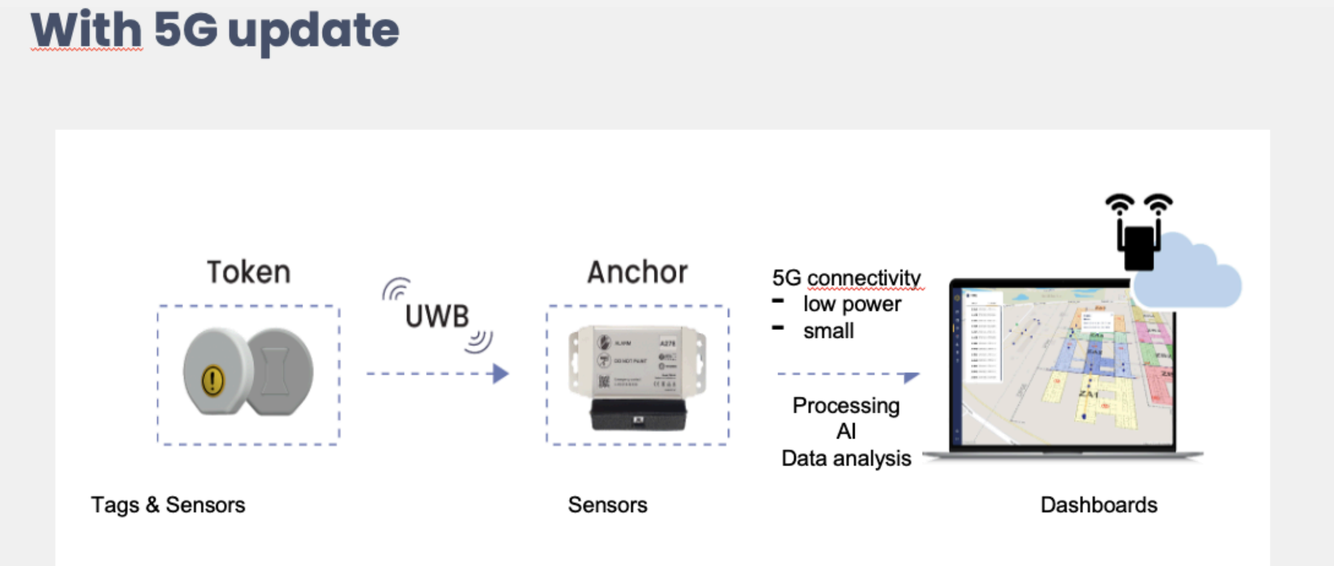

Figure 44: The TokenMe system explained with 5G update.

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ARCHITECTURE

Motivation for the project is the conversion of the LoRaWan communication to 5G.
In this project, we will build a prototype that will be used for lab and field measurements.
The measurements must reveal the most important components to decide on.
When the measurements are done, a final product will be developed.
Main parameters are for typical TokenMe messages and conditions:

- range
- current consumption
- size of the total product
- ease of production
- location accuracy

The initial product will be the TokenMe anchor. A second product will be a wearable device for construction workers and security personnel.
The development board will include the following technologies:
Wireless:

- 5G - for low power, long range communication and course locationing, in residential areas
- LoRa - for low power, long range communication and course locationing in remote and private networks
- GPS - for accurate locationing outdoors
- UWB - for accurate indoor locationing
- NFC - for identification of devices, people, and assets

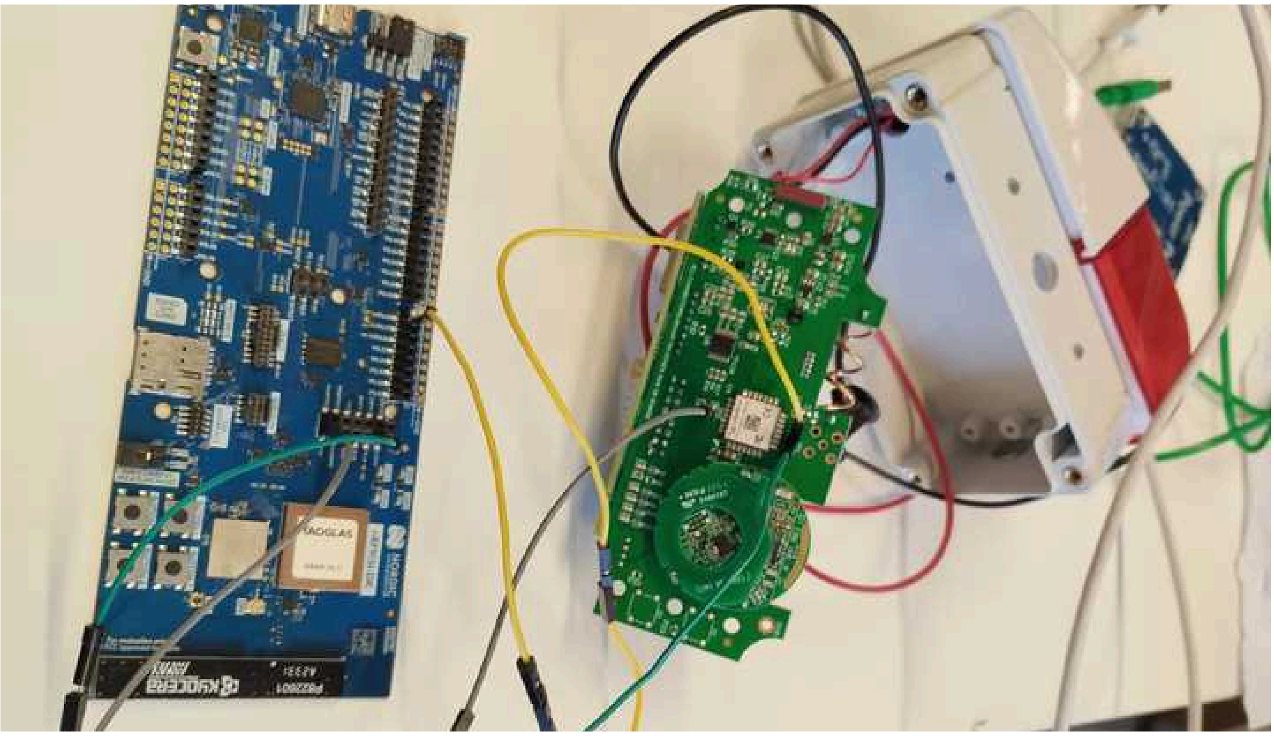

Figure 45: The test set up with device used during the development.

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TRIAL

A working prototype has been developed. This incorporates an nRF9151 development kit into our existing anchor, sending MQTT messages over LTE-M rather than LoRa.

Testing in Aachen
We did tests with LoRaWan and demonstrated successfully the ease of setup, the range, and data acquisition from tokens (mounted to helmets of participating people).

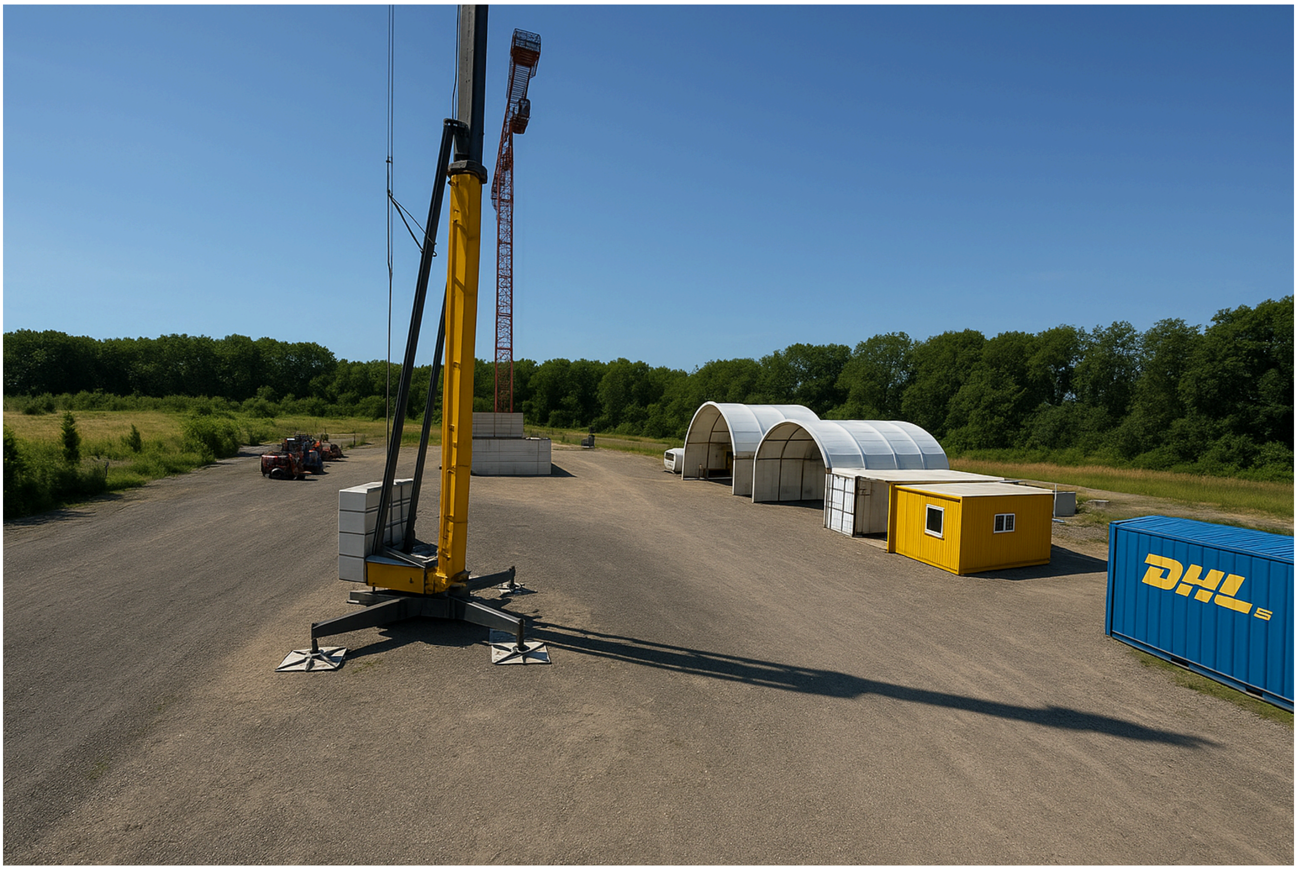

Figure 46: Testing 5G solution at Aachen (showing locations of anchors and anchor ID's).

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RESULTS

The project experienced several delays due to the availability of resources, mistakes in the design, additional certification efforts, and the complexity of the new design.
That said, we are well on our way to having a new exclusive TokenMe 5G product, which allows us several new use-cases.

The cost structure of the anchor is within the expected range, although the customised battery and additional battery-management circuitry make the design more expensive than originally anticipated.

Figure 47: The TMA06-CE.

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5G EMPOWERMENT

The resulting TMA10 TokenMe 5G product will be released early next year. It will be introduced early to multiple residential and industrial building projects. The new anchor supports the growth and success of bringing the TMA10 product to market. We are executing the following steps:

- LTE-M and GPS antenna optimization and lab verification tests for the development of a product
- verification field measurements in the unmanned valley
- update the TMA10 based on these results and manufacture the first 100-unit batch
- verification of all sensor functions, including UWB, BLE, and NFC - production-ready
- certification
- pilot projects in Netherlands, Italy, France Japan, Dubai in Q3, 2025 (awaiting for product)

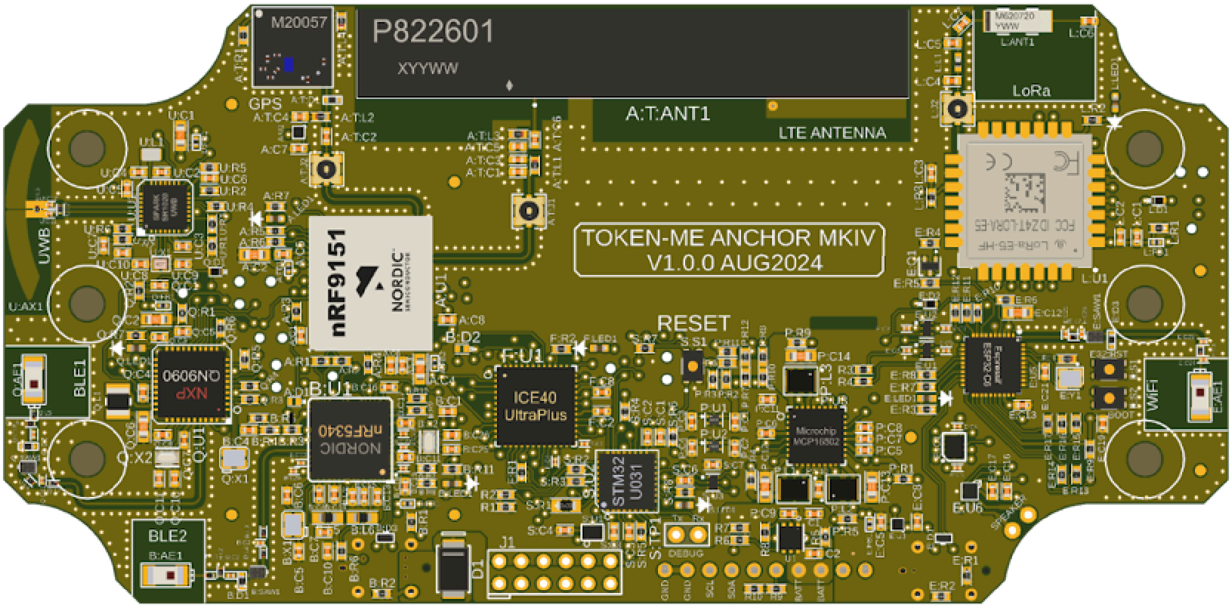

Figure 48: The board of the new TMA10.

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PROJECT NAME (ACRONYM)	TOWARDS OPTIMAL FORECASTS FOR 5G EDGE (5GEDGE_FORECASTOPTIMISER)
NAME OF BENEFICIARIES	LAMDA NETWORKS P.C.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 29/11/2024
LIST OF INVOLVED PARTNERS	RWTH -ACS

OVERVIEW

5GEdge_ForecastOptimiser (Towards optimal forecasts for 5G Edge) was a TARGET-X Call 2 project enabling Lamda Networks to test and validate our Photovoltaic (PV) power consumption forecast software using the 23-month PV consumption RWTH data set.

Our novelty derives from the fact that no single forecasting method can achieve the highest accuracy in real-life scenarios involving many different patterns of PV energy consumption. To overcome this barrier, our TARGET-X PV consumption forecasting software chooses on the fly the best prediction algorithm fitting a specific energy consumption pattern. Currently, the best algorithm is chosen amongst the LSTM, RNN, and GRU state-of-the-art deep learning algorithms, with our code being open to allow the addition of extra forecasting algorithms.

The promising technical results presented in the MS2 Project Development Report fuel our commitment to advancing towards a higher Technology Readiness Level. Our next milestone: delivering an operational prototype on a real renewable energy site - bringing our software closer to market readiness and unlocking tangible value for the industry according to our business plan presented and analyzed in MS3 Validated Market Uptake Report.

ARCHITECTURE

The architecture is depicted in Figure 49. Our software is hosted on a private cloud instance. A Kubernetes Engine (K8s) is deployed to host all the software components of our project. The main reason for choosing K8s orchestration was its capability to automatically restart a pod if the pod is 'down' for some reason, providing high resilience and reliability to our software during its operation for a PV deployment.

We leveraged TensorFlow, Flask, React.js, Vite, and SQLite software. Shortly, TensorFlow was used to devise our deep neural network models. The Flask Python3 module was used for the backend API. React.js, Vite, and SQLite packages have been used for the development of our Web User Interface.

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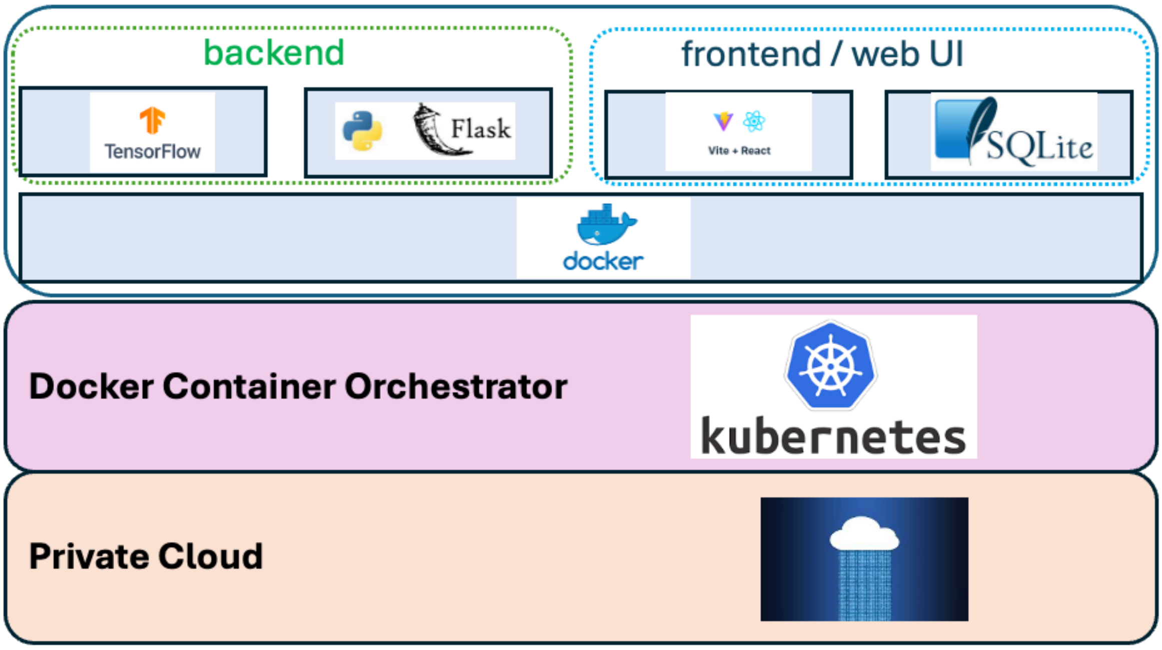

Figure 49: Architecture of 5GEdge_ForecastOptimiser.

TRIAL

The 5GEdge_ForecastOptimiser trial was conducted with the RWTH data set. The forecasting results during the trial were visualized for the trial making use of our custom web app, as we depict in Figure 50.

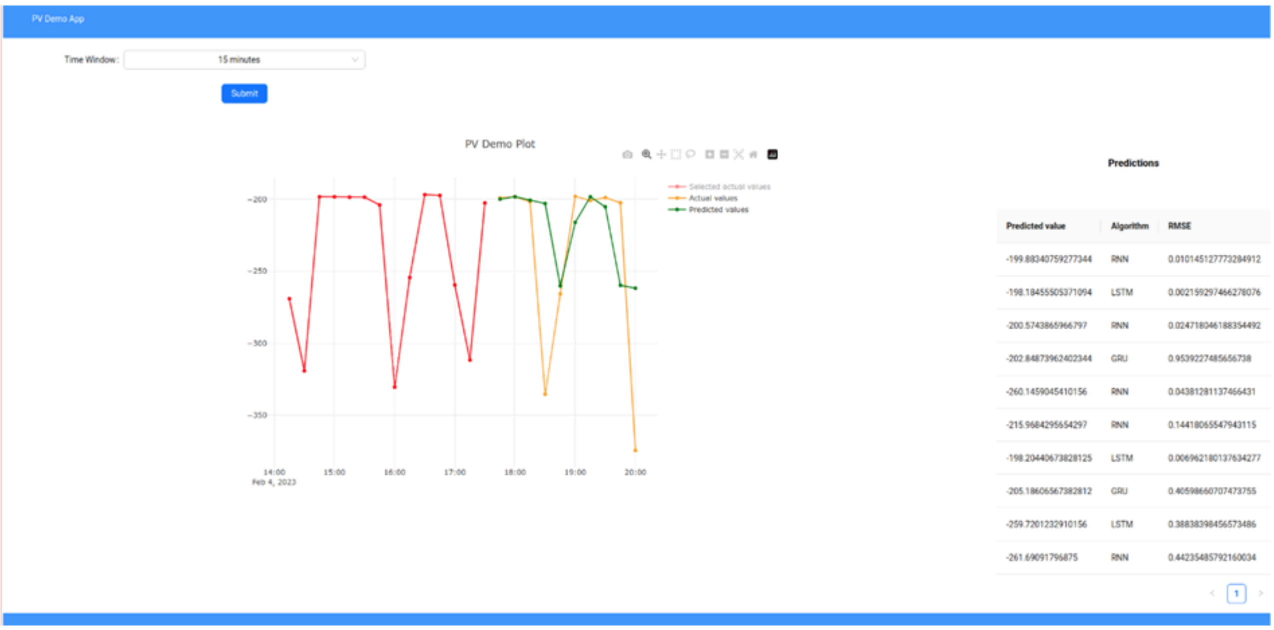

Figure 50: (a) Results of the web UI for the selected user input (highlighted with red colour and labelled as 'Selected actual values').

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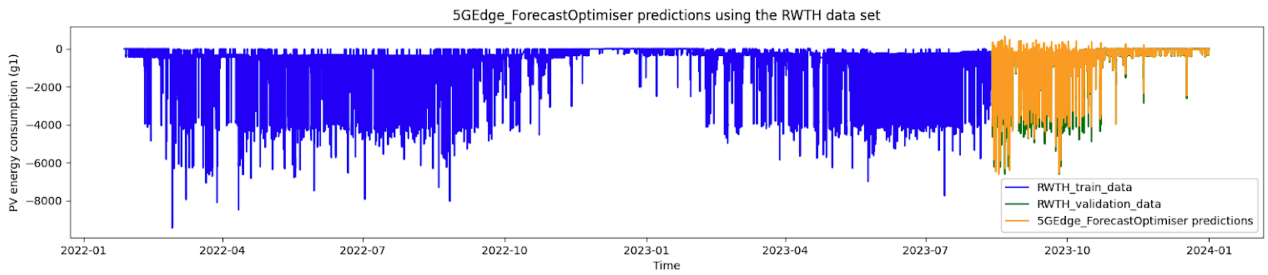

Figure 51: Behaviour of 5GEdge_ForecastOptimiser with respect to the RWTH data set.

Overall, the high accuracy of 5GEdge_ForecastOptimiser can be schematically seen in Figure 51, presenting 5GEdge_ForecastOptimiser's predictions trained and validated with the RWTH data set used in our trial.

RESULTS

The achieved Technical KPIs (as agreed in MS1) refer to the accuracy of our predictions. They are presented in Figure 52.

Technical KPIs
Statistical metrics
Pearson correlation coefficient >= 0,9
RMSE < 0,064.
MBE > -0,78
Skewness: From -3,73 to -3,36
Kurtosis > 11, 28
Variability metrics
As the forecast horizon increases, our model's statistical metrics deteriorate
Uncertainty metrics
Standard deviation of forecast errors <=372
Entropy of forecast errors ~8.44

Figure 52: Accuracy-related technical KPIs achieved by our Open Call 2 implementation which was validated in the trial.

The Business KPI is the success of our ongoing efforts to demonstrate the outcomes of the TARGET-X project to potential solar park customers for a strong initial market push, according to our commercialization plans discussed in Market Uptake Report.

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5G EMPOWERMENT

Our software receives via 5G the energy consumption measurements from the PV park. The 5G technology provides **reliable (lossless) measurements** on the current energy consumption of the PV site, and, **therefore, more accurate forecasting** of the energy that will be consumed per site in each user-defined time horizon considering that any data interpolation technique cannot produce the ground truth PV consumption data.

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PROJECT NAME (ACRONYM)	OPEN ENERGY BOX (OPEN ENERGY BOX)
NAME OF BENEFICIARIES	CONNECT IQ SP. Z O.O. F.H.P. "MAL-PAK" Leszek Mul.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 29/11/2024
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

The Open Energy Box project aimed to design and deploy a modular device for real-time energy monitoring in industrial environments. The system includes hardware, 5G connectivity, and cloud integration with Grafana dashboards. Trials took place at Mal-Pak, where 10 devices were installed on high-energy machines such as extruders and printers. The system achieved seamless monitoring, energy efficiency analysis, and anomaly detection. Using 5G reduced latency and enabled instant data access, supporting operational decisions in a demanding factory setting.

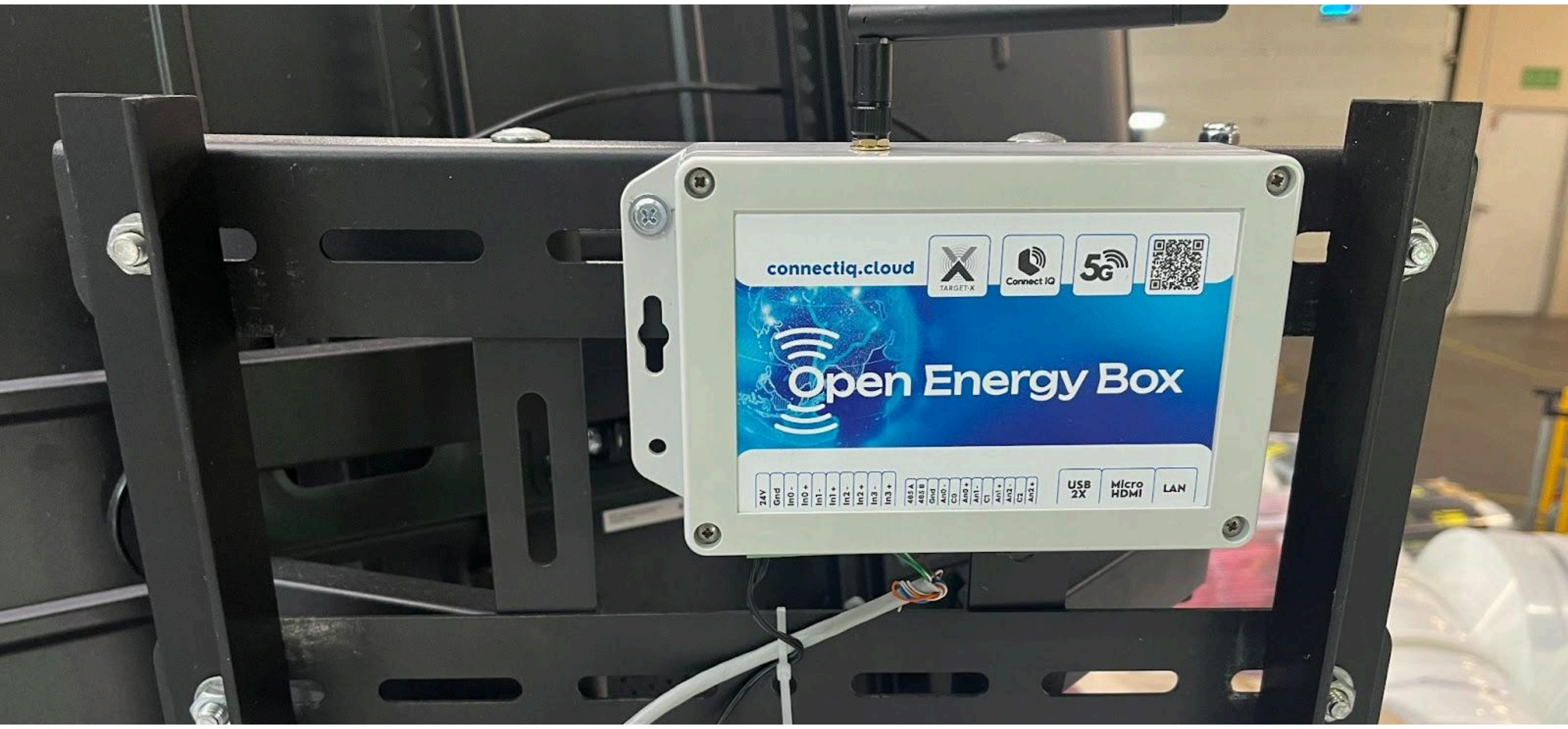

Figure 53.

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ARCHITECTURE

The architecture consists of three core layers: a hardware device with analog/digital inputs, a web-based configuration app, and a backend server for processing and visualizing data. Powered by a Raspberry Pi CM4 and SIM8262E-M2 5G modem, the device collects data from Modbus RTU meters and transmits it to a Node.js backend and InfluxDB. Grafana dashboards provide real-time insights. The UI, designed in Figma and developed in Vue.js, enables intuitive control across desktop and mobile devices. The system is scalable and supports industrial standards.

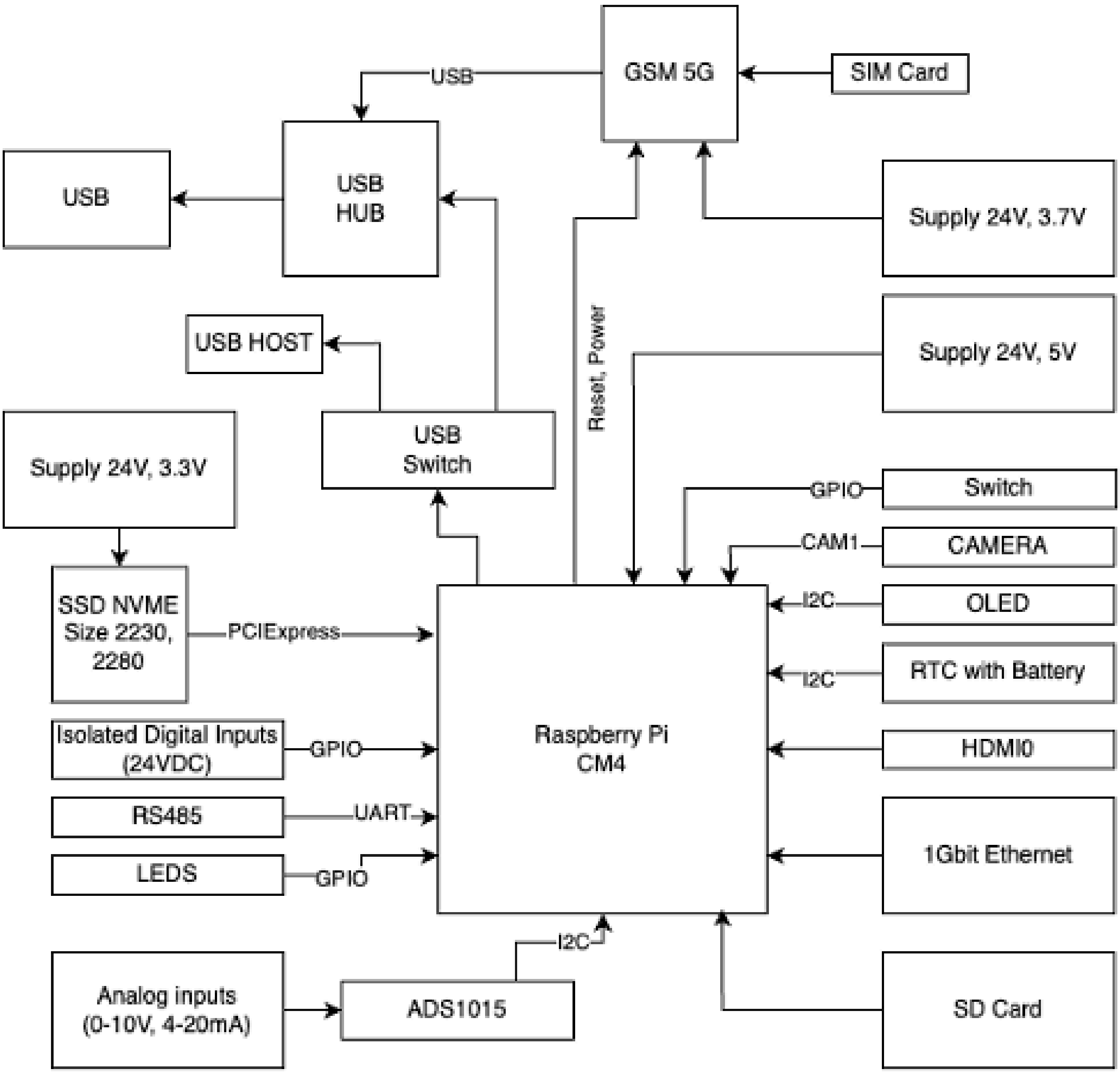

Figure 54.

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TRIAL

The Open Energy Box was deployed at the Mal-Pak facility in Poland, with 10 devices installed on machines such as printers, extruders, and winders. Devices were connected to Modbus RTU energy meters. The test setup enabled real-time monitoring of power consumption, current, voltage, and power factor, with visualizations delivered through Grafana. 5G ensured stable and fast data transmission.

Figure 55.

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RESULTS

The Open Energy Box enabled continuous monitoring of machine energy use and helped identify inefficiencies in real time. The system improved operational visibility through live dashboards and ensured accurate, reliable data flow. By leveraging high-speed connectivity, it supported timely decision-making and opened new opportunities for optimizing energy management in industrial settings.

Figure 56.

5G EMPOWERMENT

The integration of 5G enabled uninterrupted real-time monitoring, even under heavy industrial data loads. Its ultra-low latency allowed energy data to be visualized within seconds, improving operational awareness. Unlike older technologies, 5G ensured stable performance across multiple devices, paving the way for scalable, high-frequency energy analytics in smart manufacturing.

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PROJECT NAME (ACRONYM)	DISTRIBUTED ACTIVE ENERGY MONITORING AND OPTIMIZAT (DAEMON-LEC-5G)
NAME OF BENEFICIARY	RBZ ROBOT DESIGN S.L.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

DAEMON-LEC-5G proposes the implementation of a hardware-software framework in the field of monitoring and optimization of electrical energy using the 5G network capabilities. The objective is to design and manufacture an IoT device capable of analysing energy consumption, storing it, and generating analytics in a distributed framework. Data will be deployed using 5G Multiaccess Edge Computing to provide low latency.

The framework could be adapted to local (homes, offices) and global (transformation centres, energy neighbourhoods, cities) environments and will link its execution, and therefore its need for computation, based on the energy needs at different time horizons.

Hardware devices will be installed in the power distribution panels, obtaining real-time information. This information will be transmitted to an edge computing system that will work on energy-saving strategies. Moreover, users will be the owners of their own data; hence, an open data strategy will be pursued to allow users to define their data storage platforms.

ARCHITECTURE

The hardware is based on a Linux embedded system with an isolated measurement interface and its own power supply, allowing direct AC connection. It features independent inputs for a three-phase AC network and high-current measuring coils. An iMX8M Plus NXP processor handles data processing and communication based on an embedded Linux system. The device also includes a 5G modem, Ethernet, RFID, and a SIM slot. The processor locally executes Artificial Intelligence algorithms. A software framework analyzes patterns and predicts energy consumption and generation using time series data. This is done with a Block Recurrent Neural Network (BlockRNN) and Long Short-Term Memory (LSTM) cells to forecast hourly usage, enabling real-time decision-making and energy optimization.

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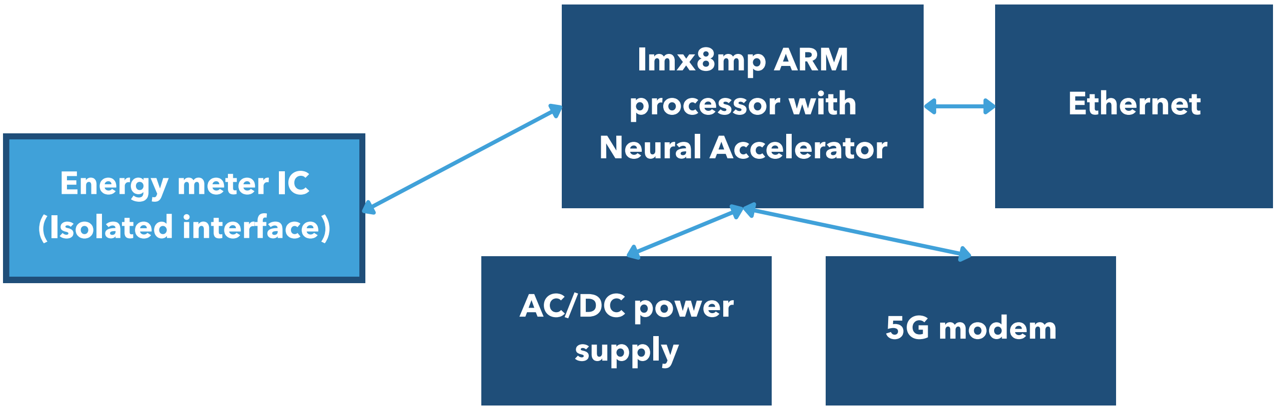

Figure 57.

TRIAL

The device has been tested, ensuring an environment fulfilling: 5G connectivity, AC voltage lines and current lines, a set of devices with varying energy consumption to test different measurements. Tests occurred at RBZ premises (UPM planned), connecting to 220V AC with loads like PCs & 3D printers to vary consumption. Software cycle: meter_read captures data; mosquitto_pub sends to ThingsBoard (MQTT); targetx_forecast.py (LSTM) predicts hourly consumption.

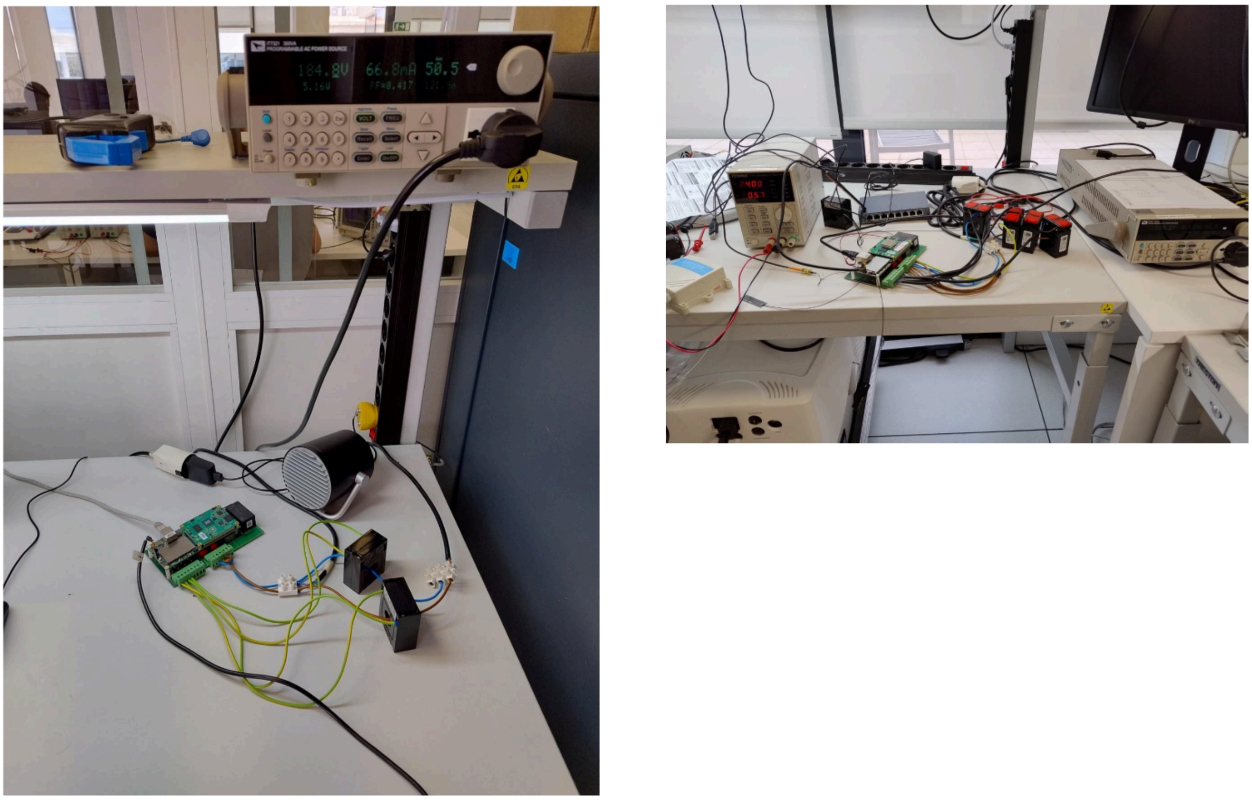

Figure 58.

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RESULTS

A functional prototype with measurement capabilities, AI prediction, and 5G connectivity was validated. 5G tests (vs. 3G/4G/Ethernet) in a location with adequate coverage showed average upload/download speeds of 46.5 Mbit/s with a lower standard deviation than 4G (43.3 Mbit/s upload, 43.5 Mbit/s download), indicating greater reliability. The 5G ping (average 53.9 ms) was comparable to that of 4G (49.7 ms) on the public network used. Energy prediction using LSTM successfully captured consumption trends.

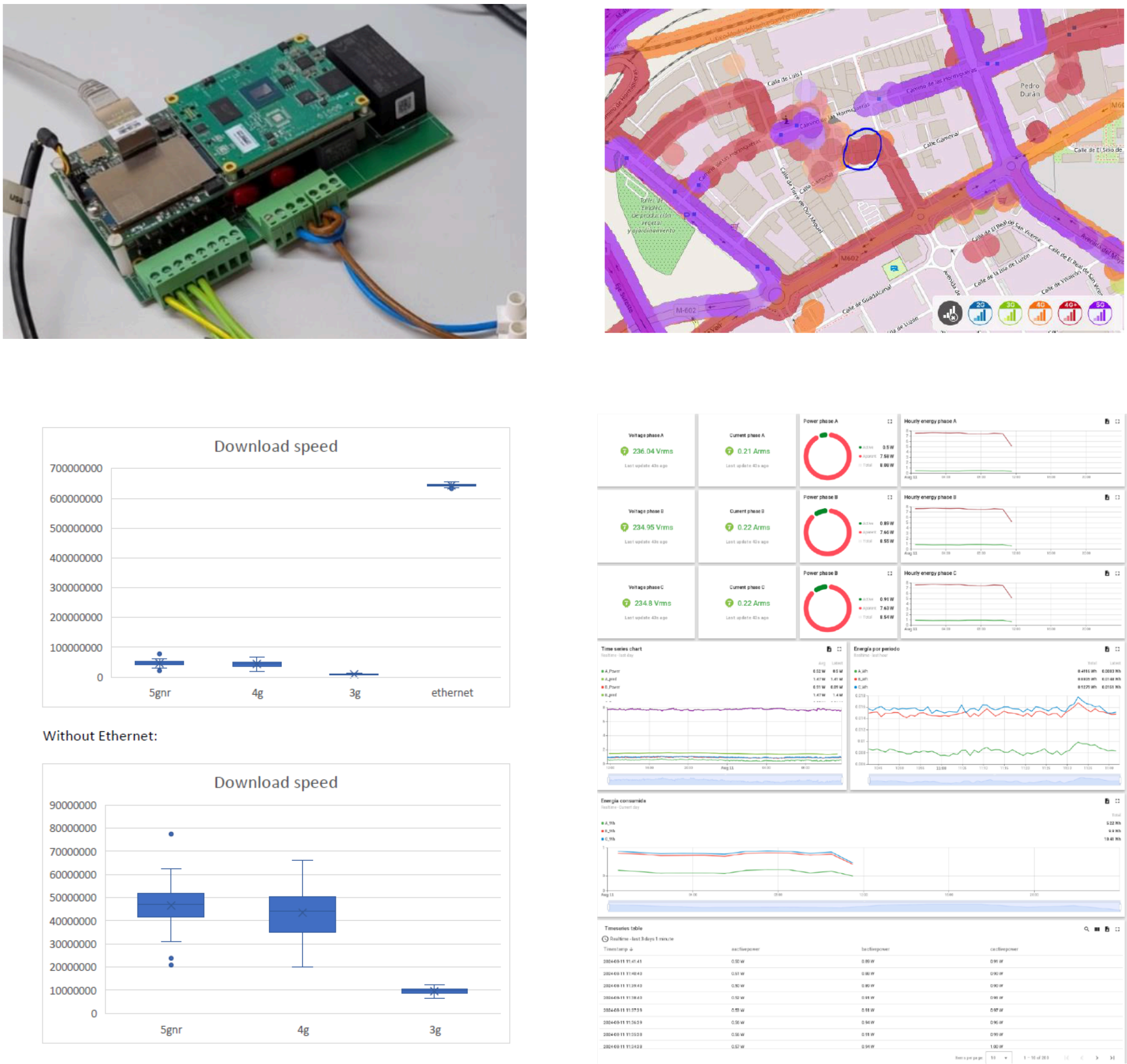

Figure 59.

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5G EMPOWERMENT

5G is key for DAEMON-LEC-5G due to its high speed, low latency, and reliable communication for real-time energy data, which is vital for local analysis and distributed decision-making. 5G demonstrated greater reliability (lower deviation in metrics) than 4G/3G, ensuring better resource allocation for multiple IoT devices. This is crucial for efficient management in Local Energy Communities. Future 5G Advanced and 6G technologies will further enhance AI integration and edge computing, enabling autonomous energy systems.

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PROJECT NAME (ACRONYM)	LOW-VOLTAGE ENERGY DISTRIBUTION NETWORK MONITORING (LENSE)
NAME OF BENEFICIARY	INSIGHIO I.K.E.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

Project LENSE aims at disrupting low-voltage electricity distribution network visibility with a flexible 5G-empowered Internet of Things (IoT) solution. The solution transforms legacy unattended hardware equipment - such as substations or even smart buildings' electricity panels- into intelligent connected endpoints, offering an unprecedented level of continuous monitoring capabilities. The driving force of this innovation is 5G technology, with its low-latency and high-bandwidth features allowing for the implementation of near real-time monitoring of remote infrastructures. LENSE brings a fundamental change to the way the energy grid is managed today, given the evolution of connectivity and IoT technology over the last years. It addresses the Energy sector, primarily the electric distribution network sub-segment, and secondarily the smart large building sub-segment. There are 4 key potential users, i.e., electricity distribution network owners/ providers, regulatory authorities, substation/feeder manufacturers, and smart building owners/managers. A TRL7 prototype has been developed with the support of RWTH Aachen University, E.ON Energy Research Center, and tested against a live 5G network in Greece in August 2024, in the premises of the company.

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ARCHITECTURE

LENSE is a flexible and modular monitoring solution not bound to a specific low-voltage equipment manufacturer, but highly customizable and dynamically expandable thanks to its agile hardware and software design, allowing to add new sensing capabilities on demand. It includes 4 core elements outlined in Figure 1, bundled together to form a non-invasive and "quick-and-dirty" way to identify infrastructure anomalies, faults, and defects. The solution includes:

- Current sensing modules are based on the split-core transformer principle.
- Connectivity is enabled by a 5G-NR modem and an edge computing module.
- An IoT endpoint, embedding sensing and connectivity control.
- An IoT Cloud Platform, integrating remote endpoints and data management.

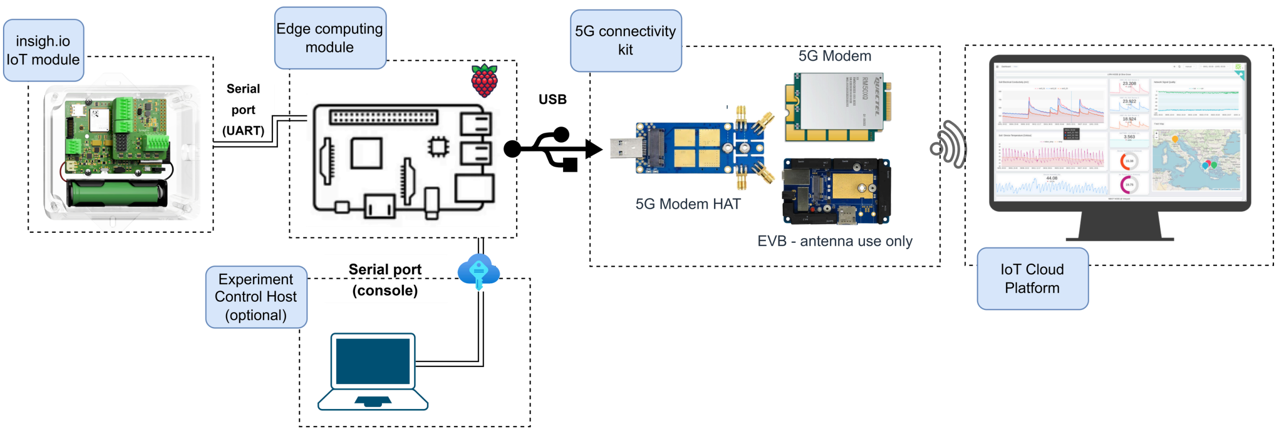

Figure 60: LENSE 5G-IoT Minimum Viable Product Architecture

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TRIAL

The LENSE trial has been performed in the premises of the Company, in Athens, Greece. We used an off-the-shelf energy monitoring system (as a "golden" unit) to verify the accuracy of our sensing module, whereas for network testing, we considered a live commercial 5G network provided by local operator COSMOTE. To implement the trial, we assembled the LENSE prototype (shown in Figure 2). This is a "plug-and-play" setup, in the sense that after installation and activation, it needs no manual intervention, i.e., starts retrieving sensor data, connects to the Cloud platform using 5G-NR technology, regularly pushes data in a suitable format, and visualizes it into a custom dashboard for further inspection and offline analysis.

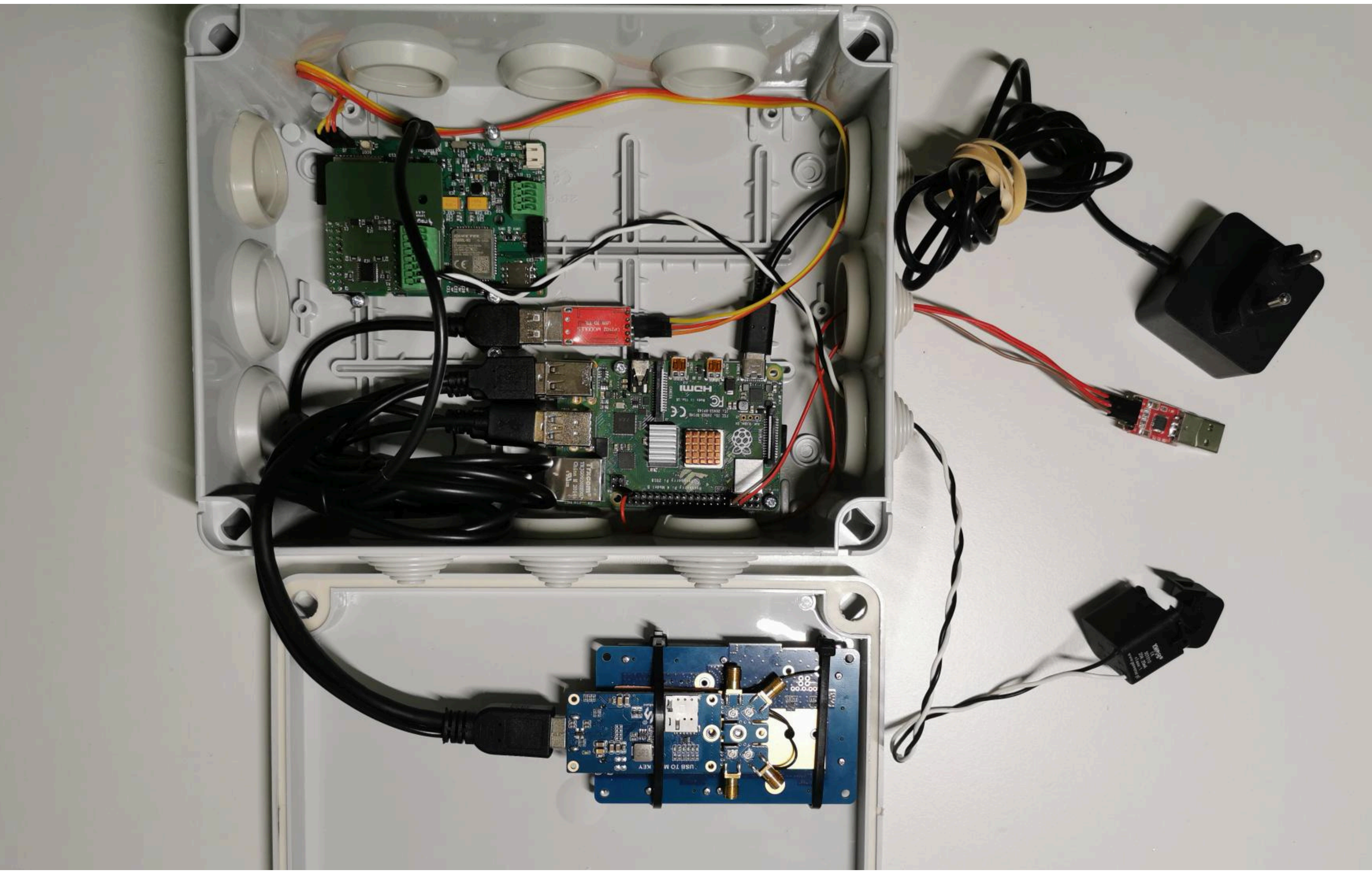

Figure 61: LENSE Trial Setup

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RESULTS

With respect to the hardware design requirements, the developed prototype was shown to support 4 current sensing inputs, each one rated up to 250A. In terms of the 5G connectivity performance levels, an average end-to-end latency of 60ms and Cloud reporting frequencies less than 1 sec were achieved (Figure 3). On the business side, we were able to deliver and showcase a functional prototype, paving the way for the productization stage, significantly accelerating the time-to-market journey.

Figure 62: Dashboard of LENSE Trials

5G EMPOWERMENT

The particular IoT solution has been developed on the basis of an existing IoT hardware & software stack using 4G NB-IoT connectivity implemented in-house. With 5G technology, we were able to experience shorter round-trip delays. This allows us to tightly remote control the deployed hardware and respond more quickly, i.e., in seconds, whereas in NB-IoT it usually takes minutes. With such latencies, we can significantly increase the energy network observability and lower maintenance costs.

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PROJECT NAME (ACRONYM)	AR WELDPATH: 5G-ENHANCED ROBOTIC WELDING GUIDANCE (SBPATH-5G)
NAME OF BENEFICIARY	METROLOGY LAB LTD.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

SBPATH-5G – 5G-Enhanced Robotic Welding Guidance helps small- and medium-sized manufacturers automate high-mix welding jobs. Led by Metrology LAB Ltd. (BG) with mentoring from WZL RWTH Aachen, the 7-month TARGET-X OC 1 project (Jan 2024 – Jun 2025) links laser seam-tracking cameras, cloud path-generation (SWPGEN), and AR/XR operator feedback through an ultra-reliable 5G link. At TRL 6 (Sep 2024 demo) the system produced full weld paths in 1.5 s and optimised parameters in 100–150 ms, cutting setup time and scrap by >25 % for partners.

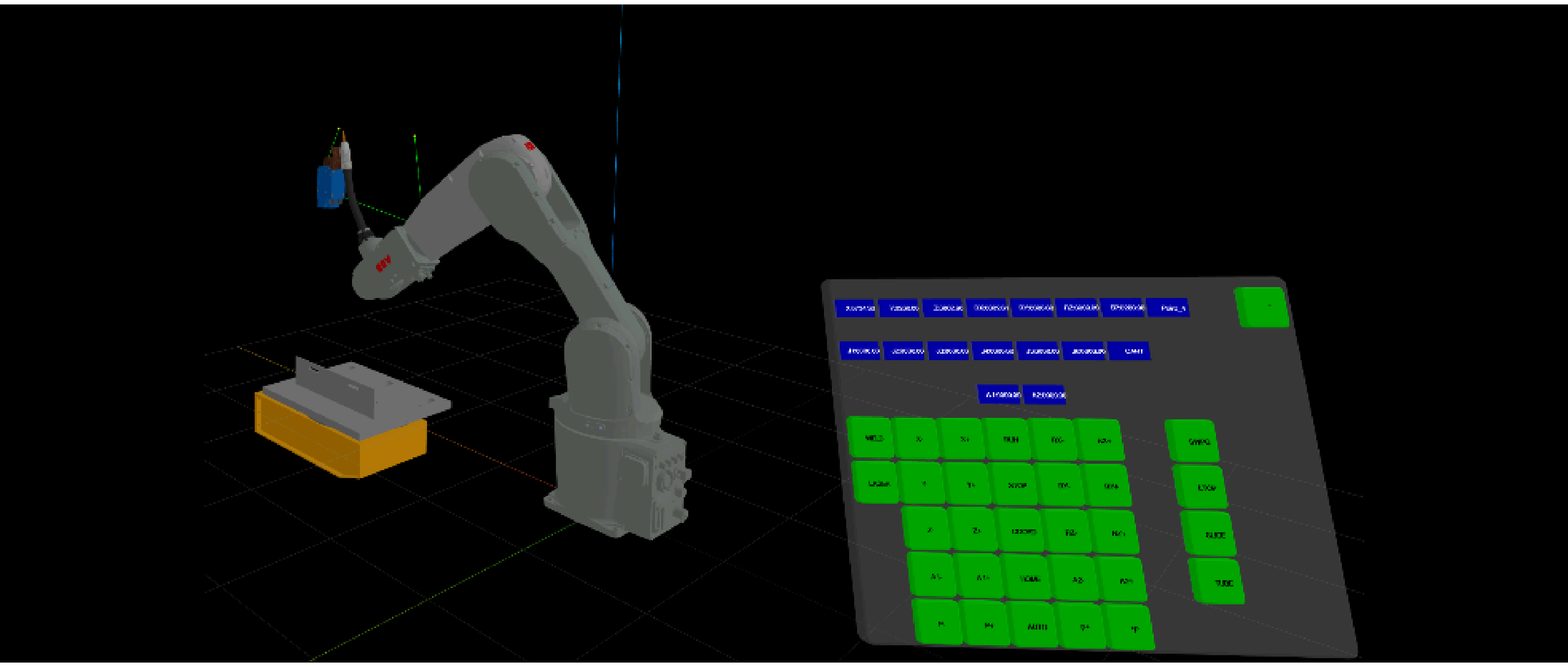

Figure 63: WEB XR based interface to Robot simulator

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ARCHITECTURE

The solution follows a hybrid edge-cloud layout. On-site, a SkyBlue controller fuses point-cloud data from a laser seam tracker with robot feedback. A private/public 5 G modem streams this data (<10 ms RTT) to cloud micro-services: SWPGEN slices the scan and proposes welding path trajectory, LASERTOP tunes welding parameters input, and Tube-Finder is used for weld programming of heatsink devices or other tube/plate welds. The resulting path and recipe are pushed back to the robot while operators view live AR overlays in a browser-based XR dashboard. Open APIs let new modules plug in as needs evolve.

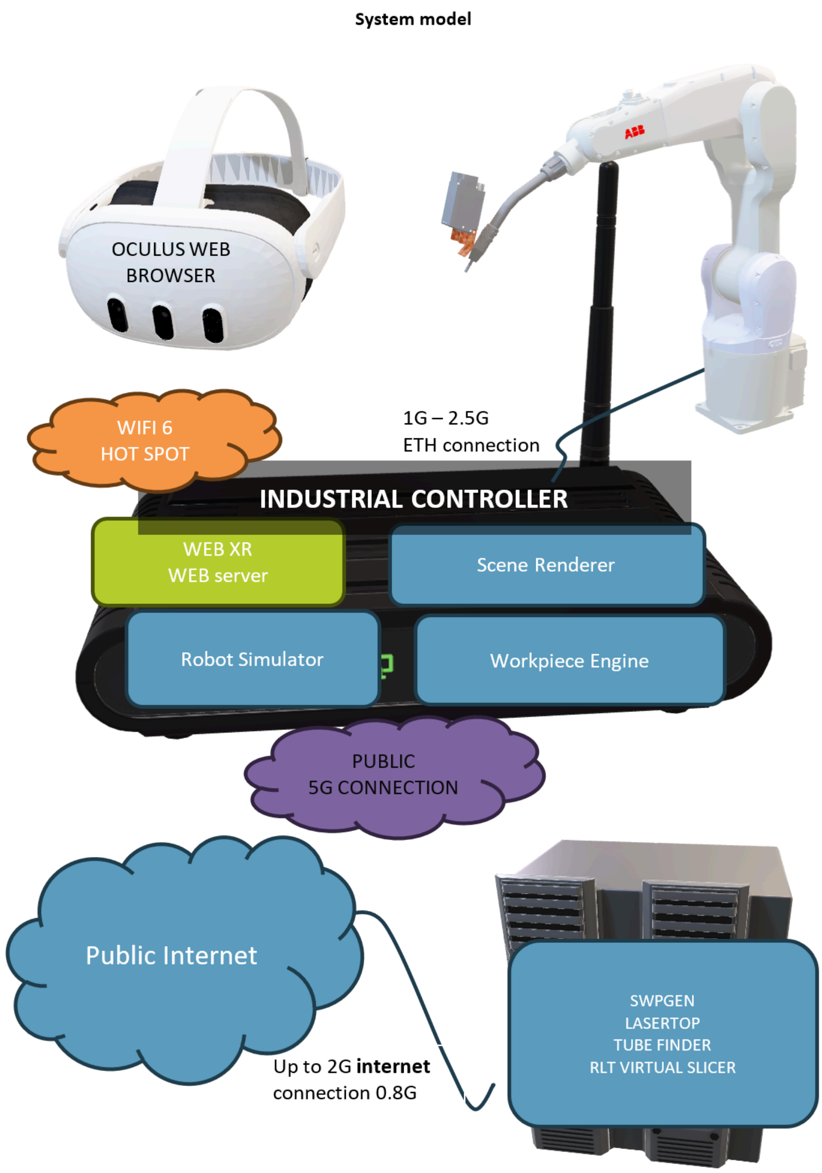

Figure 64: General scheme of the system

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TRIAL

The pilot ran at Metrology LAB's workshop in Sofia (TARGET-X SME testbed). A UR10e robot with the SkyBlue scanner has welded stainless-steel heat-exchanger plates. The edge server used a public 5 G SA slice (VIVACOM 3.6 GHz) and a VPN to the 5G-ICE core in the Second office of Metrology LAB. XR tablets and a Meta Quest 3 headset gave the crew live, in-helmet weld-path visualisation.

Key KPIs (Sept 2024 demo, TRL 6)

- Point-cloud slicing: 100 fps @ 100 mm s^{-1}
- Full path (1 M pts, 12 segments): 1.5 s
- LASERTOP parameter synthesis: 100–150 ms
- End-to-end loop (sensor → cloud → robot): <35 ms

These figures enabled flawless on-torch corrections, trimming setup time by 27 % and cutting re-work from 12 % to 3 % over a 50-part batch.

Figure 65: Test bench with 5G/WiFi edge device with OCULUS VR/XR glasses Connecting through public network to microservices server

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RESULTS

5G adds the deterministic, high-bandwidth backplane that lets heavy point clouds leave the cell. With sub-10 ms round-trip, the cloud re-optimises paths faster than the robot moves – impossible on Wi-Fi. The same link streams low-latency XR video so operators "see" the future seam before the torch moves. This turns SBPATH-5G into a subscription-based "welding brain" that SMEs can scale from a single cell to multi-site factories.

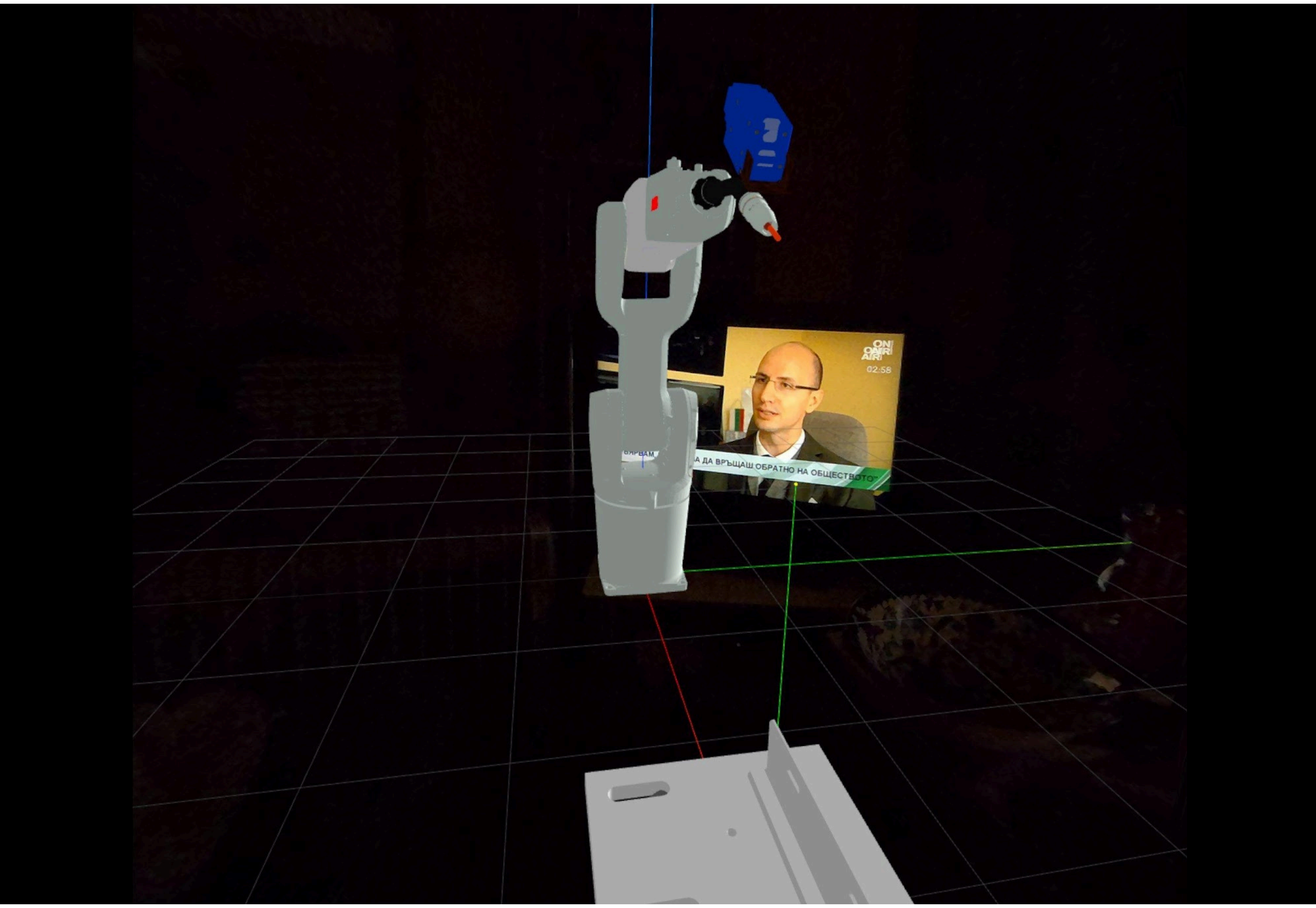

Figure 66: XR Glasses provide visualisation of proposed welding path including seam tracker simulation

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5G EMPOWERMENT

The SBPATH-5G project is a pivotal contribution to the overarching goals of the TARGET-X initiative, which seeks to accelerate the adoption of advanced technologies in industrial sectors across Europe. By integrating cutting-edge technologies such as 5G, augmented reality (AR), and virtual reality (VR) into the robotic welding process, this project not only addresses specific challenges within the manufacturing industry but also aligns with TARGET-X's mission to foster innovation and drive digital transformation in key industrial domains.

One of the most significant achievements of SBPATH-5G is its enhancement of precision in robotic welding operations. Traditionally, welding processes are prone to variability, often requiring manual adjustments and relying on legacy technologies that limit precision. SBPATH-5G overcomes these limitations by utilizing real-time data acquisition and processing capabilities. The system's ability to scan real objects or use CAD models to generate detailed point clouds ensures that welding paths are executed with exceptional accuracy. This precision reduces errors, minimizes material waste, and ultimately contributes to more sustainable manufacturing practices—an objective that is closely aligned with the goals of TARGET-X.

The integration of 5G technology within SBPATH-5G is particularly noteworthy and serves as a cornerstone for the project's success. 5G's high bandwidth and low latency are critical for executing data-intensive tasks such as point cloud processing and maintaining real-time feedback loops. These capabilities enable rapid adjustments during welding path visualization on AR glasses and optimize welding parameters based on real-time data, thereby enhancing the system's responsiveness and efficiency. Furthermore, the use of 5G enhances the scalability of the SBPATH-5G system, allowing it to handle multiple simultaneous operations and connect seamlessly with various devices, which is essential for industrial environments that are increasingly interconnected and reliant on continuous data exchange.

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PROJECT NAME (ACRONYM)	COLLABORATIVE ROBOTICS IN CARBON MANUFACTURING (COROCA)
NAME OF BENEFICIARIES	PUMACY GMBH CONSIDER CARBON GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

The prefabrication of carbon fibre reinforced polymers (CFRP) often involves heavy manual labour in many production areas with small batch sizes. Due to safety requirements, heavy-duty robots can only be used to a very limited extent in this area. The manufacturing company Consider Carbon is supported by technology provider Pumacy in facilitating these physical tasks with human-robot collaboration (HRC) technologies. The TARGET-X CoRoCa demonstration scenario aims to investigate the expansion of robotics applications with 5G communication technology and AI-controlled methods.

To this end, an autonomous, body-near sensor system was deployed at the factory in Tostedt to detect and interpret workers' activities and compare them with the movements of robots and other machines, and to test it in the context of prefabrication CFRP. As part of the project, the specific work step of pick and place of carbon coils weighing up to 200 kg was automated. To extend the communication radius of the HRC application to the entire shopfloor, TARGET-X 5G technology was tested.

The solution should later ensure safe work by anticipating the movements of people and machines and avoiding collisions. This would create a solution that would offer a new level of automation, especially for SME.

ARCHITECTURE

The main goal of the CoRoCa implementation was to utilize and compare the Wi-Fi 6 and 5G network connectivity performance for data transmission, and to analyze the transmission. The transmitted data has been captured during the lab demonstration at the facility of the partner institute BIBA in Bremen.

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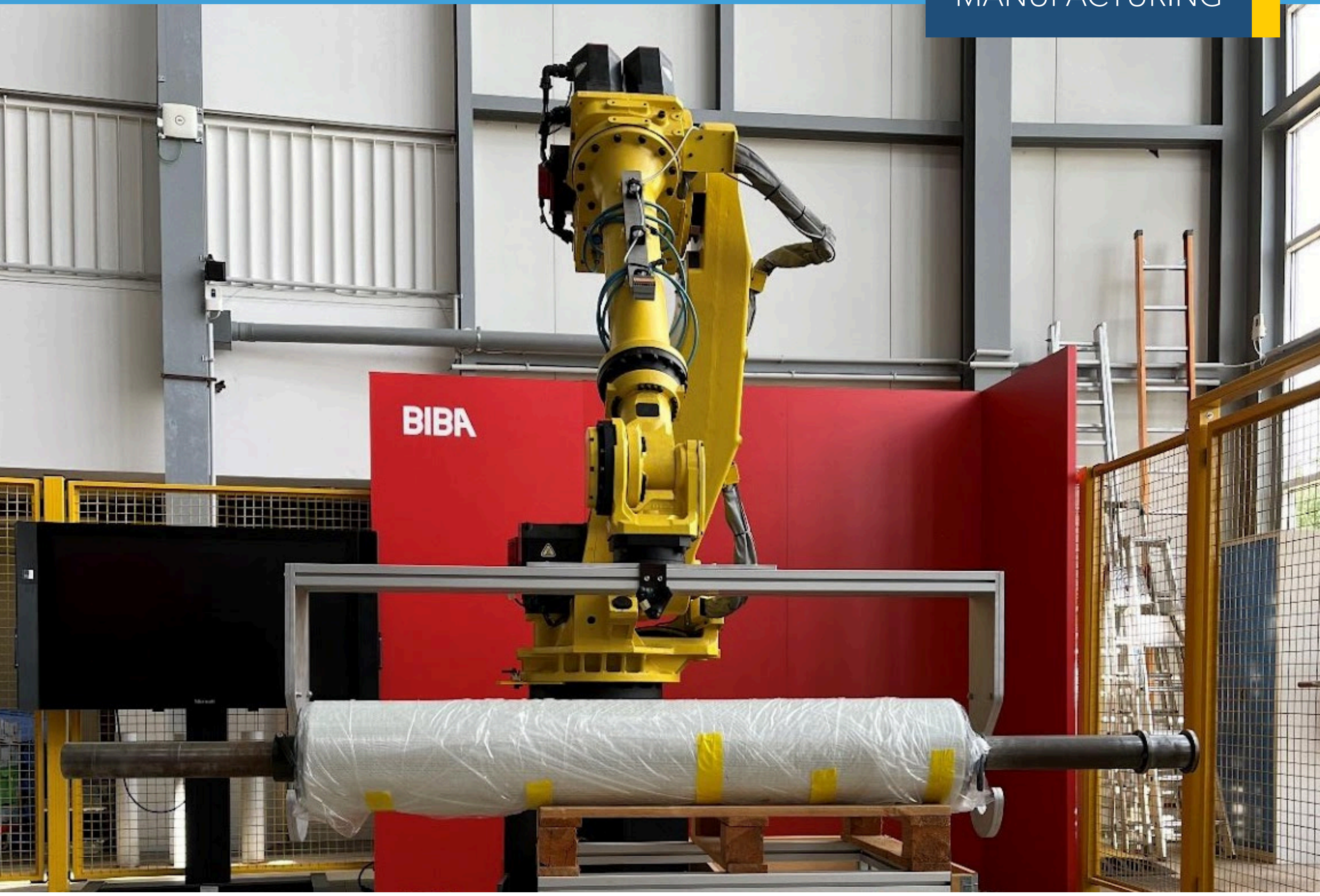

Figure 67.

The captured data consists of the position calibration of the carbon coil to automatically pick up a coil by a robot and place it into an unwinding device. Motion data has been tracked and captured using VIVE IR Trackers and a VIVE SteamVR Base Station. The last part of the implementation work was the deployment of the sensor fusion and process mining framework around the PUMACY-owned search-based application (SBA) platform Plexalytics.

TRIAL

For the setup and test implementation at the WZL RWTH testbed facility in Aachen, the focus has been on testing the connection while repeatedly transmitting the captured data from the coil core position calibration. Data has been recorded in a file-based format.

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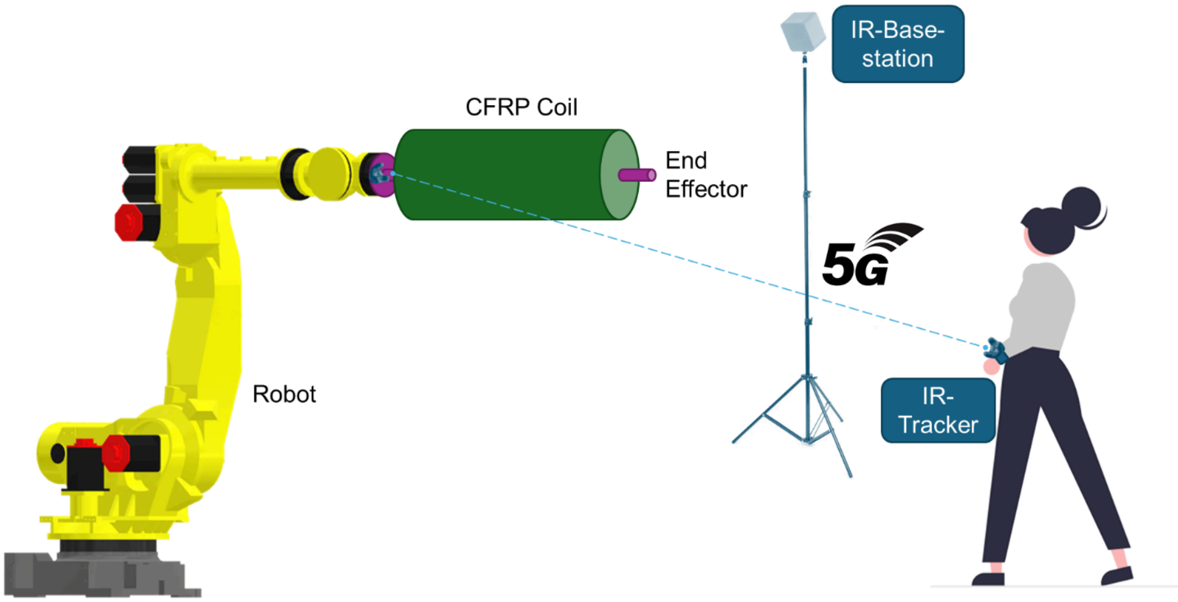

Figure 68.

The connection between the robot and the edge server was established through Zenoh (Zero Overhead Network Protocol). The robot (ROS2 publishing node – talker) repeatedly sent data to the edge server (ROS 2 subscriber node – listener). This setup has been used for both WiFi 6 and 5G test runs.

RESULTS

Four previously defined technical performance indicators (TPI) were fully achieved during the project. The implementation concept (TPI 1) delivered a report and presentation describing the advised deployment. An application framework (TPI 2) stated the HRC design, its architecture, and the integration of the Plexalytics SBA environment. The lab demonstration scenario (TPI 3) showed the setup of a carbon prefabrication HRC scenario. Lastly, the 5G implementation at test site Aachen (TPI 4) demonstrated the integration of the HRC scenario into the 5G/IoT testbed. Overall, the 5G testbeds achieved significantly better results than current WLAN environments in key parameters such as transmission and data loss rates as well as latencies.

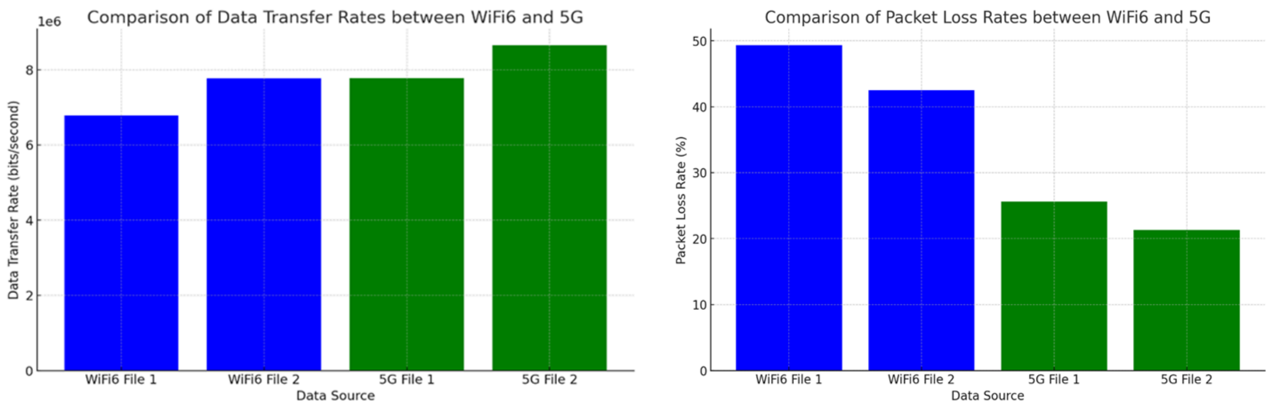

Figure 69.

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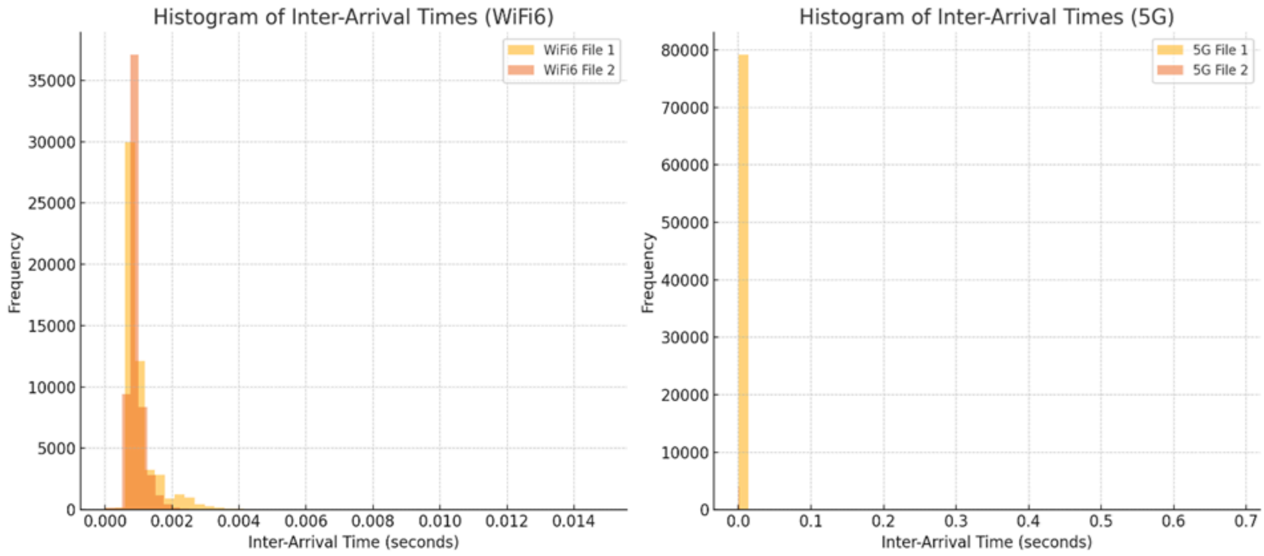

Figure 70.

5G EMPOWERMENT

CoRoCa showed that the tested 5G offers many advantages over the currently used Wi-Fi 6. Particularly in terms of data transfer rates, 5G networks outperformed Wi-Fi 6, demonstrating higher rates suitable for bandwidth-intensive applications. Analysis of inter-arrival times revealed that 5G networks had more consistent and lower times, indicating lower latency and less jitter, essential for real-time applications. Overall, the findings suggest that 5G networks offer better performance, reliability, and suitability for modern, data-intensive, and real-time applications.

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PROJECT NAME (ACRONYM)	BILEN-5G SMART MAINTENANCE PLATFORM FOR FACTORIES (BILEN-5G)
NAME OF BENEFICIARY	THE DATA COOKS BV SKATECHNOLOGIE GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

BILEN-5G aims to optimize predictive maintenance and process health monitoring in high-speed cyclic manufacturing by combining Artificial Intelligence (AI), 5G connectivity, and the Asset Administration Shell (AAS) standard. The project targets real-time quality assurance and adaptive machine control, especially in fast-cycle environments like plastic injection molding. The trial was conducted in July 2024 at the 5G-ICE testbed in Aachen, using a simulated factory setup with Advantech-based edge devices and real machine data streamed through 5G and fiber connections. Real-time cycle data was analyzed by the Process Cycle Analysis Tool (PCAT), an AI model designed to detect anomalies by comparing current cycles with historical and reference data. PCAT outputs were used for closed-loop control, sending stop or continue signals to machines. Major milestones include TPI2 (testbed deployment), TPI3 (AI model integration), and TPI5 (demo with AAS-enabled asset management). Results confirmed 5G's ability to reduce total latency to 276 ms, supporting sub-8-second cycles. Partners: SKA, The Data Cooks. Mentor: Fraunhofer IPT.

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ARCHITECTURE

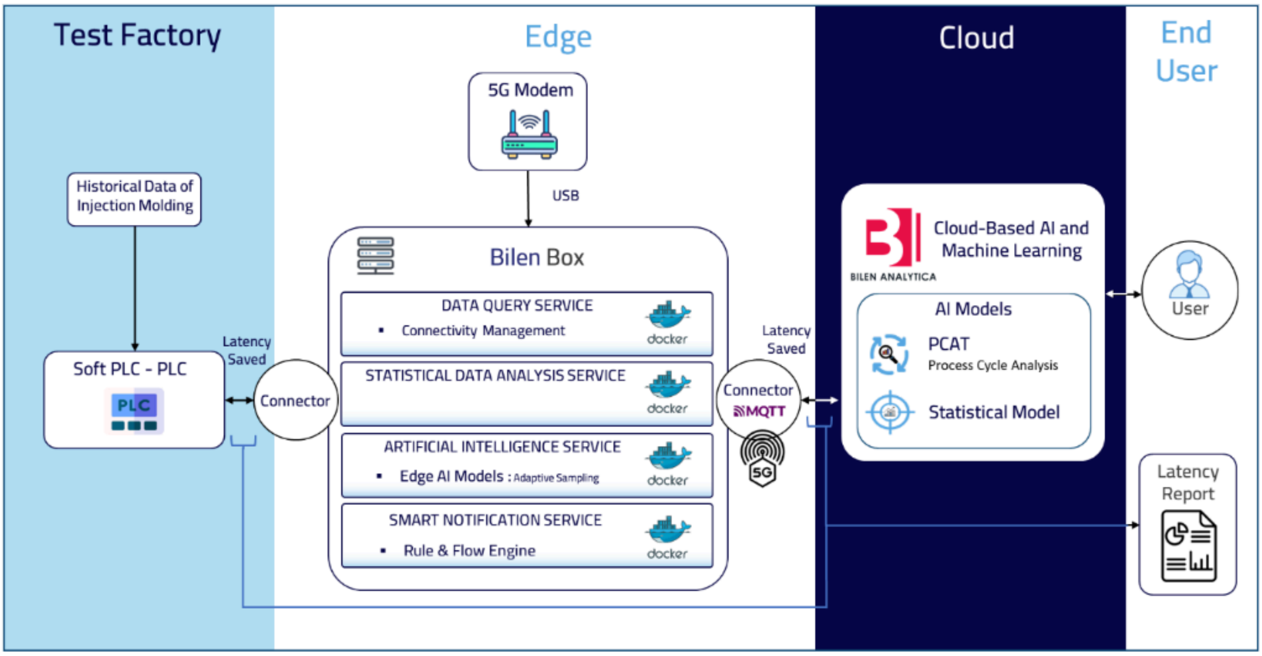

Figure 71: BILEN-5G High Level Architecture

The BILEN-5G system is built on an edge-cloud architecture(Figure 71) that enables real-time, AI-powered decision-making. Data is collected by BilenBox at the edge, where it undergoes preprocessing and initial analysis. It is then sent via 5G or fiber to the cloud-based Bilen Analytica platform. There, AI models, most notably the Process Cycle Analysis Tool (PCAT), analyze cycle-level data to detect deviations and predict quality issues. Results are returned to the edge, where BilenBox forwards adaptive control signals to the machine. The system uses Asset Administration Shell(AAS) standards to support asset interoperability and digital twin functions. This architecture supports low-latency closed-loop control in fast-paced production environments.

TRIAL

The trial (Figure 72) was conducted at the 5G-ICE testbed in Aachen in July 2024. A simulated plastic injection process was deployed using BilenBox and Advantech-based edge devices connected to cloud AI models via 5G and fiber. Latency was measured using timestamps at each system node. Network setups were switched between 3G, fiber, and 5G to evaluate closed-loop responsiveness. Deployment included real hardware, factory simulation, and multi-network scenarios.

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Figure 72: BILEN-5G Trial Day - Deployment View

RESULTS

The trial reduced total latency to 276 ms, enabling real-time control for sub-8s cycles. PCAT and AAS were validated in a live edge-cloud setup. Business KPIs achieved include a projected 20% reduction in downtime, 15% improvement in first-pass yield, and 30% faster anomaly response time. The demonstration (Figure 73) showcased BILEN-5G's capabilities, confirming both the technical feasibility and commercial potential of predictive quality in high-speed manufacturing.

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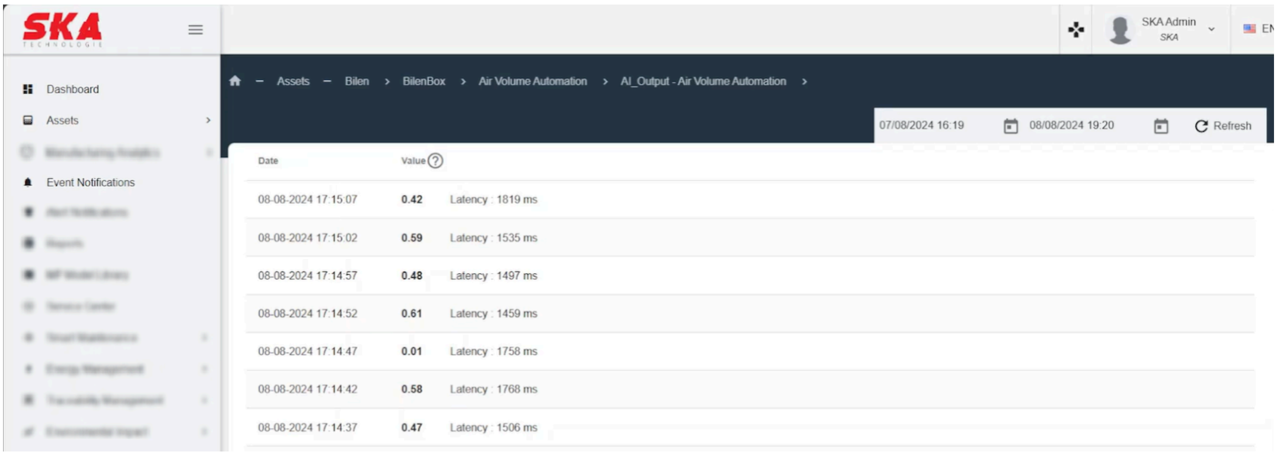

Figure 73: BILEN-5G Result

5G EMPOWERMENT

5G-enabled low-latency, high-bandwidth connectivity is essential for real-time AI-driven decision-making in manufacturing. Unlike 3G or legacy networks, 5G reduced total latency to 276 ms, making closed-loop control feasible for fast-cycle processes. It also supported stable cloud-edge communication, adaptive feedback, and rapid deployment—key for scaling predictive quality and maintenance across factories.

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PROJECT NAME (ACRONYM)	ENERGY MONITORING OF INDUSTRIAL MACHINERY USING 5G (ASTREO-ENERGY-5G)
NAME OF BENEFICIARY	ASTREO S.R.L.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 29/11/2024
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

The overall objective of the project was to develop a 5G-enabled energy sensor for industrial machines, capable of gathering real-time consumption data and sending it using a 5G network, either in a private network or public network configuration. This allowed for real-time measurements and also further deep analysis on machine performance, anomaly detection, and identification of inefficiencies.

As part of the project's development, a pilot deployment was conducted in 2024 at the Fraunhofer IPT premises, one of Europe's leading institutes for manufacturing technology. The trial focused on monitoring a drilling machine, simulating a real-world industrial scenario where energy consumption data had to be gathered, processed, and sent to a cloud platform in real time. The sensor system was integrated into the site's existing monitoring infrastructure, utilizing the 5G connectivity to transmit data with ultra-low latencies. This data was then readily available for further analysis and efficiency optimization.

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ARCHITECTURE

The project's architecture guarantees high-accuracy energy sensing and efficient data processing in real time. It aligns with the defined goals and exploits the 5G communication for fast and reliable data transmission. The 5G-enabled sensor was developed so that it is compatible with both a private and a public 5G network, depending on the use case and real-world scenario.

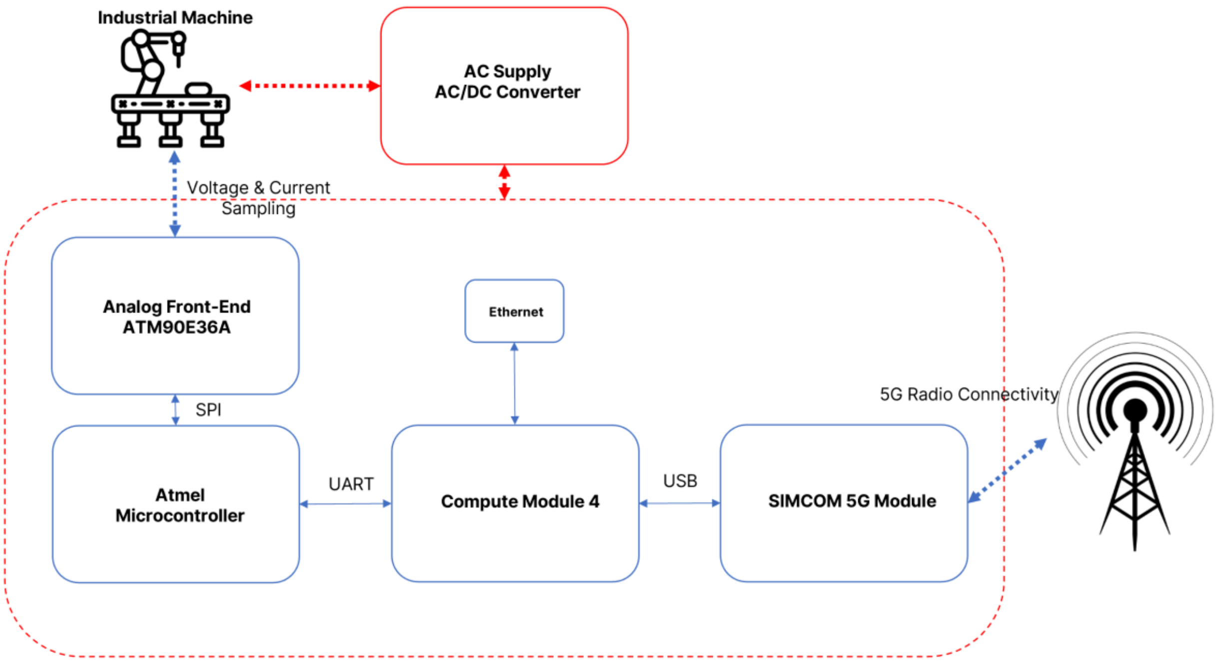

Figure 74.

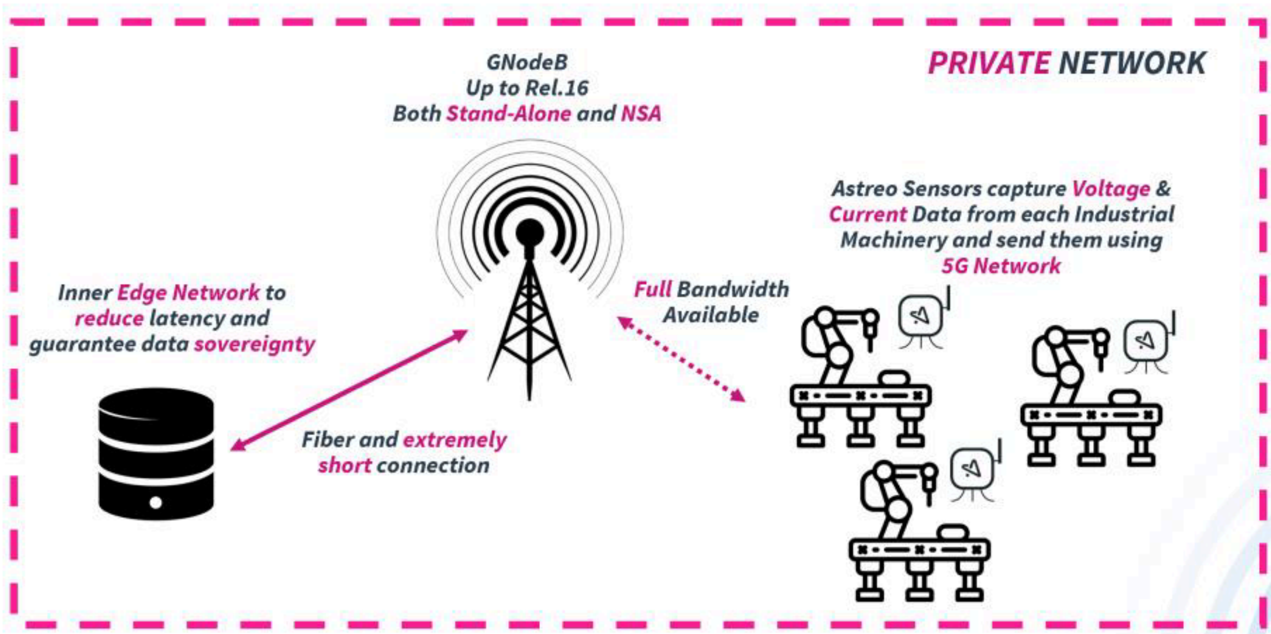

Figure 75.

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TRIAL

The trial took place at Fraunhofer's facility, where we measured the real-time electricity use of several industrial machines and sent the data to a cloud platform for viewing and analysis. For these types of machines, installation is simple. The system is plug-and-play and starts collecting and sending data immediately. Within just a few weeks, the smart algorithms can identify the machines' operating patterns and suggest ways to improve efficiency by removing waste and inefficiencies.

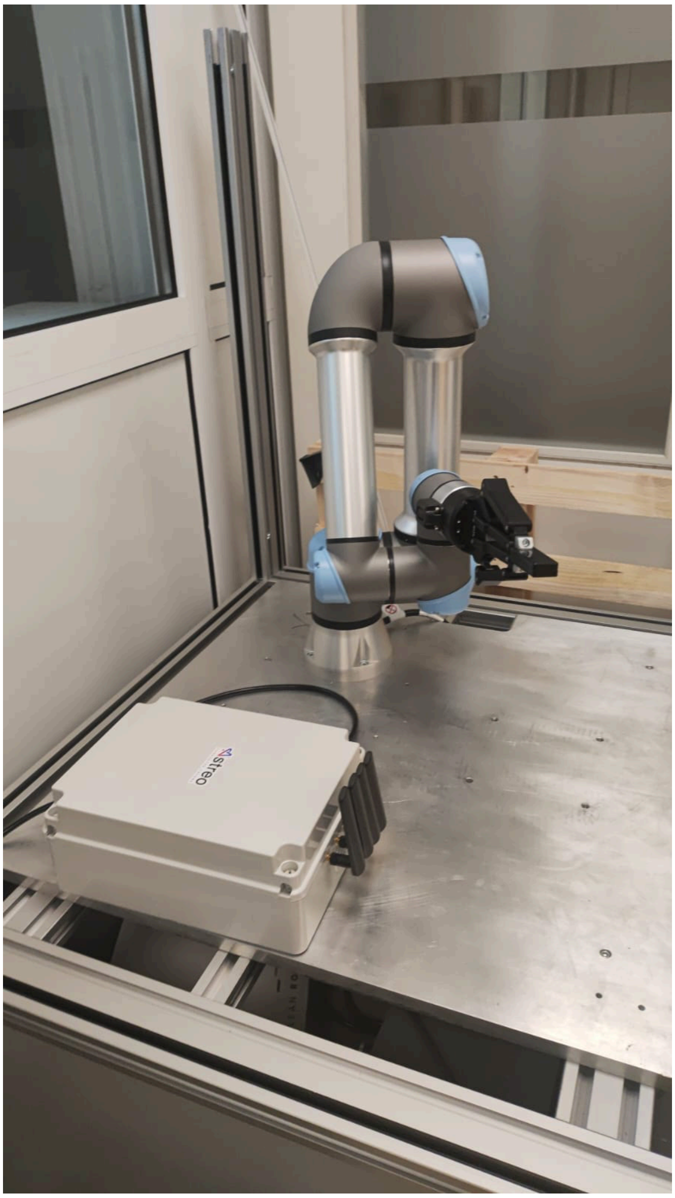

Figure 76: System deployment at Fraunhofer IPT premises.

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RESULTS

The system's ability to gather, process, and transmit energy data in real-time solves critical needs in industrial monitoring. The pilot deployment validated the system's operational reliability, demonstrating accurate energy measurements and consistent data transmission under real-world conditions. The system has shown promising results by adding data analysis, where we identify working states of each machine, we can identify inefficiencies and suggest how to optimize, reaching a potential 10% energy consumption optimization.

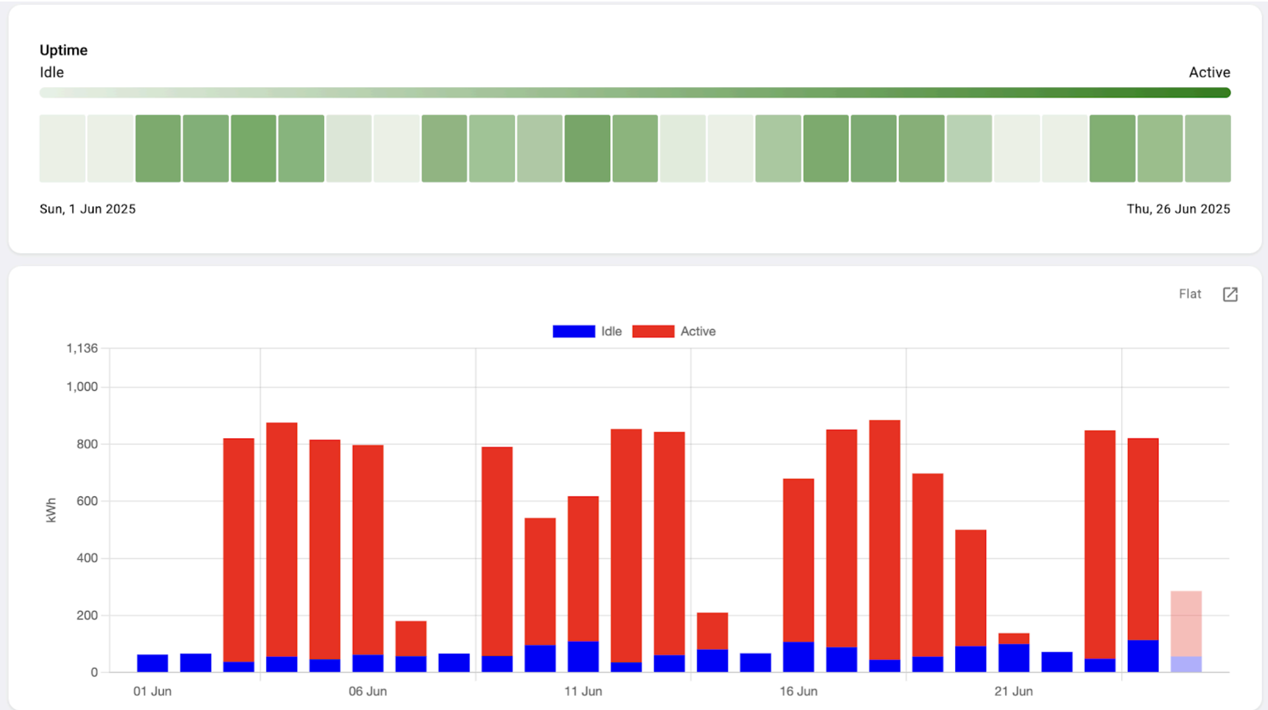

Figure 77: Energy data of and industrial machine and analysis where working state is identified.

5G EMPOWERMENT

Designing a system with performance similar to wired technologies, especially in terms of low latency, is a game-changer for real-time applications in industrial settings, particularly where complex infrastructure is a challenge. Solutions like this, which offer clear cost-saving benefits, can significantly shorten the ROI by up to 2x, compared to what was previously expected for such advanced technologies. This is made possible by the strong capabilities that 5G brings to industrial environments.

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PROJECT NAME (ACRONYM)	BENCHMARK MEASUREMENTS FOR VERTICAL (5G-BENCHMOTIV)
NAME OF BENEFICIARY	FERON TECHNOLOGIES
DATES OF THE SUPPORT PROGRAMME	TARGET-X 1st Open Call 13/02/2024 - 13/09/2024
LIST OF INVOLVED PARTNERS	EDD

OVERVIEW

5G verticals impose competing QoS requirements in coexisting configurations. Moreover, there is a lack of open benchmarking and monitoring tools spanning from radio access, through the network, to the application. Existing solutions are generally not portable or application/network/hardware-specific.

5G-BenchMotiv is a prototype measurement tool combining a portable unit (Golden Unit) and agile SW, allowing for controlled, active/passive tests from the Golden Unit to a varying network depth, benchmarking 5G performance:

- It provides an open-source toolbox for network benchmarking and various 5G traffic profiles.
- It is a low-cost and agile solution that is able to cope with an extended list of KPIs.
- It incorporates on-demand applications and traffic profiles in the benchmarking measurements, potentially interfacing with industry automation protocol data.
- It offers an automated processing stream for (re-) configuring the monitored data plane of network assets.
- It sets the baseline for network/slice performance.

Our project is classified under Technology Evolution beyond 5G. Tests were performed (July 2024) in cooperation with Ericsson and Fraunhofer to validate the toolbox by assessing the private 5G network at Fraunhofer facilities in Aachen.

ARCHITECTURE

5G-BenchMotiv defines a client-server network benchmarking architecture for various paths and protocols, spanning from the user to edge and backend services.

It implements a dual-agent measurement scheme: the HW prototype (“golden unit”), a computing unit with multiple radio interfaces and comprehensive network analysis software; and the SW agent serving as a vantage or end point for benchmarking, comparative analysis, and bottleneck detection.

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It evaluates TCP/UDP and application-specific profiles (HTTP, FTP, VoD, industrial automation), extracting KPIs including throughput, latency, packet losses, jitter, retransmissions, and radio metrics.

It automates orchestration, collection, processing, and visualization, and provides both API and GUI for configuration.

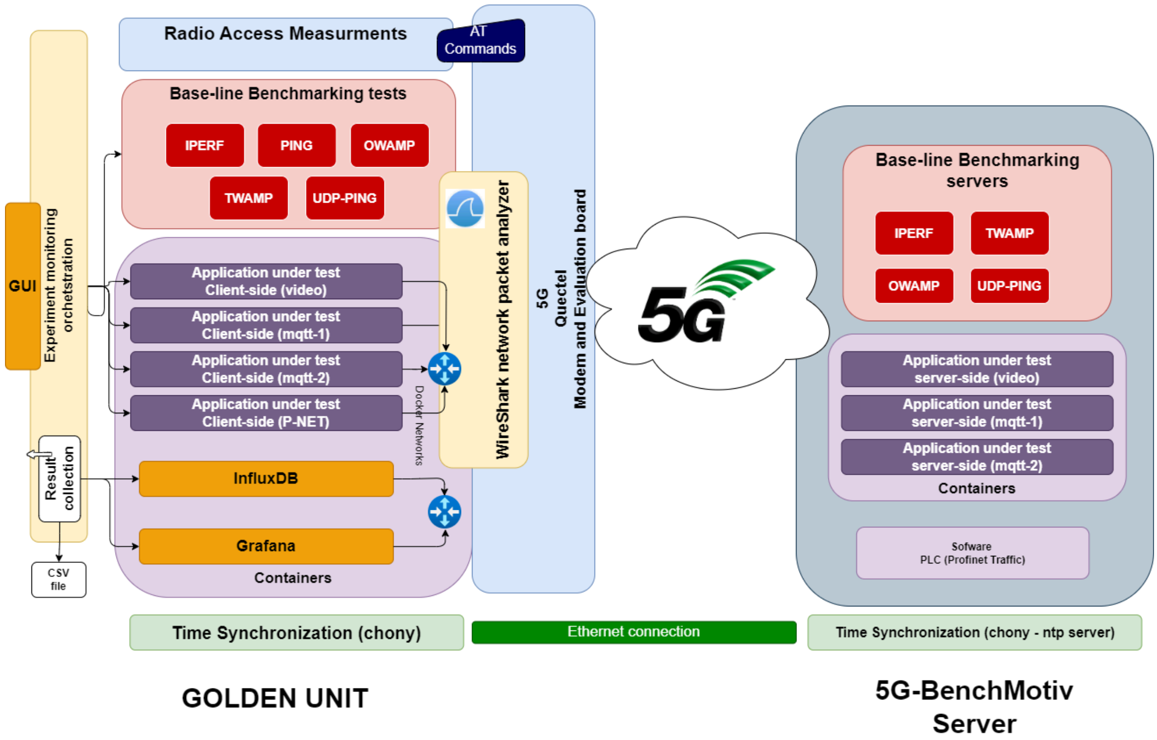

Figure 78: System deployment at Fraunhofer IPT premises.

TRIAL

Measurements were performed in Fraunhofer IPT and Ericsson facilities, benchmarking the deployed networks. Performance was assessed in the radio, network, and application levels.
Various traffic profiles were tested, and emulation of industrial automation traffic (PROFINET over 5G) was performed. Active and passive test cases through a configurable dashboard for NSA, SA, FR1, and FR2 setups were executed. KPIs included throughput, jitter, 1-way/2-way delays, packet errors, radio KPIs and more.

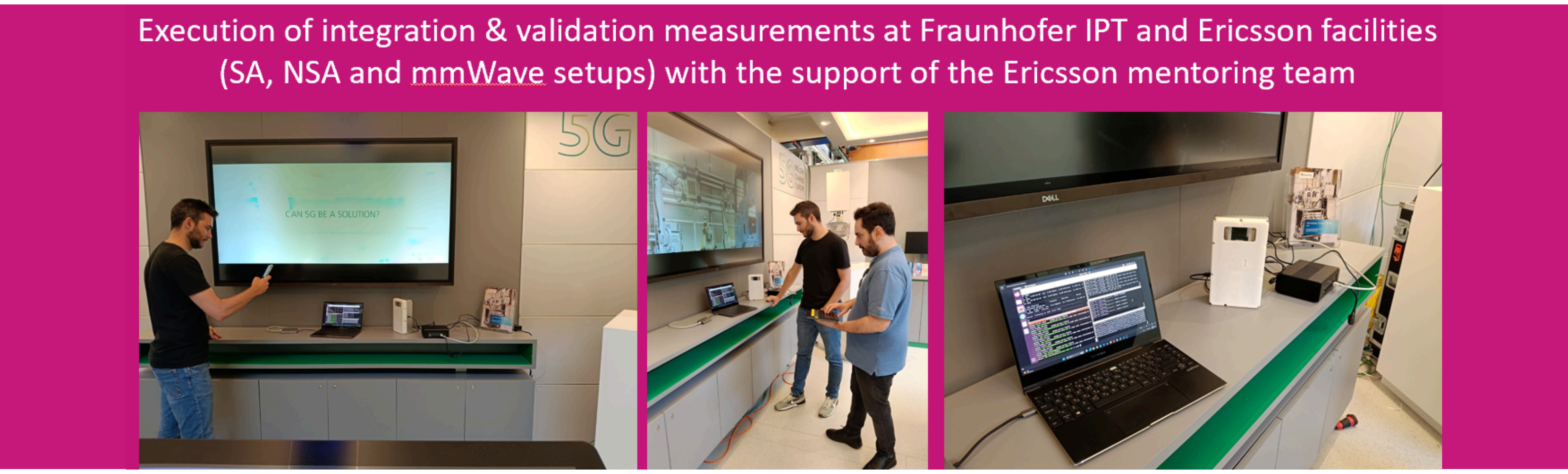

Figure 79: System deployment at Fraunhofer IPT premises.

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RESULTS

5G-BenchMotiv is an open tool available at github.com/feron-tech/5G-BenchMotiv

Benchmarking is possible at the radio, network, and application levels, where the performance of each application or protocol can be evaluated separately or jointly to assess performance under real-world conditions.

Measurements were performed at Fraunhofer IPT & Ericsson research networks – supporting 5G-SA, 5G-NSA, and mmWave (FR2) deployments.

The tool is modular, extendible, and new applications can be integrated seamlessly.

Figure 80: System deployment at Fraunhofer IPT premises.

5G EMPOWERMENT

5G verticals impose competing QoS network requirements in coexisting configurations. Moreover, attention should be given to time-critical services, including industry automation. Beyond 5G networks, through intelligent reconfigurability and slicing, can adjust to the requirements. However, performance assessment through network KPIs for users to troubleshoot 5G networks & detect capabilities for given network configurations is necessary – and 5G-Benchmotiv is here to help.

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PROJECT NAME (ACRONYM)	5G TRACKING OF A CIRCULAR FACADE ELEMENT (5CADE)
NAME OF BENEFICIARIES	TECHNISCHE UNIVERSITÄT DRESDEN MEDICKE GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-IP, CCR

OVERVIEW

The project progressed from concept to realization in two key phases. Following the research, a conceptual design for a facade greening system was developed as the first key phase, with a circular design that includes material selection and construction methods in line with the principles of a circular economy. As the circularity of the facade element was a particular focus, the project team developed linear planters with a Low-Tech maintenance approach, which was designed with reuse, disassembly, and material recovery in mind. The other key innovation was the incorporation of 5G sensor technology into the facade element, or more specifically, into the water reservoir and the substrate of the planters. A 5G technology setting was conducted in Chemnitz in February 2025 in collaboration with the subcontractor temides GmbH, before its integration into the prototype of the planters. In collaboration with Wirth & Wiener GmbH, a further trial run was performed in April and May 2025 to establish the substrate and the long-term fertiliser according to the selected plants. The final trial run is the construction of twelve prototype planters with four different plants, which are tested in Aachen on the demonstrator facade since June 2025.

ARCHITECTURE

The project focused primarily on the design of a circular facade element and the integration of 5G-capable sensors. In the conceptualisation phase of the project, the project team swiftly opted for a wall-based, linear facade greening system. In line with the concept of circularity, which encompasses more than the selection of materials and their connection in relation to one another, the team developed a planter system that employs a low-tech and low-maintenance approach. Therefore, the irrigation functions through gravity. The water is led along the facade up to the upper planters, and from there, it flows into the water reservoir of each planter. It then continues, through a controlled manner, into the planter below. Maintenance of the planter will be facilitated by its installation in front of a movable module.

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This module can be opened from within the building in a manner comparable to opening a window. In case of plant failure or if the plants require additional care, each planter is accessible from the inside and can be removed. In accordance with the principles of circular construction, the circular planter will be constructed using recycled cold-drawn aluminium instead of virgin bent aluminium profiles. Additionally, the end will not be welded on but instead screwed on via integrated screw channels. This makes the circular planter fully dismantlable. The use of secondary materials and detachable connections, in combination with the 5G sensors, is a key factor for considerable resource savings. The 5G sensors are used to measure the water level in the reservoir. This information is then used to trigger the automated irrigation system to operate at pre-determined watering intervals. Additionally, the 5G-capable sensor measures the substrate moisture to provide preliminary indicators of the plants' vitality.

TRIAL

Medicke GmbH constructed the waterproof aluminium box for the sensor technology and tested it with Temides GmbH on the prototypes of the planter.

Figure 81.

Wirth & Wiener GmbH conducted the first tests on the substrate using plants from last year
Twelve prototype planters vegetated with Vinca Minor, Epimedium, Luzula, and Asplenium were installed in Aachen.

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Figure 82.

RESULTS

Please find below the design of the prototype and the circular planter. The prototype demonstrates the irrigation system's function and establishes the foundation for the development of the circular planter. Sensors accurately measure the moisture content of the substrate and provide readings of the water level in the reservoir. The system can be monitored efficiently in real-time.

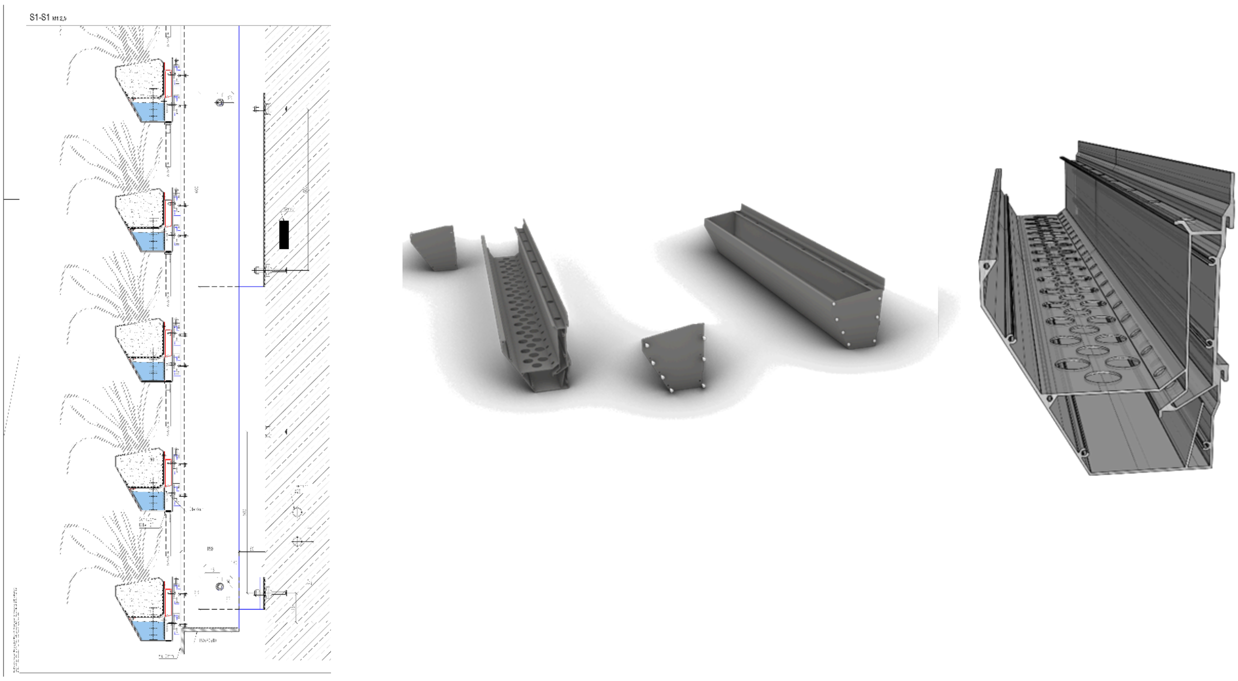

Figure 83: Design of the prototype planter, drawn for the installation in Aachen

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5G EMPOWERMENT

For the 5G technology within a greening system, wide area coverage and a stable wireless connection are essential in order for the irrigation to work properly at any time.

In addition, the scalability of the network infrastructure is crucial to ensure seamless integration of a high number of sensors across different buildings and locations.

Equally important is secure and energy-efficient data transmission of high-quality data, allowing for long-term, low-maintenance operation of moisture and temperature sensors as well as real-time visual monitoring by integrating a camera module.

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PROJECT NAME (ACRONYM)	MEASURING COEXISTING APPLICATIONS IN 5G (MEASURE-X)
NAME OF BENEFICIARY	UNIVERSITY OF PISA
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	EDD

OVERVIEW

Measure-X is a tool designed for network measurement in 5G environments. It collects classical metrics, such as throughput and latency, while also supporting more advanced indicators like Age of Information (AoI) and energy consumption. AoI is an end-to-end metric that reflects the freshness of received data, making it especially important in scenarios where timely information delivery is critical. Measuring energy consumption is also highly relevant in 5G use cases, as many devices are battery-powered and cellular communication can be a major energy drain. In addition to monitoring these metrics, Measure-X nodes can generate controlled background traffic, enabling researchers to evaluate how a coexisting application affects network performance and energy use. This makes Measure-X particularly useful for realistic, scenario-based evaluations of emerging 5G and IoT deployments. Measure-X was used in an experimental campaign, carried out at the Fraunhofer Institute for Production Technology at the beginning of April 2025, to estimate the impact of a coexisting application on energy consumption and AoI, and to find the message rate that provides the best AoI. Measure-X nodes are based on commonly available hardware, and the code is available according to an open-source license.

ARCHITECTURE

Measure-X features an architecture composed of multiple probes, a coordinator, and an MQTT broker (Figure 84). Probes are responsible for executing measurements such as throughput, latency, energy consumption, and AoI. They can also emulate coexisting applications by generating background traffic. The coordinator receives experiment configurations through a REST API, converts them into specific commands, dispatches them via MQTT, and stores measurement results in a database. Each probe runs modular software capable of handling commands and executing the related measurements. MQTT topics are used for communication between coordinator and probes, including commands, statuses, results, and errors.

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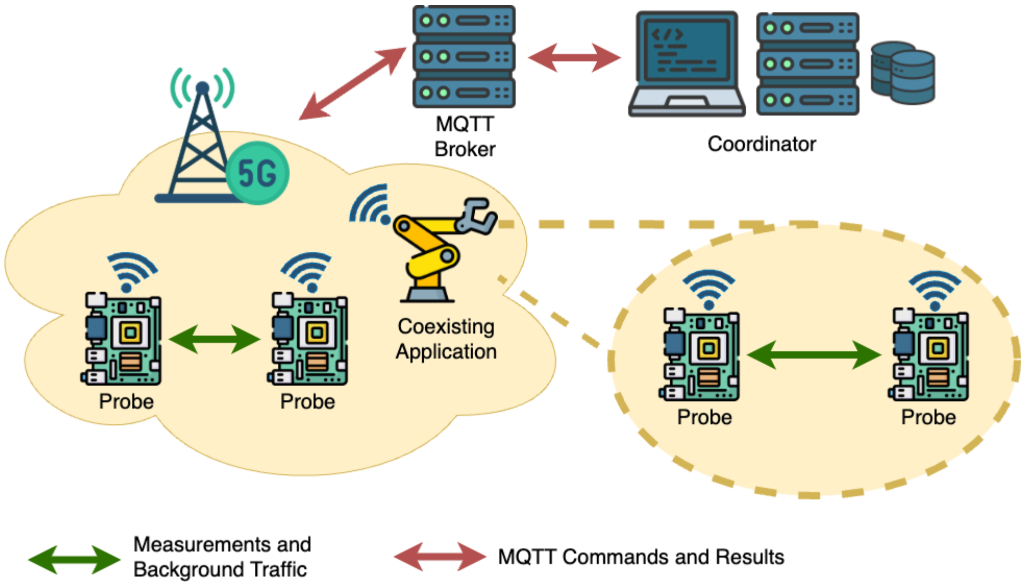

Figure 84: Measure-X architecture.

We run our experiments at the Fraunhofer Institute for Production Technology. We used some probes to collect the main network metrics, the Age of Information, and the energy consumption due to communication. Other probes were used to inject the background traffic of the coexisting application, to evaluate its impact on the metrics of interest. One of the probes used during the trials is depicted in Figure 85. Probes are made of a Raspberry Pi 5, with a HAT hosting the 5G module.

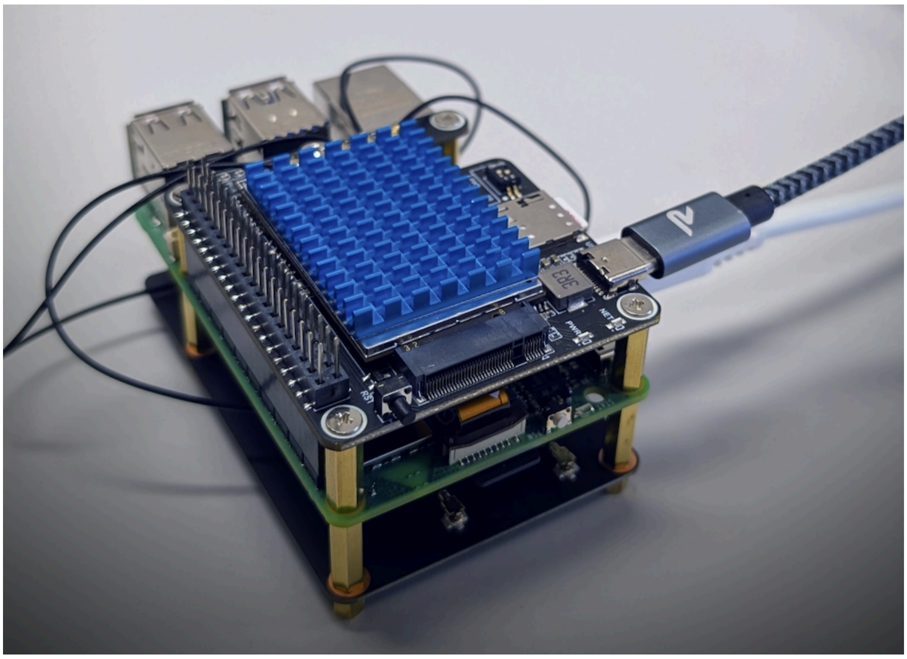

Figure 85: a Measure-X probe.

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RESULTS

We experimentally evaluated the AoI when using different message rates to find its optimal value (Figure 3). For the considered application, increasing the rate above 1000 msg/s does not provide any benefits in terms of AoI, while additional energy is needed. We also measured the impact of a coexisting application on the energy consumption (Figure 4). For the considered operational parameters, the impact was in the order of 2-3%.

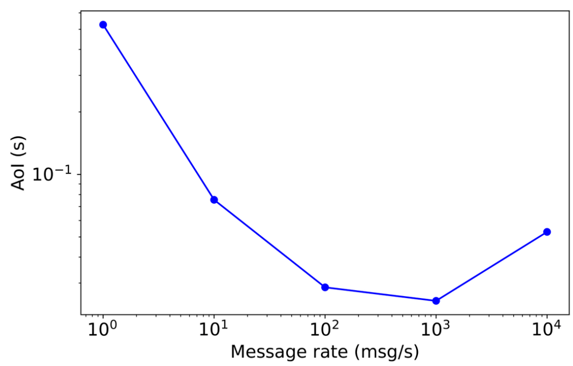

Figure 86: AoI when varying the message rate.

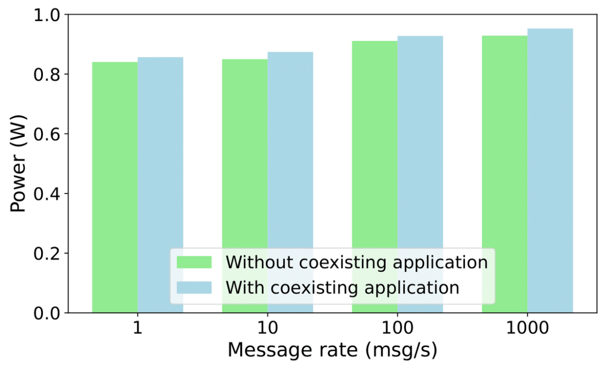

Figure 87: energy consumption when varying the message rate.

5G EMPOWERMENT

To fully exploit 5G-and-beyond technologies, evaluating the network performance of a deployment is a necessary step. If the scenario is related to the Internet of Things, collecting additional information about the energy consumption and the freshness of information of possibly different communication schemes is essential. Measure-X allows network engineers and developers to easily obtain such information, also in the presence of a coexisting application.

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PROJECT NAME (ACRONYM)	MOBILE AUTONOMOUS ROBOTIC SCANNING (MARS)
NAME OF BENEFICIARIES	CABOTO SRL EXWAYZ SAS
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

The MARS project aims to address the growing need for mobile 3D mapping solutions across sectors such as construction (site digitization and BIM) or manufacturing (industrial object inspection). These industries increasingly require accurate digital twins of large environments. Traditional static scanning systems struggle to meet these needs efficiently. This technology could also have applications in the preservation of historical heritage through digital twins.

MARS proposes a robot-based system capable of autonomous navigation and high-resolution scanning of defined Regions of Interest (ROIs). The robot operates fully at the edge and transmits processed data over a 5G network to a remote server for visualization and further processing. Thus, it eliminates the need for on-site infrastructure.

A key milestone was the successful pilot in April 2025, in Turino, Italy: the quadruped robot demonstrated end-to-end scanning of a large object. This validated the technical integration by producing dense point clouds of the ROI, which were viewable on a remote server a few seconds after data capture.

The project showcases a promising demonstration for scalable deployments of autonomous 3D reconstruction systems.

ARCHITECTURE

The MARS architecture combines an autonomous quadruped robot equipped with a LiDAR on a robotic arm, onboard computing for navigation (SLAM and path planning), and point cloud processing, as well as a 5G modem for communication.
All mapping and localization are performed at the edge.

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Once the ROI is scanned, the processed 3D point cloud is sent asynchronously to a remote server via 5G. The server handles post-processing and integration with external tools (e.g., CAD or BIM systems). It is also accessible to a remote client for visualization.

This architecture ensures infrastructure-light deployment through 5G, and it is also very scalable with its edge autonomy.

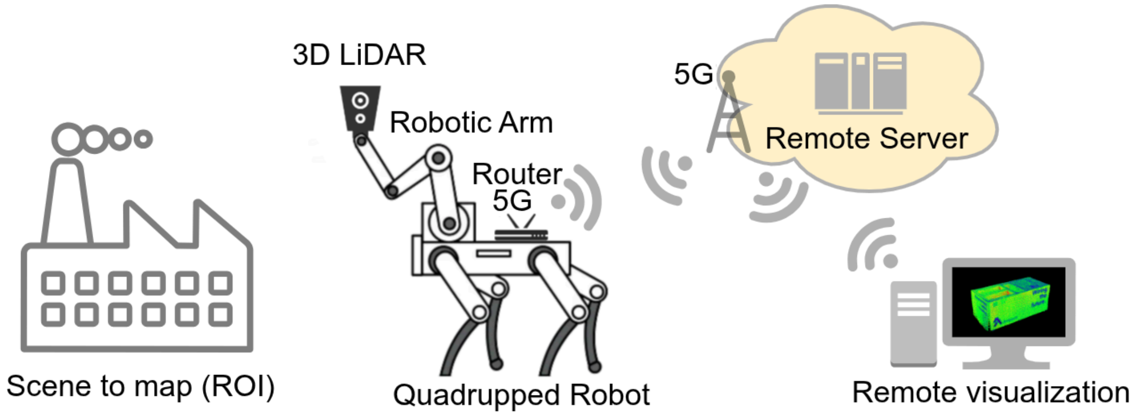

Figure 88: MARS schematic architecture of the robot, remote server and remote client

TRIAL

The trial was conducted at the Caboto's Headquarters in Turin. We deployed our quadruped robot equipped with a LiDAR scanner and 5G modem. It navigated autonomously from its base station to the defined ROI, then drove around the ROI while capturing a 3D point cloud of the desk placed in the ROI. It punctually extended its arm to change view heights. Once the capture is completed, one performs a dense map object reconstruction and sends it over 5G to a remote server for post-processing or visualization.

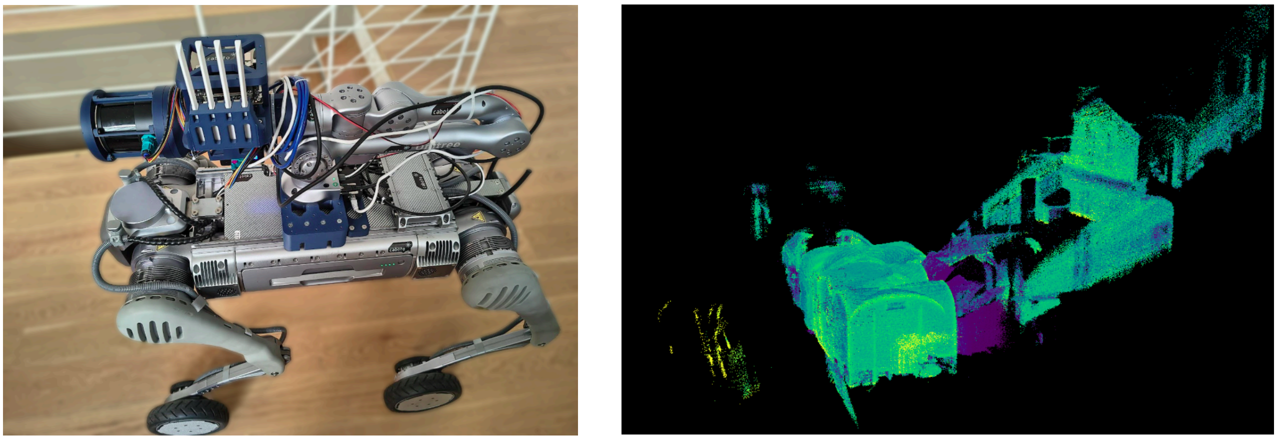

Figure 89: left - robot fully equipped (arm, lidar, mini-computer, 5G Modem); right: map of the full scene

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RESULTS

The MARS project demonstrated autonomous 3D scanning with a quadruped robot using edge SLAM and 5G communication.
Key outcomes include: an accurate ROI scanning (<10 cm of drift error), a precise reconstructed point cloud (with a standard deviation of 1.1 cm compared to a CAD model), the ability to produce full on-edge processing on a low consumption board (10 Watts), and reliable point cloud transmission to the remote server.

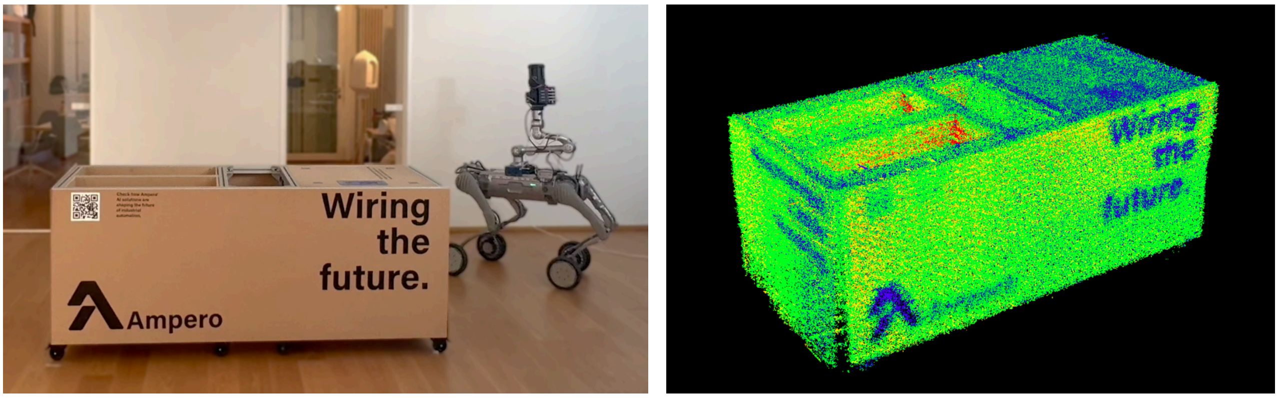

Figure 90: left - robot scanning the desk in the ROI; right: The reconstructed map of the desk

5G EMPOWERMENT

5G provides low-latency, high-bandwidth, and wide-area coverage, enabling real-time data transfer from mobile robots without additional infrastructure.

Unlike previous generations, 5G supports reliable edge-cloud communication, essential for high-resolution 3D mapping and remote visualization. This allows scalable deployments in large, complex environments with minimal setup.

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PROJECT NAME (ACRONYM)	INDOOR 5G SIGNAL MAPPING AND VISUALIZATION (INSIGHT5G)
NAME OF BENEFICIARY	FLANDERS MAKE VZW
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	EDD

OVERVIEW

The INSIGHT5G project has developed a novel tool to measure the quality of signal (QoS), such as signal strength, of a private 5G network, leveraging smartphone sensors and using localization methods such as ultra-wide band or Bluetooth. An Android application has been developed in which users can set up and perform the measurements, interactively visualize the results, and create a map of their environment - all within a smartphone.

It has been tested twice at the FSTP testbed from WZL RWTH in Aachen in April, with successful results. The project brings alternative ways to address 5G performance in industrial environments with minimal technical knowledge required, which offers opportunities for network adjustments and layout improvements for processes or infrastructure that rely on 5G QoS.

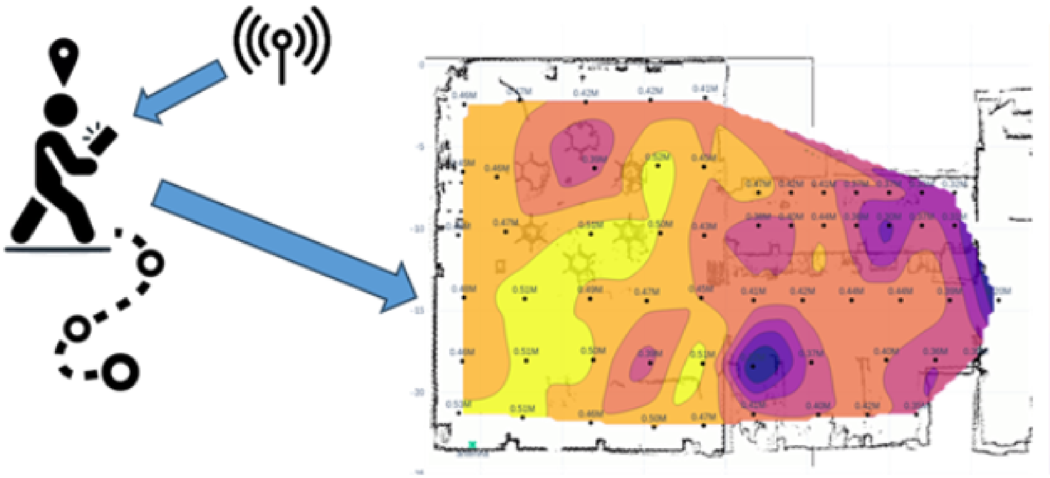

Figure 91: Overview of the INSIGHT5G project results

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ARCHITECTURE

The setup comprises three main elements: an Android app, a localization system (Bluetooth or ultra-wide band (UWB)), and an InfluxDB database storing the results. All of them should be connected to the same network (which can be the 5G one being evaluated) to share data.

The localization systems use tags that should be attached to the smartphone to provide the (x, y) coordinates when taking the measurements, which are sent via MQTT. The InfluxDB database is stored in a server or edge device and is accessed both when storing data while taking measurements and when accessing data for visualization.

The Android app provides a means to trigger the tests to gather the data and a screen to visualize results. It also offers options to configure the tests, the connection with the other two elements, and to create a map of the environment using the camera of the smartphone.

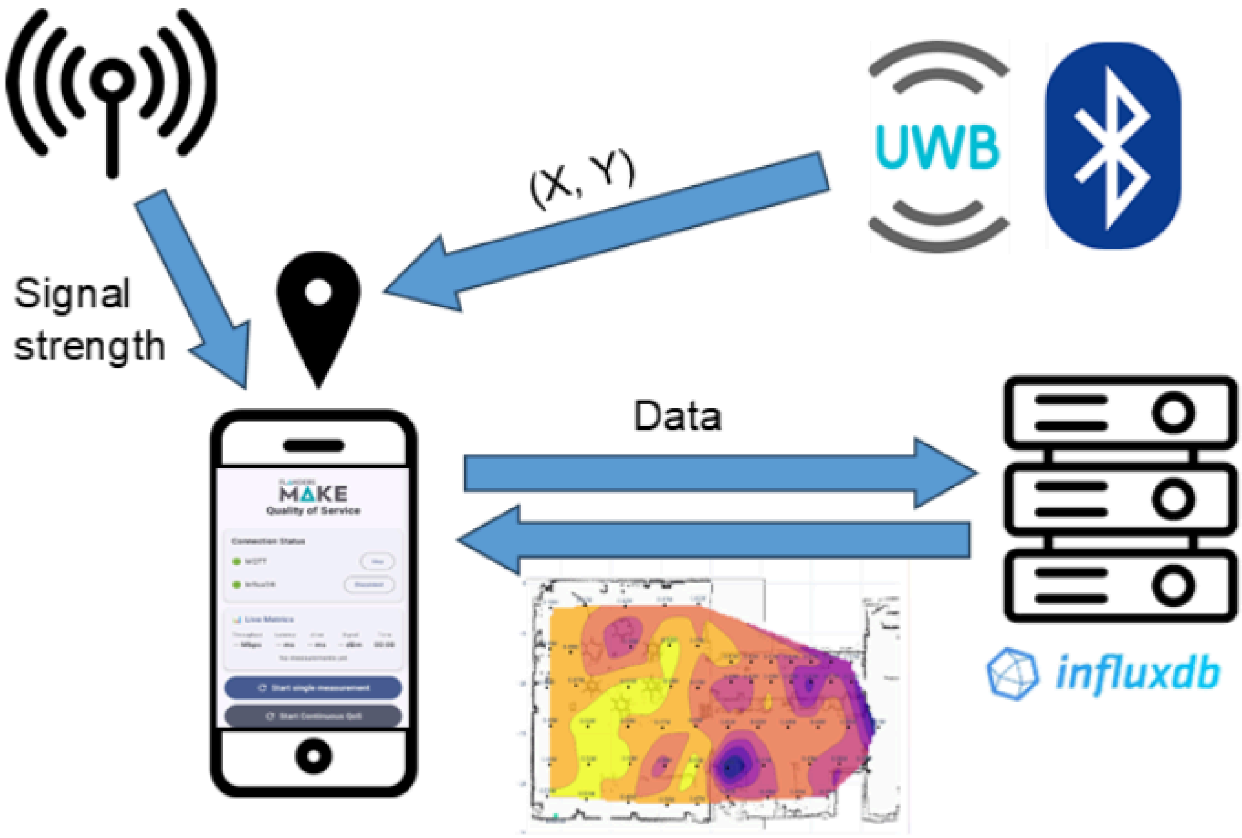

Figure 92: INSIGHT5G QoS measurement tool architecture overview.

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TRIAL

The tool developed was tested at the factory floor at WZL RWTH Aachen and at Flanders Make's offices in Kortrijk; both have a private 5G network. Both localization systems, UWB and Bluetooth, were tested separately, covering around 30m2 each. The InfluxDB database was on a server in a location, and we used a Huawei 5G portable router to connect the smartphone to the localization systems and the database. Throughput, packet loss, delay, and jitter were measured from the 5G networks and then showcased as heatmaps.

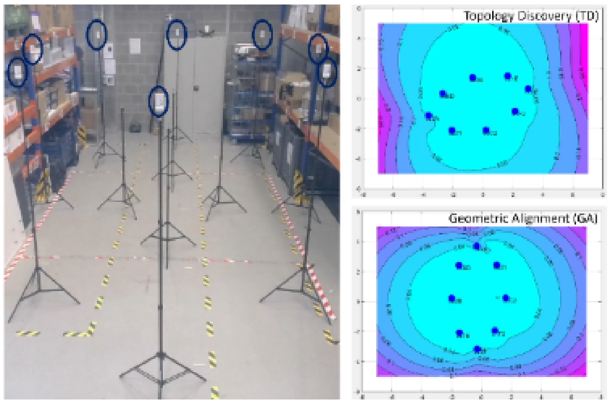


Figure 93: UWB setup and coverage

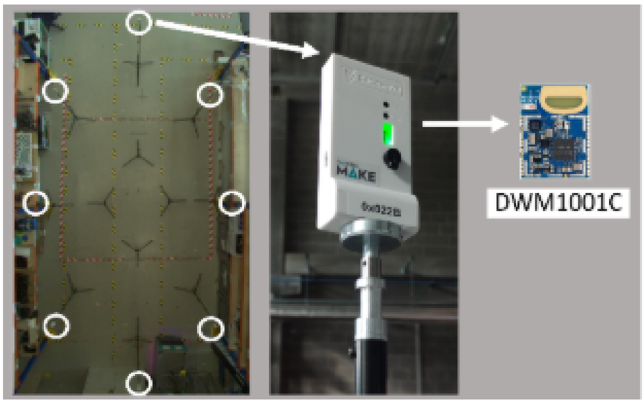
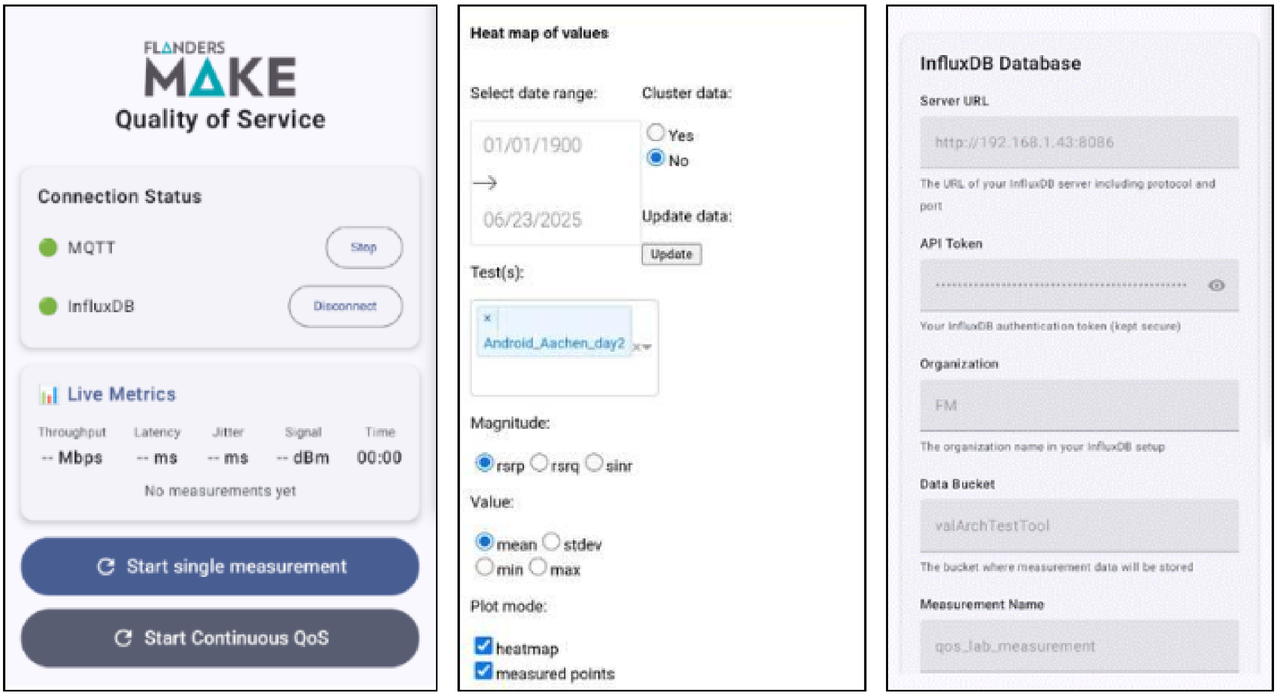


Figure 94: UWB anchor tags



Figures 95, 96, 97 Android app developed test.

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RESULTS

The project developed a smartphone app to measure the QoS of a private 5G network, along with integration of supporting technologies such as localization, connection to a (remote) database, and visualization. It offers an affordable alternative suited for less technical users to set up, execute, monitor tests, and visualize their results.

The novelty resides in the integration within a smartphone, a ubiquitous tool, to increase the accessibility of such a service. Alternatives rely on dedicated equipment, extensive testing, and technical knowledge to produce results.

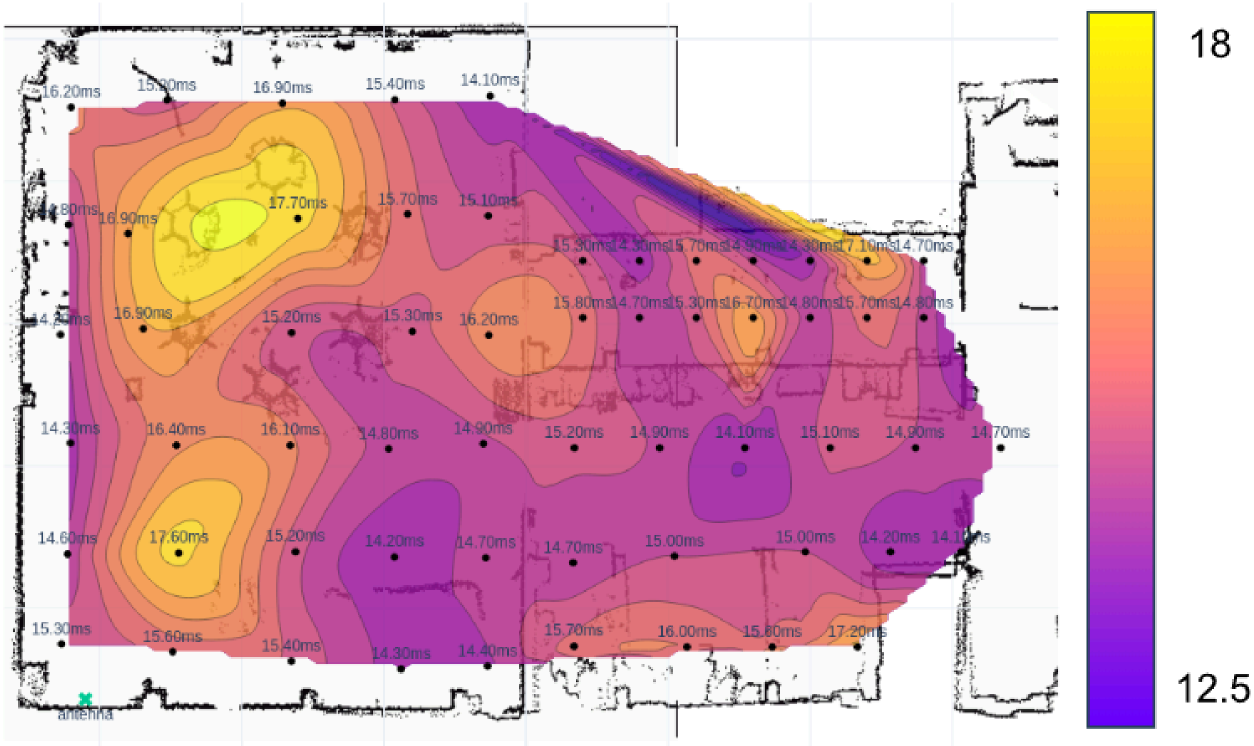

Figure 98: Example QoS heatmap. Delay of a private 5G network, in ms

5G EMPOWERMENT

5G brings increased coverage, reliability, and throughput, which pose significant benefits for a vast number of industrial applications. Moreover, thanks to Open RAN, it is now possible to design and deploy small-scale private cellular networks that support robust, high-bandwidth communication in local areas. This brings significant benefits for industry, since this is something not feasible with the traditional, closed RAN architecture used in previous generations (LTE/4G, 3G). In this case, our developed tool can help 5G adopters optimize their setup for their use cases.

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PROJECT NAME (ACRONYM)	5G SECURE AUTHENTICATION FOR INDUSTRIAL IOT (5G-SAIIOT)
NAME OF BENEFICIARIES	I46 S.R.O INSTITUT MIKROELEKTRONICKÝCH APLIKACÍ S.R.O.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

The 5G-SAIIoT project, co-funded by the European Union under the TARGET-X initiative, addresses pressing challenges in cybersecurity, interoperability, and scalability within IIoT environments. Its primary objective is to deliver a future-proof, quantum-resistant solution focused on secure device-to-device, device-to-cloud, and proximity-based authentication.

Key partners involved in the project include i46 s.r.o. and IMA s.r.o. Trial and pilot use cases have been implemented at the Fraunhofer facility in Aachen and at Witte Automotive, a leading supplier of mechatronic locking systems. A significant trial commenced at the Fraunhofer facility in Aachen on February 10, 2025, specifically for 5G Standalone (5GSA) integration. Demonstrations of the authentication system are also planned for the Witte pilot and the Aachen pilot.

A major achievement is the successful development of innovative solutions for securing IoT and 5G systems. This includes the integration of a test environment with the 5G Standalone core network, enabling robust testing of 5G-specific authentication mechanisms and demonstrating seamless IoT device communication over 5G.

ARCHITECTURE

Distinct from standard 5G protocols that primarily authenticate SIM cards, the 5G-SAIIoT system prioritizes strong device-level authentication.

The architecture is built upon several core components:

- a Key Management System (KMS) for cryptographic key handling,
- a dedicated Proximity Server that enhances IoT device security through physical proximity verification, and advanced mechanisms for device-to-device, device-to-cloud, and 5G authentication.

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Typical deployments, such as the test environment at Fraunhofer, integrate an LTE router, an IoT gateway with a 5G modem, and diverse IoT devices capable of acting as both endpoints and servers. Authentication operations for services like 5G single-time authentication and device-to-cloud communication are facilitated by an i46 server, often involving IoT devices running on platforms like Ubuntu and Raspberry Pi. This comprehensive, integrated 5G/proximity authentication system is designed to provide superior security for industrial IoT applications, offering a wider range of responses to authentication failures than traditional IoT cloud scenarios.

TRIAL

Testing commenced on 02/10/25 at the Fraunhofer facility in Aachen. It was equipped with an LTE router, 5G modem-integrated IoT gateway, and various IoT devices, providing 5GSA core network access for validating authentication mechanisms.

Further trials include use case analysis and demonstrations at Witte Automotive. For advanced authentication services, an i46 server facilitates operations with IoT devices, including Raspberry Pi-based setups, in simulated real-world conditions.

Figure 99: 5G Single-time Authentication - testing environment.

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RESULTS

Results include rapid device-level authentication: downloading 10,000 keys in approximately 0.26 seconds and authenticating them in approximately 0.59 seconds on high-performance setups. Performance critically hinges on CPU and disk speed, with Mini PCs proving faster than Raspberry Pis for these demanding tasks. The proximity service reliably covered distances up to 20 meters in an office environment. Milestone 3 signals the project's transition to pre-commercial deployment and market readiness.

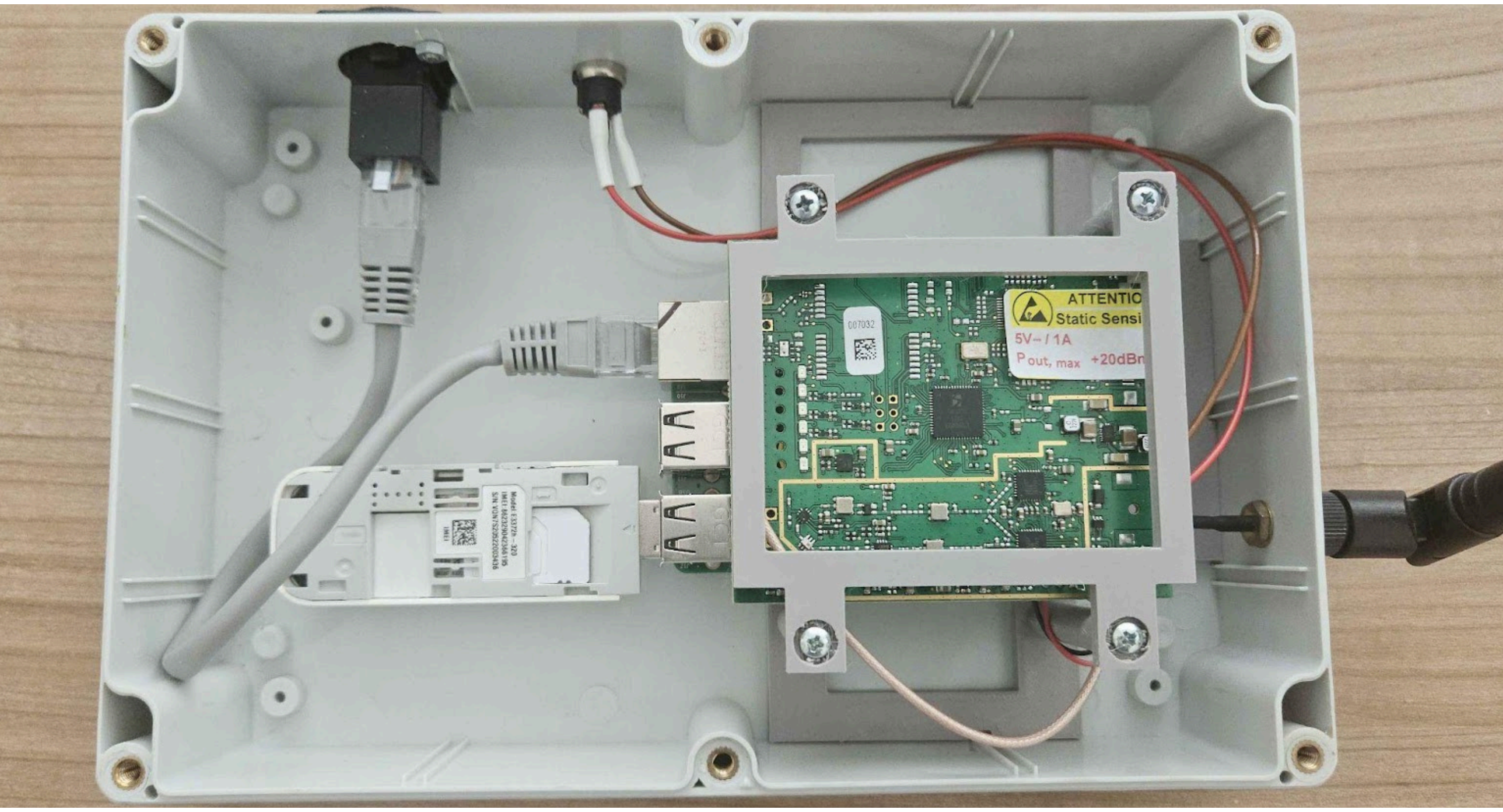

Figure 100: Interior of a sensor.

5G EMPOWERMENT

Our project leverages 5G's enhanced security, surpassing traditional IoT-to-cloud models. Unlike prior generations that primarily authenticate SIM cards, our 5G-integrated solution focuses on device-level authentication, vital for industrial security. This provides a future-proof, quantum-resistant defense against emerging threats. 5G allows for seamless device-to-network communication and a wider range of responses to authentication failures, capabilities unmatched by previous generations.

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PROJECT NAME (ACRONYM)	ENVIRONMENTAL MONITORING IN CONSTRUCTION USING 5G (EMIC5G)
NAME OF BENEFICIARY	IMST GmbH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 31/07/2025
LIST OF INVOLVED PARTNERS	CCR, RWTH-IP

OVERVIEW

Efficient use of technology is now crucial for the success of companies in almost all industries. This is especially true in the construction sector, which faces increasingly complex demands and requires innovative solutions to manage resources effectively and optimize processes.
The goal of the EMIC5G project is the integration of modern radio technologies into a 5G network infrastructure.

Project Objectives

- Development of a universal 5G gateway for use in the construction industry.
- Improvement of energy and material monitoring through Low Power Wide Area Network (LPWAN) technologies.
- Seamless interface between LPWAN and 5G infrastructure.
- Promotion of sustainable development in the industry through increased efficiency.

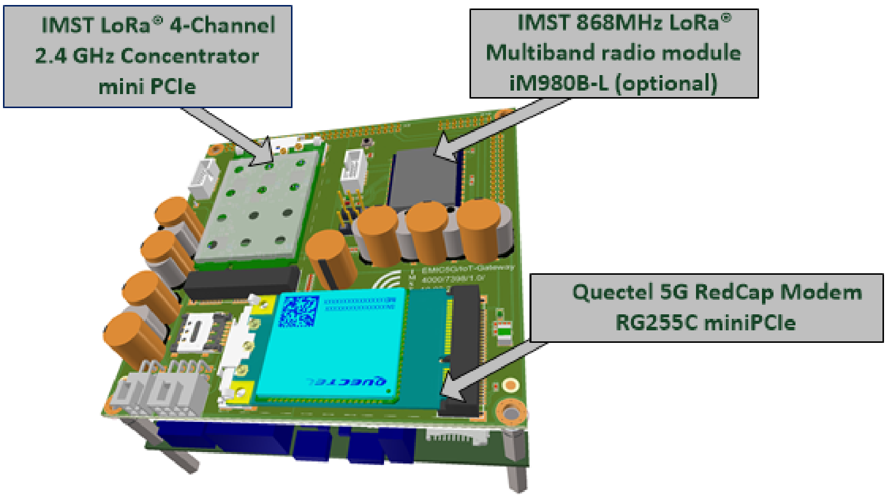

Figure 101: Extension Board design

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ARCHITECTURE

The project revealed strong synergies with the TARGET-X project 5G-FACT by GROPYUS and Ludwig System, which also required a 5G gateway and a weather station connected via LPWAN. It was therefore decided to jointly use the 5G-FACT weather use case and adopt the hardware solution for the EMIC5G platform. The requirements of 5G-FACT were taken into account when selecting components and were included as a use case.

Figure 22 provides a rough overview of the software architecture of the IoT-Gateway. There are three main applications associated with the EMIC5G and 5GFACT project:

- Part of Ludwigsystems: Provides information for the hooks and load cells
- Part of GROPYUS: Communicates with the PLC
- Part of IMST: Communicates with the weather station and provides the 5G interface

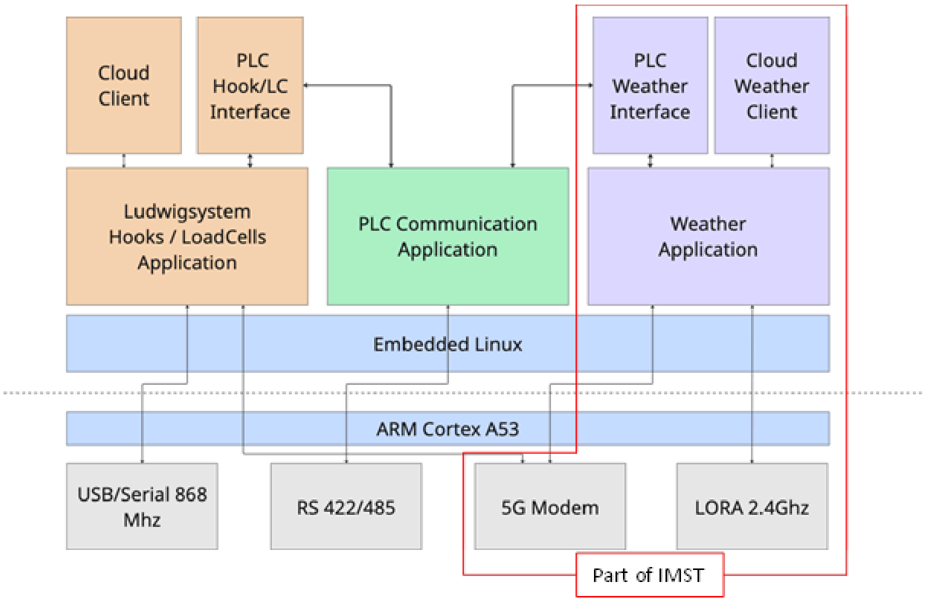

Figure 102: Software architecture of the IoT-Gateway

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TRIAL

In the EMIC5G project, we are developing a communication gateway with interfaces for safety-critical infrastructure (e.g., load cells, hooks, weather stations), PLCs, and non-critical applications such as data logging. These are essential for operating the automated lifting unit FACT in the FACT-5G project. The main focus is the wireless connection of the weather station via LPWAN – a typical use case for this technology.

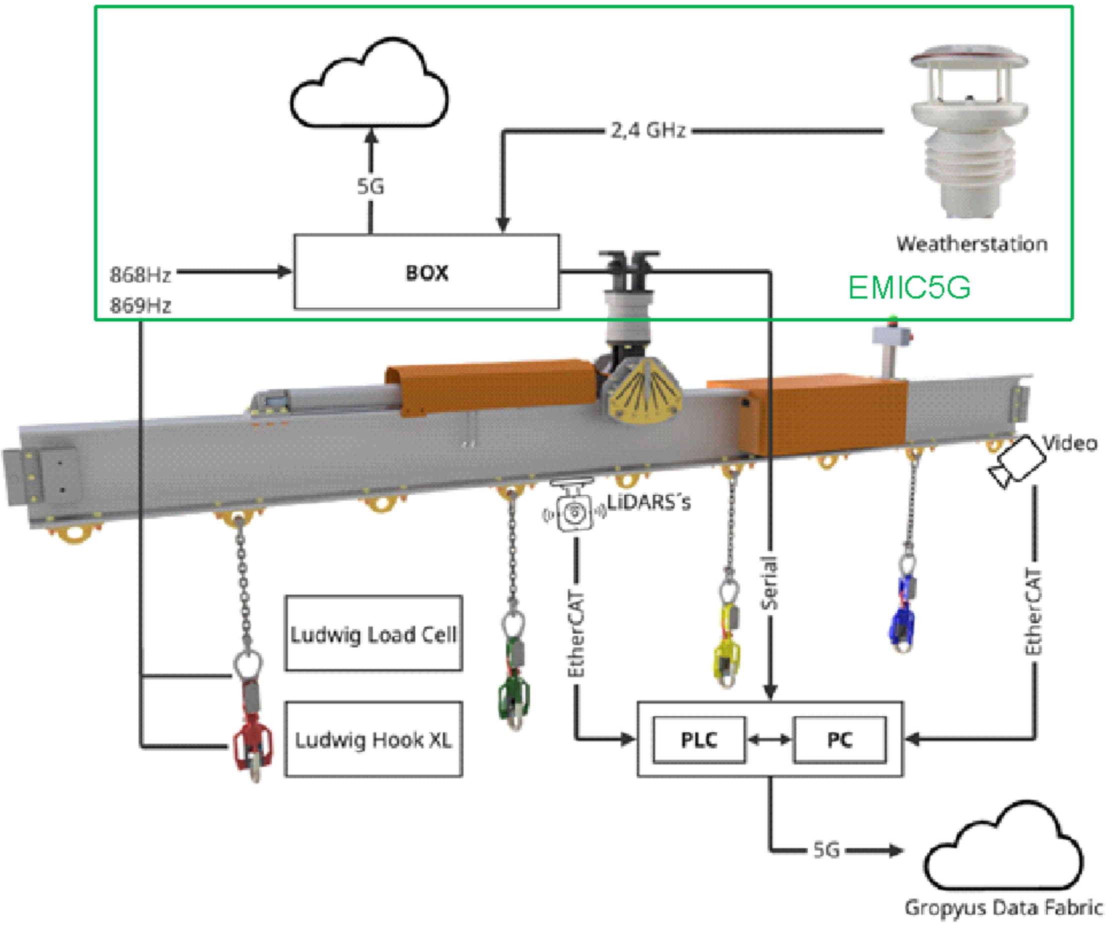

Figure 103: FACT-5G functional diagram

The integration and the first tests of the IoT gateway were primarily carried out by Gropyus in Steinhausen (Austria).

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RESULTS

The EMIC5G project aims to develop a universal 5G gateway for use on construction sites. It will enable the monitoring of energy and material flows, leveraging a combination of LPWAN technologies (e.g., LoRa, NB-IoT) and 5G infrastructures. The current status is a functional prototype in the proof-of-concept stage.

5G EMPOWERMENT

During indoor laboratory tests, intermittent interruptions in 5G connectivity were observed. These disruptions were partially attributed to environmental factors such as weather conditions that affected radio signal propagation. Despite indoor use, signal attenuation caused by rain, humidity, or other atmospheric disturbances resulted in reduced connection quality and occasional data loss. These results underscore the need for improved robustness of both hardware and software components, as well as optimization of antenna placement and signal processing algorithms to minimize environmental impacts on the 5G communication link.

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PROJECT NAME (ACRONYM)	CONSTRUCTION SITE MONITORING BIM TOOL (BIMONITOR)
NAME OF BENEFICIARIES	SABIEDRĪBA AR IEROBEŽOTU ATBILDĪBU "WATCHBUILT" LLC ASSOCIAÇAO BUILT COLAB - COLABORATIVE LABORATORY FOR THE FUTURE BUILTENVIRONMENT
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-IP

OVERVIEW

WatchBuilt's TARGET-X project, BIMonitor, focused on real-time construction site monitoring using 5G-enabled LiDAR scanning and Building Information Modeling (BIM). The solution allows project stakeholders to compare as-designed and as-built models for improved accuracy, schedule adherence, and decision-making.

From October 2024 to June 2025, WatchBuilt coordinated development and testing activities in Latvia and at the Aachen 5G testbed (Germany). Together with partners BuiltCoLab and support from RWTH Aachen, the team built and field-tested handheld 5G-compatible devices, developed upgraded software, and validated performance in live construction environments.

The trials demonstrated data upload speeds of 8–12 MB/s, enabling rapid point cloud transfer over 5G. Integration with BIM and real-time telemetry proved feasible. An important milestone was achieved in May 2025, when the full system was deployed at the Aachen site with measurable gains in monitoring accuracy and workflow efficiency.

ARCHITECTURE

The BIMonitor system architecture integrates three key components: a 5G-enabled scanning device, a cloud-based processing platform, and a web-based user interface. Together, they create a real-time monitoring loop between the construction site and decision-makers.

The scanning device captures 3D LiDAR point clouds and telemetry data (location, scan status, storage, connectivity). It includes a compact computing unit and a 5G modem, allowing fast upload to the cloud. A gateway server (on-site or remote) handles data buffering and transmission when direct 5G coverage is limited.

In the cloud, captured data is aligned with as-designed BIM models, generating visual comparisons to track construction progress. A web platform allows users to view scan results, validate alignment, and export reports.

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The architecture is modular and scalable: clients can start with simple 3D scanning and scale up to full BIM integration and automated reporting. The system supports offline-first operation and open formats like IFC, ensuring flexibility and interoperability with industry tools.

TRIAL

WatchBuilt deployed BIMonitor at the 5G testbed in Aachen, Germany (7–8 May 2025), integrating 5G-enabled LiDAR scanning and BIM model alignment. The handheld device captured color point clouds, transmitted over public and private 5G networks, and compared them with the BIM model to validate progress. Upload speeds reached up to 12 MB/s, enabling real-time tracking.

Figure 104.

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RESULTS

BIMonitor successfully demonstrated real-time construction monitoring using 5G-enabled LiDAR. Point cloud-to-BIM alignment worked reliably; upload speeds reached 8–12 MB/s. Achieved TRL5 with validated performance in live tests. Key KPIs met: scan-to-cloud <5 min, upload reliability >90%. Early adopter discussions started.

https://www.watchbuilt.com

https://youtu.be/5Pfi1xkUFdI

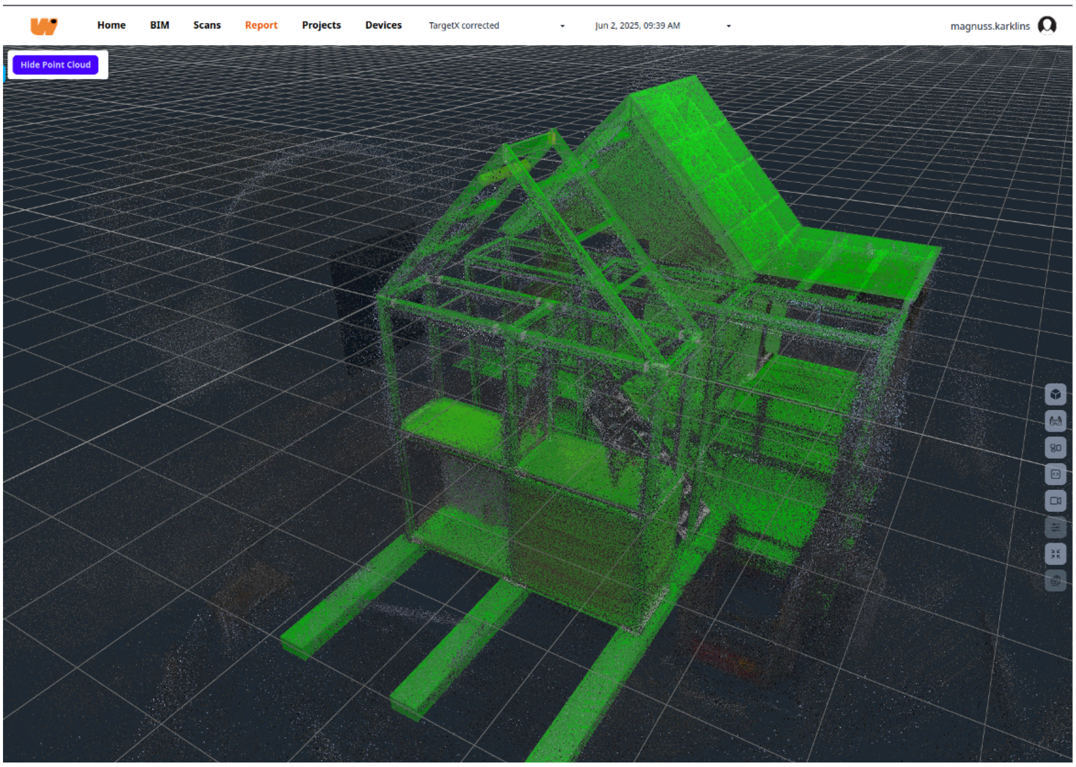

Figure 105.

5G EMPOWERMENT

5G enabled BIMonitor to transmit large 3D scan files (2GB+) in minutes, enabling near real-time progress tracking. Compared to 4G, 5G offers higher upload speeds (8–12 MB/s), lower latency, and stable connectivity–crucial for on-site monitoring. This allows faster decision-making, reduced rework, and more efficient coordination–benefits not feasible with previous network generations.

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PROJECT NAME (ACRONYM)	MOBILE MANIPULATORS FOR INDUSTRIAL ASSEMBLY (MM-IA)
NAME OF BENEFICIARIES	ALDAKIN AUTOMATION IKERLAN S. COOP.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

The MM-IA project aims to provide mobile manipulators with the technology to avoid collisions in flexible manufacturing environments, adapting the planned trajectory to dodge them without interrupting the production. This objective has been accomplished through a novel distributed control solution, where the path planning will be executed in high-computational-capacity hardware to subsequently send the commands to the mobile platform through 5G connectivity.

This solution has been successfully tested and validated in IKERLAN's laboratories for the assembly process of battery cables for EVs in the automotive industry. The validation tests have demonstrated the technical feasibility of using 5G communications for the distributed control of a mobile manipulator in industrial scenarios. The implemented system successfully integrates reactive navigation, vision-guided manipulation, and real-time task execution, all supported by a modular and scalable software architecture.

The outcomes show clear advantages in terms of efficiency, responsiveness, and safety. Furthermore, the system maintained low communication latency and high reliability throughout the tests, validating its applicability in time-sensitive industrial processes.

ARCHITECTURE

The robotic edge computing framework consists of three layers (Figure 106):

- The robot layer comprises the robot's hardware, sensor configurations, and essential low-level software modules. Integrated network devices within the robot allow for data transfer and command communication with the edge system.
- The edge system layer acts as the central intelligence of the framework, handling sensor data processing and decision-making. It includes both hardware components and software modules that enable the mobile manipulator's capabilities.
- The communication layer forms the backbone for data transfer between mobile manipulators and the edge system.

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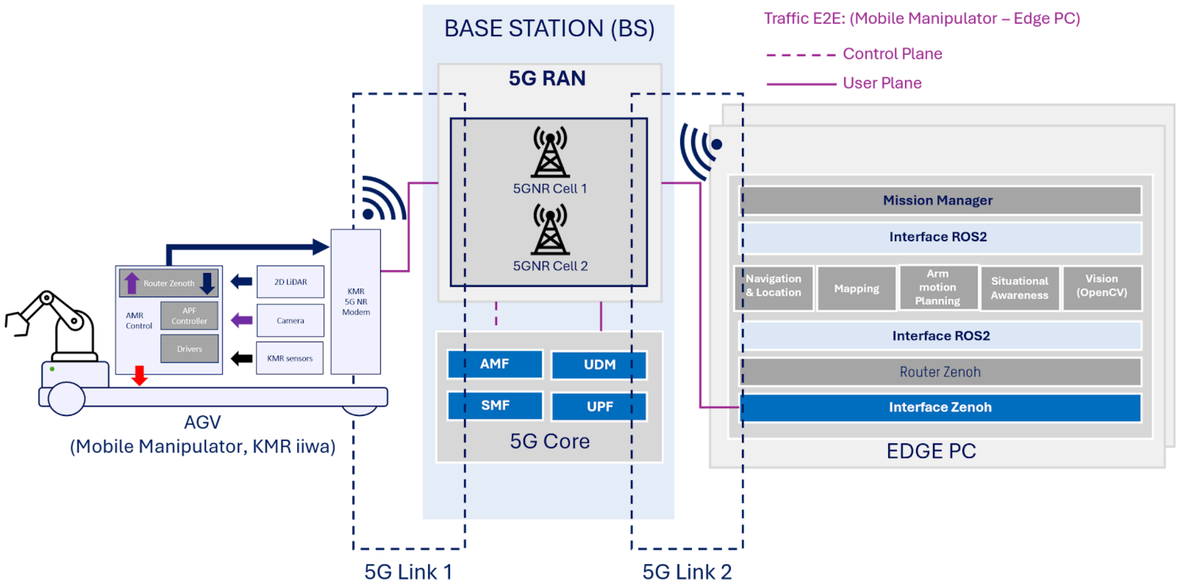

Figure 106: MM-IA: Function architecture of 5G communications

TRIAL

This solution has been successfully tested and validated in IKERLAN's laboratories for the collaborative assembly process of battery cables for EVs in the automotive industry. The assembly operation of the batteries (connection of the battery cells in each battery pack) has been represented in a significant way, and the AMR has been equipped with the necessary components (gripper, cable connector, and supply racks) to perform the operation.

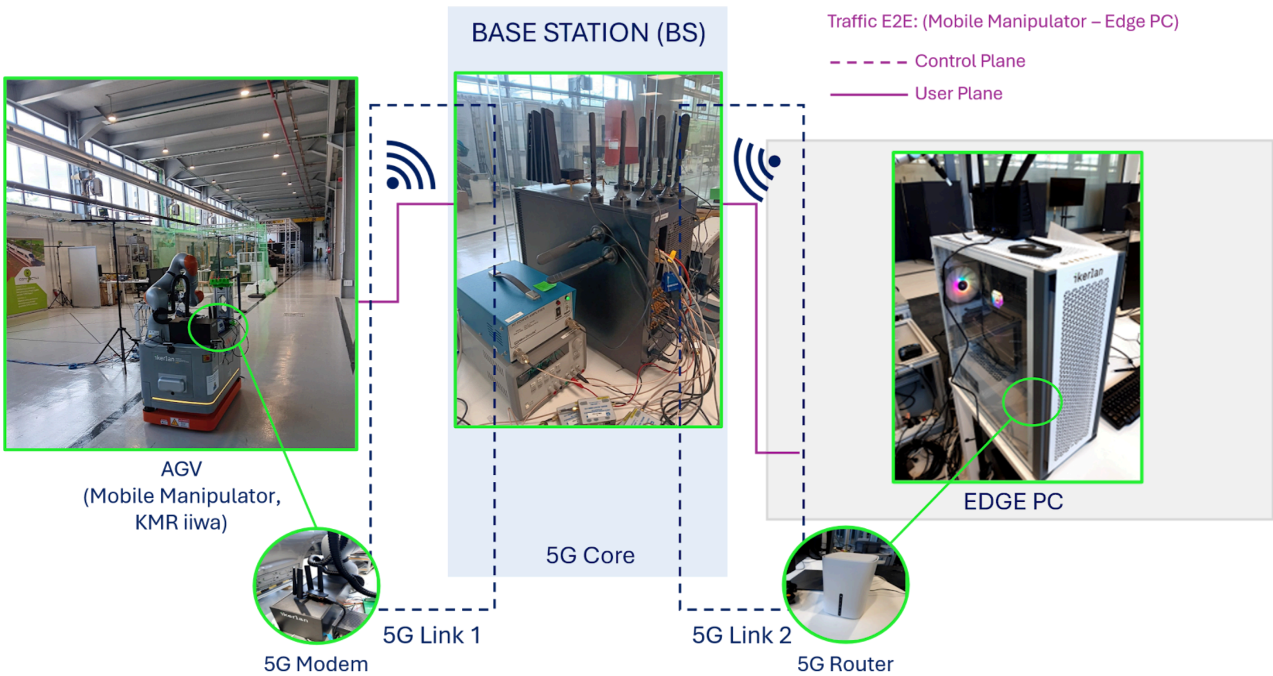

Figure 107.

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RESULTS

The outcomes confirm the soundness of the solution, showing clear advantages in terms of efficiency, responsiveness, and safety. The integration of 5G-enabled distributed control has led to smooth task execution and a reduction in unnecessary stops, enabling the robot to operate more fluidly even in dynamic environments. Furthermore, the system maintained low communication latency and high reliability throughout the tests, validating its applicability in time-sensitive industrial processes.

#	Description	Result
TPI1	**Assembly process and product data:** object and obstacle detection capability in the identification of working points.	• Identification of the connectors (100%) • Obstacles detection (100 %)
TPI2	**Process variability:** absorption capacity of the battery assembly tolerances.	Absorbing the assembly tolerances (88 %).
TPI3	**Task execution:** ability to perform wire assembly tasks correctly.	Wires connection (88 %).
TPI4	**Cycle time reduction** (Tred) compared to standard mobile manipulator behaviour in highly dynamic environments (before and after integrating the proposed solution).	Tred_total = 21.52%
TPI5	**Overall equipment efficiency (OEE):** the OEE calculation will be performed before and after integrating the proposed solution.	OEE_before = 73.33% OEE_after = 80%
TPI6	**Work accident risk in manufacturing:** defined as the number of safety stoppages during assembly (before and after integrating the proposed solution).	3 stops/cycle
TPI7	**Latency**	20-40ms (RTT time) 60-100ms (E2E time)
TPI8	**Reliability:** Reliability KPIs assess the network's ability to maintain consistent and stable connections.	min: 90,9; avg: 95,9; max: 98,9
TPI9	**Coverage:** Coverage available and granted in the testbed area.	RSRP: -98; RSRQ: -11; SINR: 10,5

Figure 108: Main Technical Performance Indicators (TPI)

5G EMPOWERMENT

The use of 5G communications provides clear benefits for the deployment of distributed mobile robotics control solutions:

- Guaranteed high bandwidth for demanding data streams such as video or raw sensor data.
- Greater control over communication flows to prioritise certain messages and guarantee real-time applications.
- Scalability in scenarios with multiple mobile manipulators with distributed control architectures.

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PROJECT NAME (ACRONYM)	AUDITING SYSTEM FOR AS-BUILT MATERIAL PASSPORTS (AFAM)
NAME OF BENEFICIARY	CONCULAR GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 31/08/2025
LIST OF INVOLVED PARTNERS	CCR, RWTH-IP

OVERVIEW

The Auditing System for As-built Material Passports (AFAM) bridges the gap between "as-planned" data and the actual "as-built" conditions on site. Built on Concular's Circular Audit App, it combines integration in the platform with 5G connectivity to enable real-time verification, documentation, and synchronization of construction data.

Using detailed object lists, auditors and craftspeople can check installed components directly on site, identify deviations, and instantly update the digital material passport. The result is a dynamic, accurate record that evolves throughout the building's lifecycle, capturing specifications, mounting conditions, and circularity indicators such as deconstructability. This information supports reuse, design-for-disassembly, and transparent lifecycle management.

AFAM is tested in both controlled and real-world environments, including the CCR Reference Construction Site in Aachen and urban 5G locations in Berlin. It also demonstrates circular construction by integrating reclaimed components from a donor building in Hürth. With sub-second audit transmission and seamless audit-to-platform synchronization, AFAM reduces rework, ensures compliance, and improves collaboration, aligning with EU goals for sustainable and transparent construction.

ARCHITECTURE

AFAM's architecture connects BIM-based planning data with on-site verification in a continuous feedback loop. The process begins with the upload of BIM models containing detailed object metadata. From these, the system generates an as-planned material passport, which is then transferred to the Circular Audit App for use in the field.
On-site, auditors and craftspeople use 5G-enabled mobile devices to access the passport, locate components, and verify their installation against the original specifications. Any deviations, updates, or notes are entered directly into the app. Through an API-based synchronization, this verified as-built data is transmitted back to the central platform in real time, updating the material passport.

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This low-latency setup allows immediate access to accurate building information for all stakeholders, supporting design-for-disassembly, reuse planning, and regulatory compliance. By linking digital models, field inspections, and central data storage, AFAM ensures the material passport remains a living, accurate record throughout the building's life.

TRIAL

AFAM has been tested in both controlled and real-world settings to evaluate performance and usability. One trial site is the CCR Reference Construction Site in Aachen, where simulated deviations between as-planned data and on-site conditions were used to verify real-time updates of the material passport via 5G.

Additional trials in Berlin tested the system on public 5G networks as a simulation, while reclaimed components from a donor building in Hürth were integrated into a demonstrator in Aachen. These trials confirmed AFAM's ability to handle both new and reused materials, maintain low latency, and ensure seamless synchronization between the platform and mobile devices.

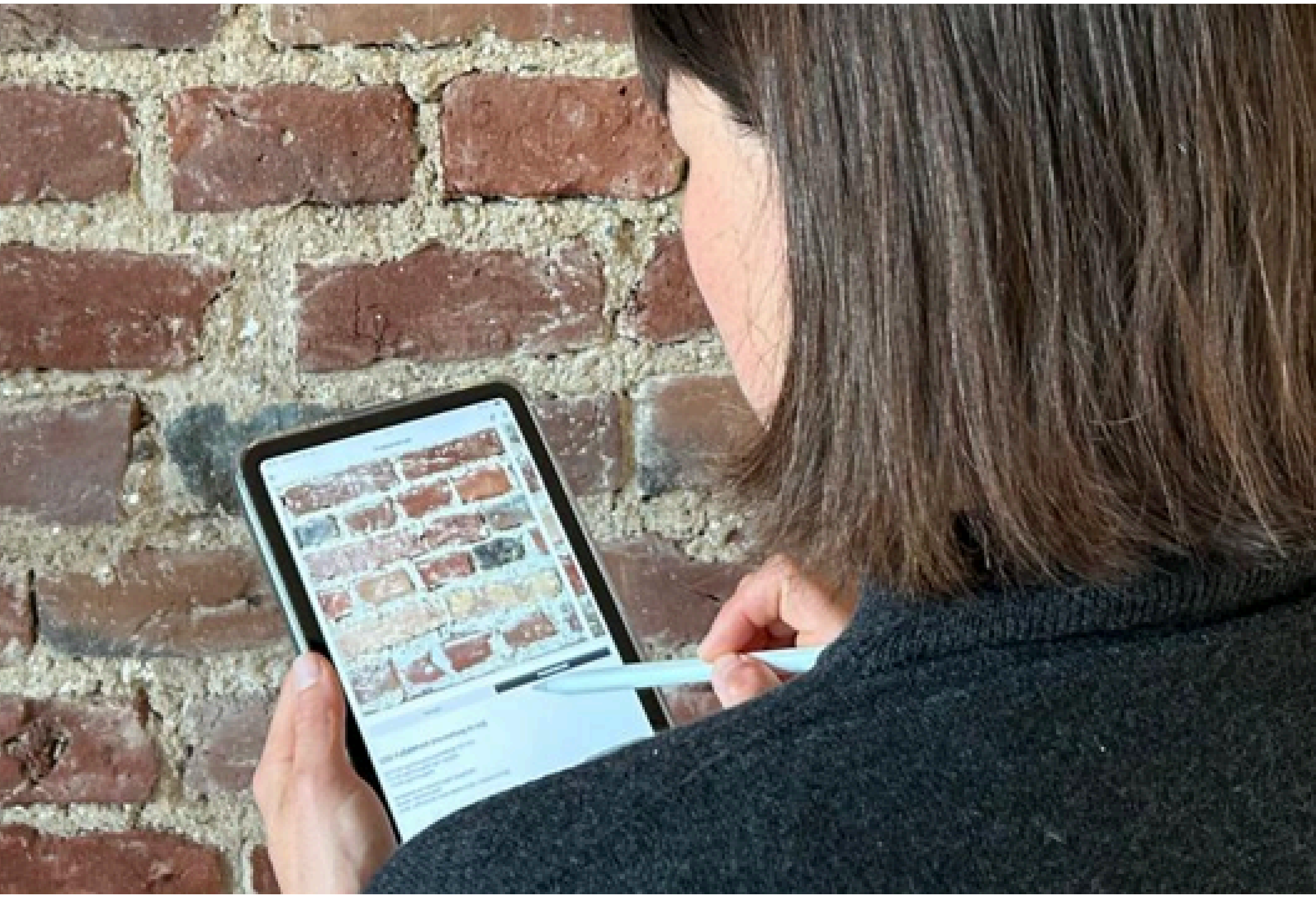

Figure 109.

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RESULTS

AFAM proved that 5G-enabled, real-time updates between on-site checks and models are possible with sub-second latency. The system integrated data into the Circular Audit App, enabling accurate, low-latency updates to material passports in both controlled and real-world trials.

Key achievements include reduced rework risk, improved compliance, and effective documentation of both new and reclaimed components with all the circularity values, supporting circular construction and better asset management.

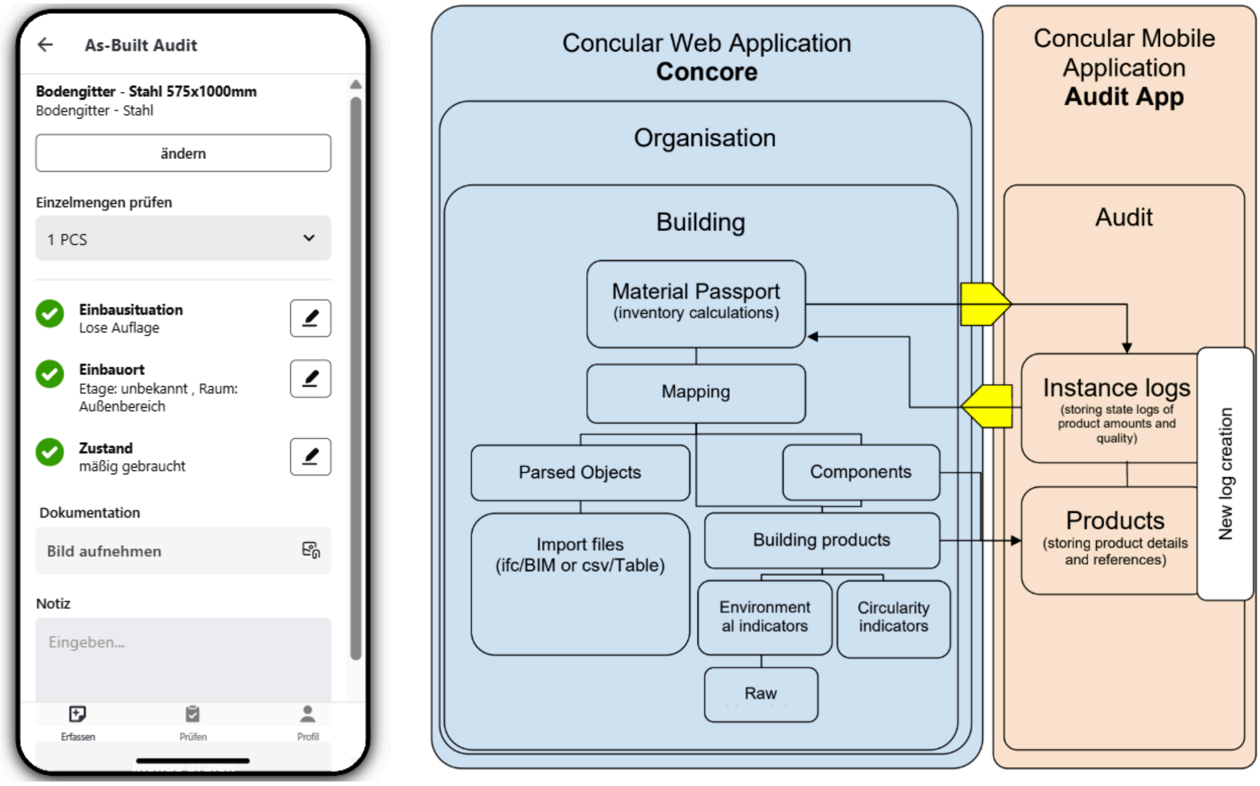

Figure 110.

5G EMPOWERMENT

5G enables AFAM to synchronize large, detailed datasets with on-site mobile devices in real time, something not possible with previous network generations. Low latency and high bandwidth allow instant updates to material passports, even in complex construction environments, reducing delays and preventing rework.

Compared to older networks, 5G provides more stable connectivity on large or remote sites, supports simultaneous multi-user access, and ensures smooth operation for data-heavy tasks like BIM model handling. Looking ahead, 6G could add advanced capabilities such as AI-driven data processing, richer IoT sensor integration, and immersive AR tools, further enhancing real-time construction verification.

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6G SNS

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PROJECT NAME (ACRONYM)	VIDEO INTEGRATED SAFETY TRANSPORT ASSISTANT (VISTA)
NAME OF BENEFICIARIES	PI.PE GMBH MOTOR AI GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 31/08/2025
LIST OF INVOLVED PARTNERS	i2CAT

OVERVIEW

Figure 111.

VISTA (Video Integrated Safety Transport Assistant) is an EU-funded project addressing a major barrier to deploying fully autonomous public transportation vehicles: the need for reliable remote human supervision when complex traffic situations arise that AI alone cannot resolve, and to ensure a clear pathway to regulatory approval.

A Berlin-based consortium of |pipe| and MOTOR Ai has equipped a Level 4 autonomous shuttle with embedded "watchdog" software, creating a secure, ultra-low-latency video, audio, and data link over LTE/5G. Independent from the driving stack, it allows a remote supervisor to connect at any time, assess the situation, and, if needed, guide or authorise a manoeuvre – putting a human briefly back in the loop for safety and compliance.

ARCHITECTURE

The VISTA architecture is built around three core elements:

- Autonomous Shuttle – MOTOR Ai's Level 4 vehicle, fitted with cameras, microphones, sensors, and VISTA's embedded "watchdog" software. This module runs independently of the main driving stack.
- |pipe| Transport Layer – a secure, ultra-low-latency video, audio, and data channel operating over LTE/5G networks. It maintains an always-on connection between the shuttle and the remote supervisor.
- Remote Supervisor Station – equipped with real-time monitoring displays, diagnostic tools, and control/authorisation interfaces.

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The shuttle's onboard systems continuously send live video, audio, and telemetry via the |pipe| connection, while also receiving control signals and authorisations when needed. Because the transport layer is independent, connectivity and supervision are maintained even if the autonomous driving system is in safe mode. This architecture ensures a human can monitor and, when necessary, intervene in operations at all times.

TRIAL

Trials began at Berlin's former Tegel Airport, then moved to live street testing in the districts of Friedrichshain and Kreuzberg. The shuttle operated in mixed traffic, with the VISTA link enabling uninterrupted remote supervision at all times. Testing included scenarios with network load, complex junctions, and unpredictable traffic behaviour.

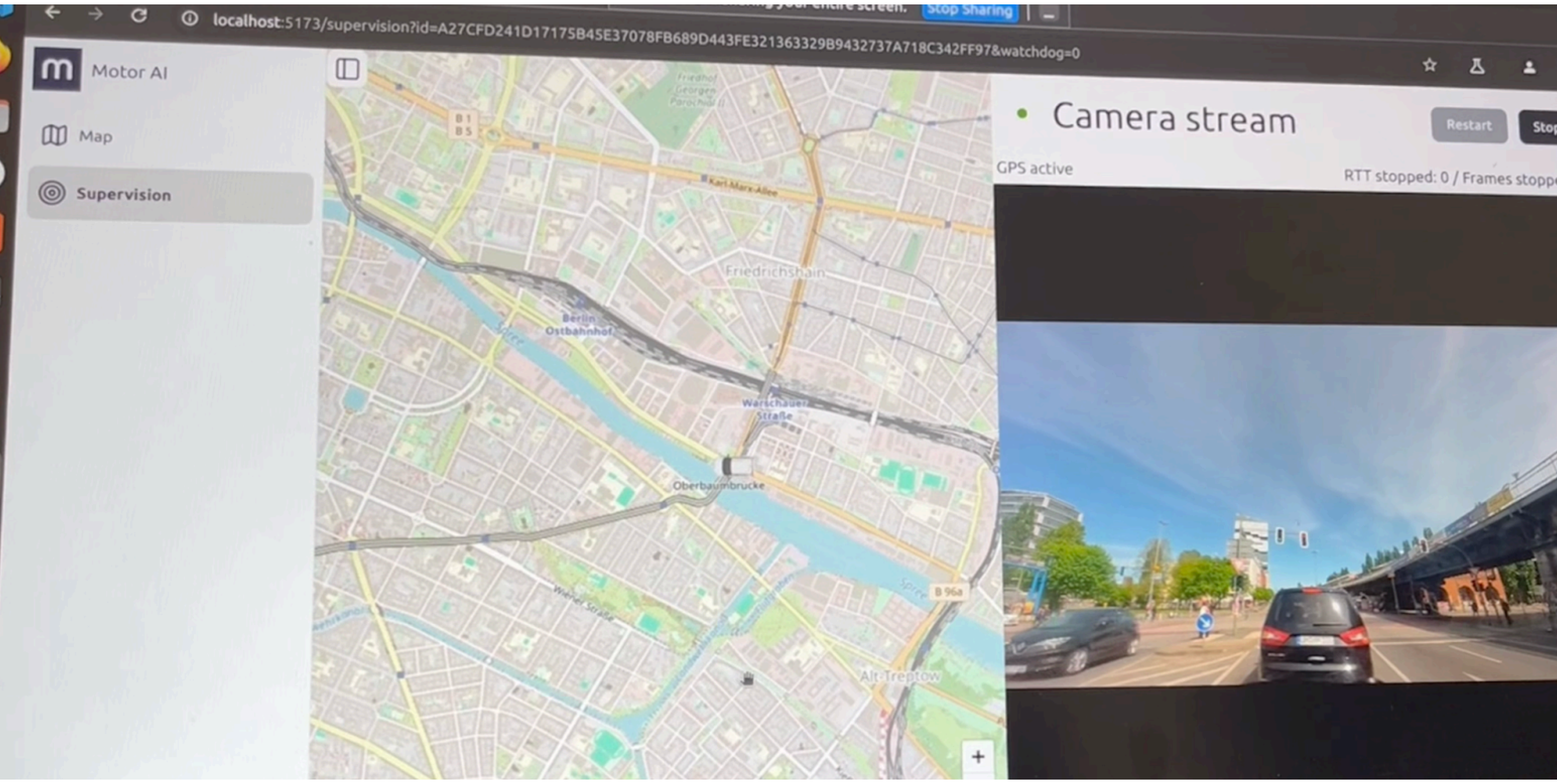

Figure 112.

Testing on the road in Berlin

In the middle is the map of Berlin with the vehicle's position being updated in real-time. On the right is the Camera Stream panel. You see a green dot beside "Camera stream," which indicates the Watchdog's status (in this case, healthy). Next to that, you see a "Restart" and "Stop" button. This allows the Technical Supervisor to end actively streaming the camera ("Stop") or to restart the stream ("Restart"). Below you see several status messages being transferred live via VISTA, namely GPS status (in this case active), RTT, and Frames stopped, which indicate if there are any latency issues.

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RESULTS

Demonstrated uninterrupted supervision at times of heavy urban network congestion and in areas with weak or patchy signal, showing resilience for public transport use – including in rural areas. Trials showed stable LTE/5G uplinks above 5 Mbit/s, latency under 50 ms, and near-zero packet loss, enabling smooth video, audio, and control flows without interruption.

Figure 113.

Start of the Tegel Airport test

The interface is a backend analytics platform by |pipe|; the bottom right screenshot captures the streamed VISTA camera data, which was being processed via the Motor Ai Technical Supervisor system. Being measured were the Frames per second, the Mbits per second, and the bus.

5G EMPOWERMENT

VISTA's secure, low-latency link works over both LTE and 5G, maintaining performance even at the network edge. Extending 5G into rural areas would enable safe, reliable autonomous public transport – from shuttles to robo-taxis – to operate at scale. This can help revitalise rural economies by improving mobility, reducing car dependency, and connecting communities to jobs, services, and opportunities.

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PROJECT NAME (ACRONYM)	5G-ENABLED ENVIRONMENTAL REPORTING PLATFORM FOR CONSTRUCTION SITES (5G ERCS)
NAME OF BENEFICIARY	EMBNEUSYS PC
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	CCR

OVERVIEW

5G ERCS developed and integrated a 5G-enabled telematics system for real-time environmental monitoring of construction machinery. The key objectives were: (1) to track equipment-related CO_2 emissions through vibration and temperature sensing; (2) to automate environmental reporting for job sites; and (3) to build a compact, energy-efficient, modular device using 5G connectivity.

A laboratory pilot trial was conducted in April 2025 to validate 5G integration, assess communication performance, and evaluate power management. The device successfully registered on COSMOTE's 5G SA network in Greece, achieving uplink speeds of 12–15 Mbit/s and average latency under 50 ms. During the same period, TPI1 (Development of SDK for 5G modem) and TPI2 (Hardware integration, PCB design, and lab testing) were completed, with successful modem control, OTA packet transmission, and pre-production evaluation.

Field testing with a 3.7V Li-Po battery demonstrated that 5G operation was not viable on battery power alone. Future considerations for using 12V/24V engine-coupled and auxiliary port power supplies could be examined for project continuation. The project was led by Embneusys PC and represents a major milestone in advancing smart construction site monitoring aligned with EU emissions regulations.

ARCHITECTURE

The project architecture consists of a compact, modular telematics device with three stacked PCB layers: a Main Board with an MCU for sensor data processing and system control; a Power Board that accepts 3.7V input from a Li-Po battery and manages voltage regulation and power efficiency; and a Communication Board hosting the Quectel RM520N-GL 5G modem and Beitian BN-220 GNSS receiver. The system samples vibration and temperature data, processes it locally, and transmits packets to the cloud every 15 minutes via 5G. Its rugged, IP-rated enclosure and plug-and-play design support retrofitting on construction equipment, enabling scalable deployment and automated emissions reporting.

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Figure 114.

TRIAL

The lab trial simulated real-world use by mounting the device on a vibration rig and applying heat to mimic engine conditions. A 3.7V Li-Po battery powered the system to measure current under 5G activity. The device connected to COSMOTE's 5G SA network via the Quectel RM520N-GL, transmitting data every 15 minutes. Configuration included SIM activation, APN setup, and cloud sync. The trial validated power behavior, modem control, and real-time data transmission.

Figure 115.

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RESULTS

The project successfully integrated 5G into a compact telematics device, achieving uplink speeds of 12–15 Mbit/s and latency under 50 ms. Key milestones include SDK development, hardware integration, and real-time lab testing. Battery testing revealed 5G's high power demand, leading to a future shift toward engine/auxiliary power. Business KPIs met: device readiness for pilot deployment, regulatory-aligned emissions reporting, and strong market interest in retrofit solutions for CO_2 compliance.

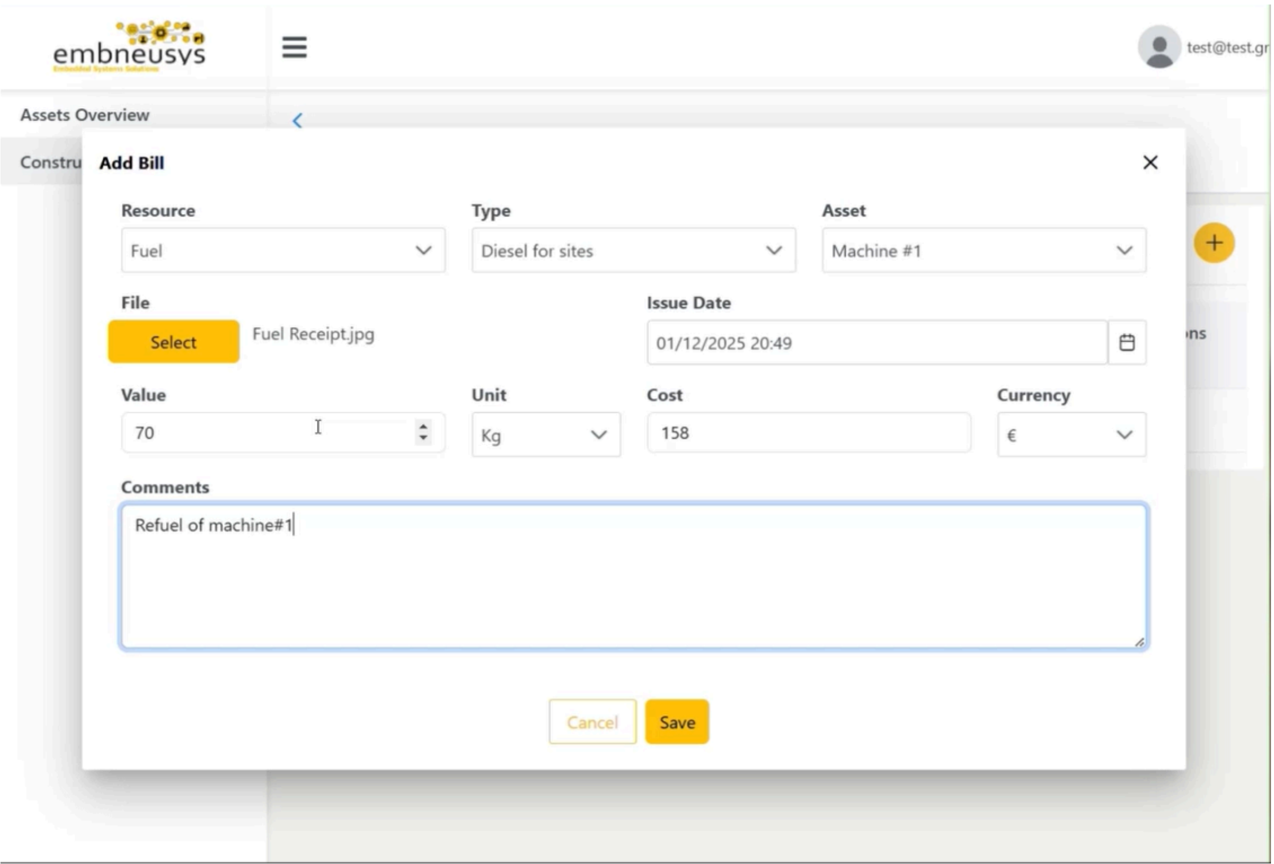

Figure 116.

5G EMPOWERMENT

5G enables ultra-low latency (<50 ms), high uplink speeds (>12 Mbit/s), and real-time connectivity–critical for live telemetry and emissions reporting in construction. Unlike 4G or NB-IoT, 5G supports dense data from multiple sensors with high reliability, even in motion. 5G Advanced will offer improved energy efficiency and RedCap support, enabling longer runtimes. Future 6G will enhance positioning and AI integration, enabling autonomous analytics. These capabilities unlock smarter, safer, and greener worksites.

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PROJECT NAME (ACRONYM)	5G MONITORING DURING LIFE CYCLE OF STEEL COMPONENT (5G STEEL MONITORING)
NAME OF BENEFICIARIES	WURST STAHLBAU GMBH LASERSCAN OM GMBH & CO.KG
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	CCR, RWTH-IP

OVERVIEW

The 5G Steel Monitoring project was carried out by the two companies WURST Stahlbau GmbH and Laserscan OM GmbH & Co. KG as third-party participants within the "Construction" vertical of TARGET-X's Second Call. While the prefabrication of components in many areas of steel construction is automated using CNC cutting tables, drill saw lines, and robot welding machines, quality assurance in steel construction is still largely a manual process.

The project aims to implement reproducible and partially automated quality inspection and progress tracking processes in steel construction using 3D scanning technology.

A central area of application is the as-planned/as-built comparison: The registered point cloud is compared with the planned 3D CAD model in order to detect deviations between design and execution at different construction stages. In this way, dimensional inaccuracies, tolerance violations, assembly errors, or time delays can be efficiently identified and documented.

Figure 117: Steel Construction

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ARCHITECTURE

The 5G Steel Monitoring project utilizes a central data processing system that is integrated into the company via various interfaces.
3D models (primarily in IFC format) from the design department, as well as point clouds from 3D laser scans (primarily in .e57 format), are transmitted to the system for as-is vs. as-designed comparisons. On construction sites, 5G technology ensures fast and reliable data transmission.

The measurement results undergo semi-automated analysis and are stored for long-term documentation.

To enhance automation, semantic segmentation of the captured point clouds is applied, enabling relevant components to be easily filtered from their surroundings.

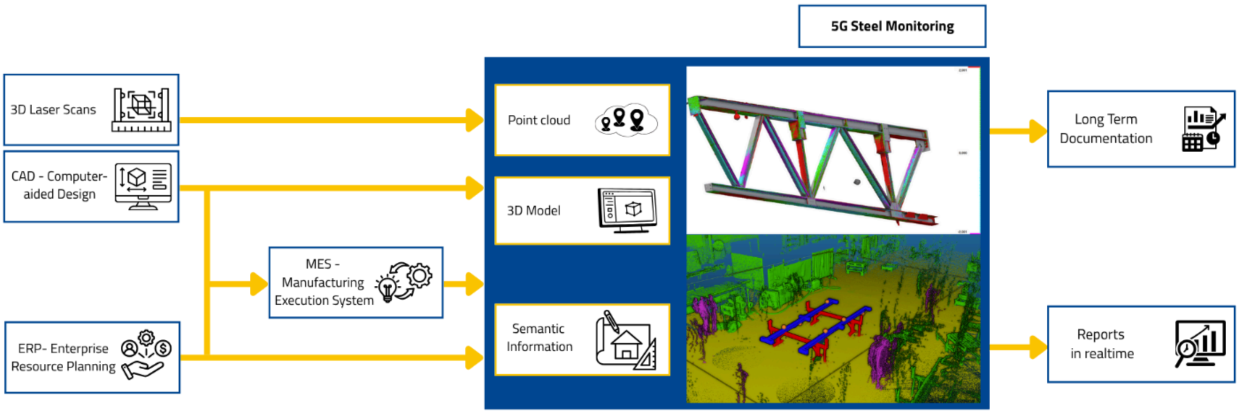

Figure 118: Integration of 5G Steel Monitoring

TRIAL

As part of the project, a demonstrator was built in collaboration with other research participants. Status tracking and QA trials were conducted both at WURST Stahlbau's production site and during installation at the Center Construction Robotics testbed at RWTH Aachen University. Key challenges in applying 5G Steel Monitoring include small batch sizes (often batch size 1) and high variability in component dimensions (e.g., 0.5 to 25 meters in length).

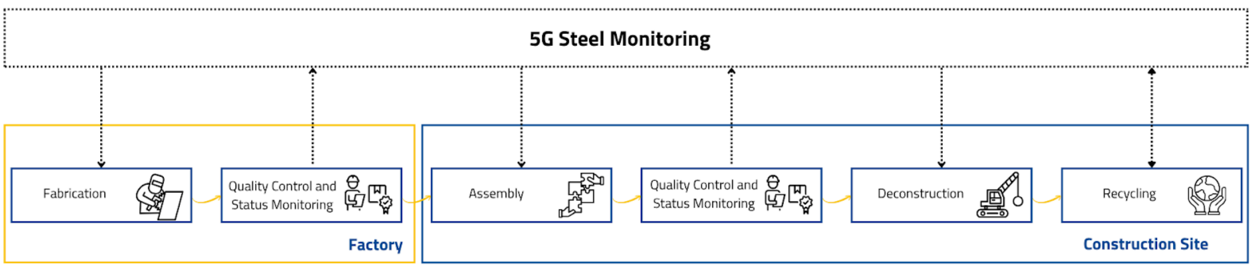

Figure 119: Processing in 5G Steel Monitoring

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RESULTS

5G Steel Monitoring enables full digitalization of QA processes. 3D laser scanning significantly improves measurement reproducibility. Even in its current unoptimized state, the developed method rivals manual inspections in time efficiency, especially for complex components. Final evaluation of the measurement results is still performed by qualified personnel. Further automation requires advanced methods that can detect relevant technical dimensions across diverse component types and evaluate deviations.

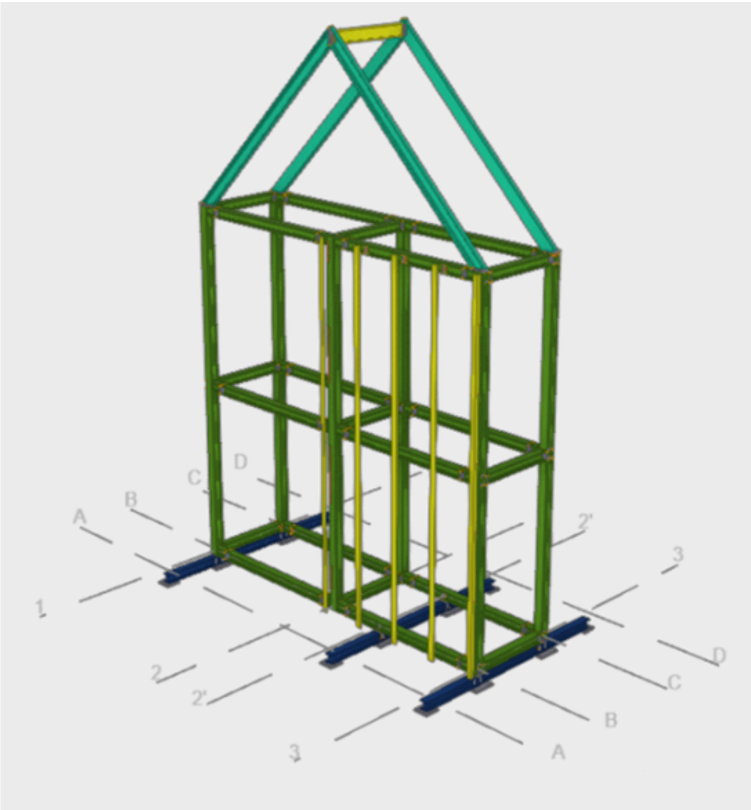

Figure 120: Steel Construction

5G EMPOWERMENT

5G Steel Monitoring generates large volumes of data. Raw point clouds can reach several Gigabytes depending on the size of the scanned area.

These datasets must be transmitted to a central data processing system. While this is typically unproblematic in controlled production environments, it poses a challenge on construction sites.

The use of 5G technology enables near real-time data transfer directly on-site, allowing it to be seamlessly integrated into construction workflows without interfering with ongoing operations.

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PROJECT NAME (ACRONYM)	UNIVERSAL ROS BUS BRIDGE WITH 5G/6G CONNECTIVITY (ROS6GBUSBRIDGE)
NAME OF BENEFICIARIES	LOGIIDEV GMBH COMMISSARIAT À L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

ROS6GBridge aims to implement a 5G/6G connected Field Programmable Gate Arrays (FPGA) bridge solution (including hardware, software, and architecture) for devices equipped with industrial Ethernet bus protocols to communicate with ROS2 devices. This enables real-time control, monitoring, and digital twin using advanced 5G/6G. ROS2 bridging is a challenging task due to the fundamental differences between industrial bus protocols and ROS2, including variations in data types, session management, and messaging patterns. The result of this project is promising to overcome the interoperability demands in Industry 4.0 and 5.0.

This system was successfully tested and validated at WZL RWTH Aachen University's laboratory, demonstrating seamless integration of multiple industrial robotics interfaces–including Modbus TCP, OPC UA FX, EtherNet/IP Class, and CANopen–over a 5G network.

This holistic project enables existing robotics-based production lines to incorporate 5G/6G connectivity and modern protocols in real time, allowing AI algorithms to be deployed directly on production lines without the need for costly replacement of industrial PLC systems. This significantly reduces upgrade barriers and accelerates the digital transformation of manufacturing environments.

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ARCHITECTURE

Each communication protocol has a method to identify its data sources; thus, the Network Protocols Bridge (NPB) needs a mechanism to unify them so it can forward data from one interface to another. This mechanism must be able to cover all data source identifications of all related communication protocols. Up to now, NPB has been limited by wireless technology due to unpredictable delay, no real-time latency of data, and limited coverage.

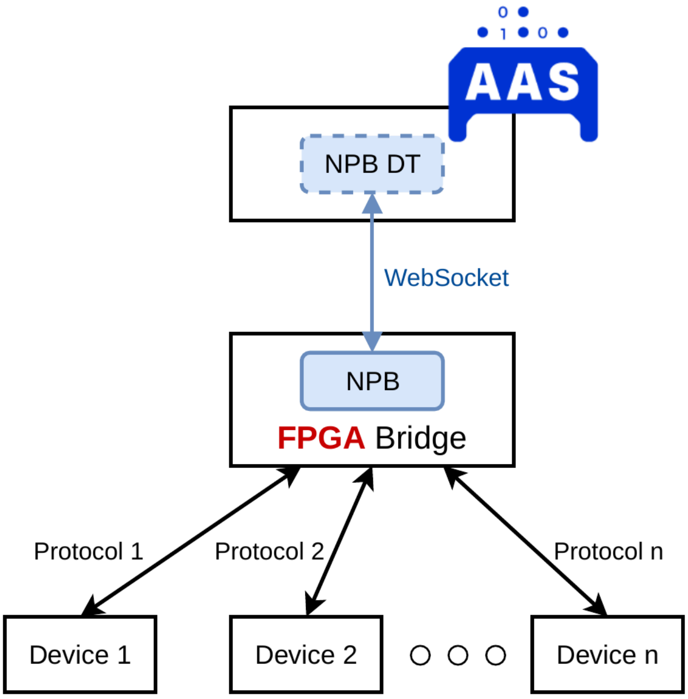

Figure 121.

The differences between communication protocols cause three main interoperability issues:

- Data type incompatibility – Modbus TCP uses different data types, and ROS2's custom composite types aren't recognized by the others.
- Feature mismatch – ROS2 supports advanced features (read, write, action calls, services), while the others are limited to read/write.
- Messaging pattern conflict – ROS2's publish-subscribe model is asynchronous, unlike the synchronous client-service models of the others.

This FPGA platform is currently 5G-ready and highly flexible, allowing integration with new industrial buses and technologies such as Bluetooth Low Energy (BLE), Time-Sensitive Networking (TSN), 6G, and WiFi 6 when needed.

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TRIAL

This deployment was validated as the manufacturing plant: the UR3e robot connects to NPB via EtherNet/IP Class 1, T3WP via ROS2, Opta PLC via Modbus TCP, and Raspberry Pi 2 via OPC UA FX. PAL DT also uses Modbus TCP, as it's the only supported protocol that does not require the same local network.

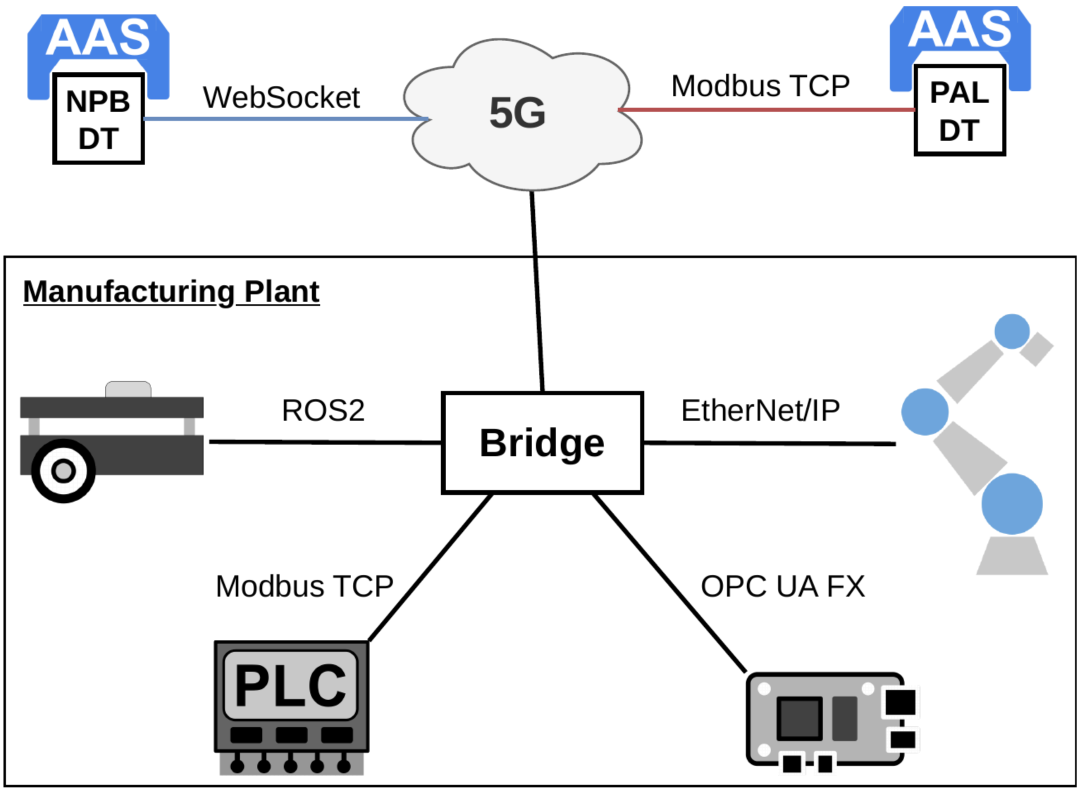

Figure 122: Production Assembly Line use case.

With 5G connectivity, the NPB ensures reliable communication across protocols and unifies data source identifiers despite differing locations, where OPC UA FX with the UADP UDP/IP profile supports diverse data types for real-time industrial use.

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RESULTS

Figure 123: Real time communication testing.

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5G EMPOWERMENT

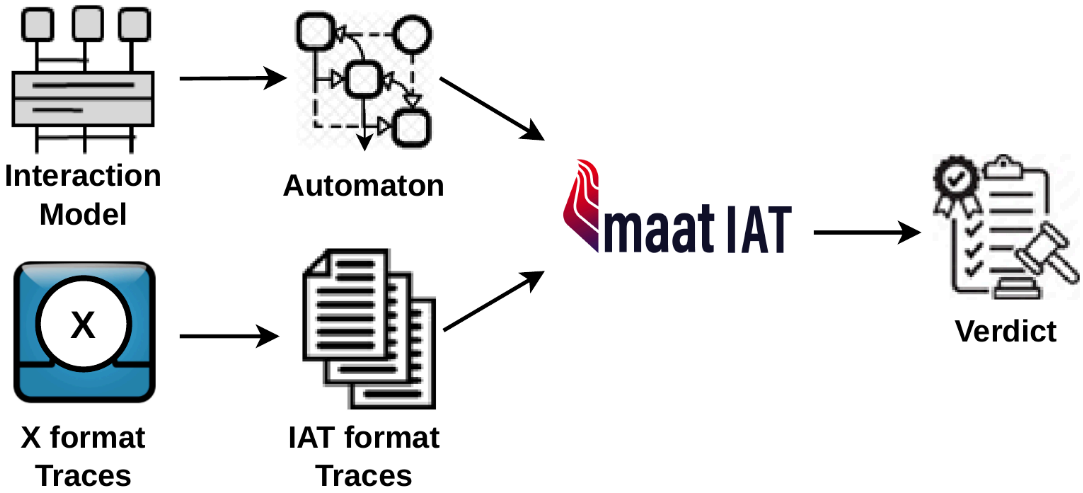

Figure 124: Conformity testing using Runtime Verification & Maat IAT.

Based on the experience of using WiFi and BLE, the following are the advantages of enabling the communication based on 5G/6G for Industry 4.0 with Robotics:

- Ultra-low latency enables real-time robotic control, far surpassing WiFi/BLE.
- Guaranteed high bandwidth supports demanding video, sensor, and AI data streams.
- Superior reliability and network stability under heavy device loads—essential in mega factories.
- Supports massive, seamless mobile connectivity for fleets of robots, unlike BLE's limited range or WiFi's frequent disconnects.

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PROJECT NAME (ACRONYM)	ROS2 BANDWIDTH AWARE NETWORKING DYNAMICS AND INTEGRATION TOOLKIT (ROS2-BANDIT)
NAME OF BENEFICIARY	BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

ROS2-BANDIT (Bandwidth Aware Networking Dynamics and Integration Toolkit) is a software toolkit designed to reduce unnecessary wireless data traffic in modern robotic systems. Most robotic applications inherit a traditional design from wired environments, where all data streams are always kept active. However, in wireless factory setups with multiple robots and modern sensors (e.g., 3D cameras, LiDAR), this results in massive data volumes—much of which is not needed at every moment. Even advanced 5G/6G networks can become overloaded by this constant, real-time traffic.

ROS2-BANDIT introduces smart dynamic control: it filters communication based on robot state, location, or task, thus saving bandwidth without disrupting performance. It integrates seamlessly into Robot Operating System (ROS2)-based systems and includes a user-friendly interface for configuration and monitoring.

Trial 1. April–May 2025, BME HSNLab 5G Test Lab (Hungary)
First working setup of ROS2-BANDIT in a collaborative pick-and-place task using a robotic arm and a mobile rover. Demonstrated seamless operation and integration.

Trial 2. June 2025, WZL RWTH Aachen (Germany)
A robotic arm and a quadruped robot cooperated to transport items. Achieved over 30% bandwidth reduction and 30% increase in robot capacity on the same network.

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ARCHITECTURE

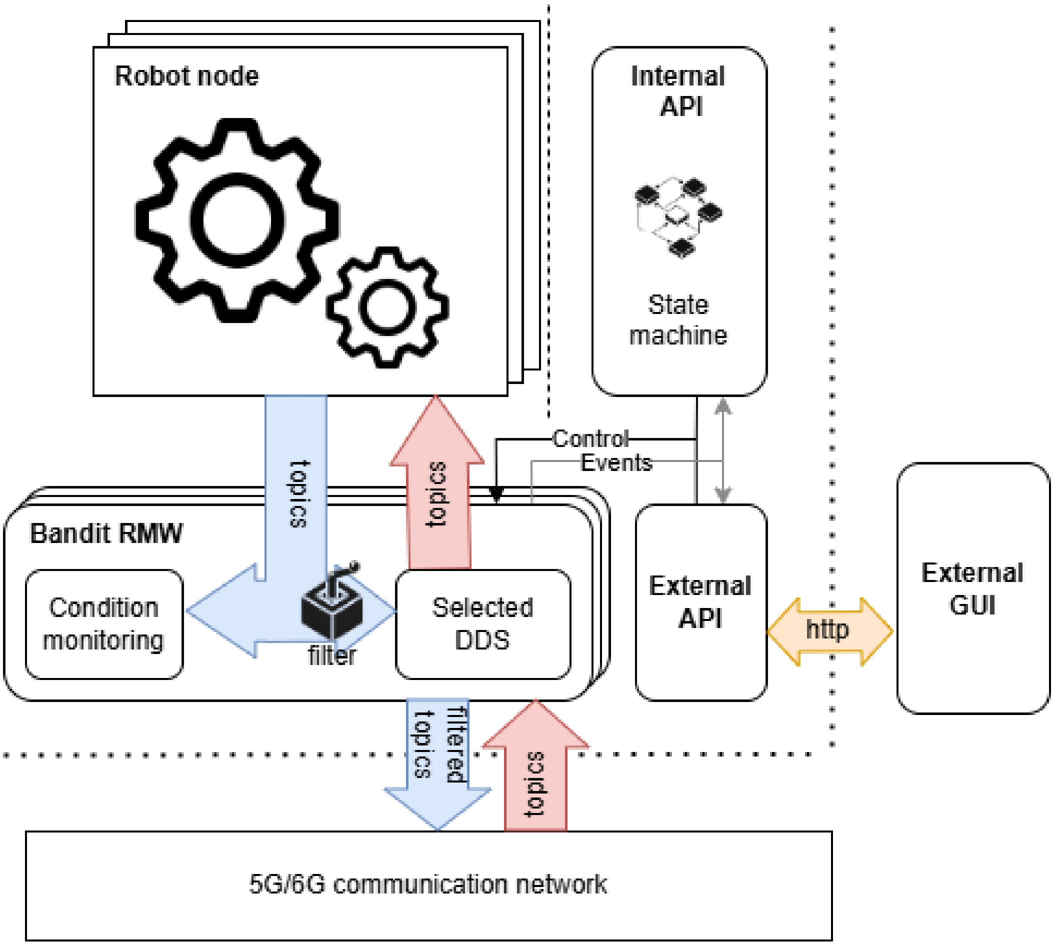

Figure 125: ROS2-BANDIT Architecture.

The ROS2-BANDIT architecture, shown in Figure 125, includes several connected parts working together. Each robot runs a Bandit ROS Middleware (RMW) layer that watches and filters ROS2 messages in real time. These filtering decisions are guided by a flexible state machine that reacts to events like control commands, location, or time. An External API links the robot's internal logic with outside tools. It helps manage message filtering and provides live system data. It also supports a secure web interface where users can view and adjust communication settings. The system works smoothly with standard DDS middleware, making sure that only allowed messages are sent over the network. Communication runs over a 5G/6G link, with data flows adapting automatically to the robot's current activity.

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TRIAL

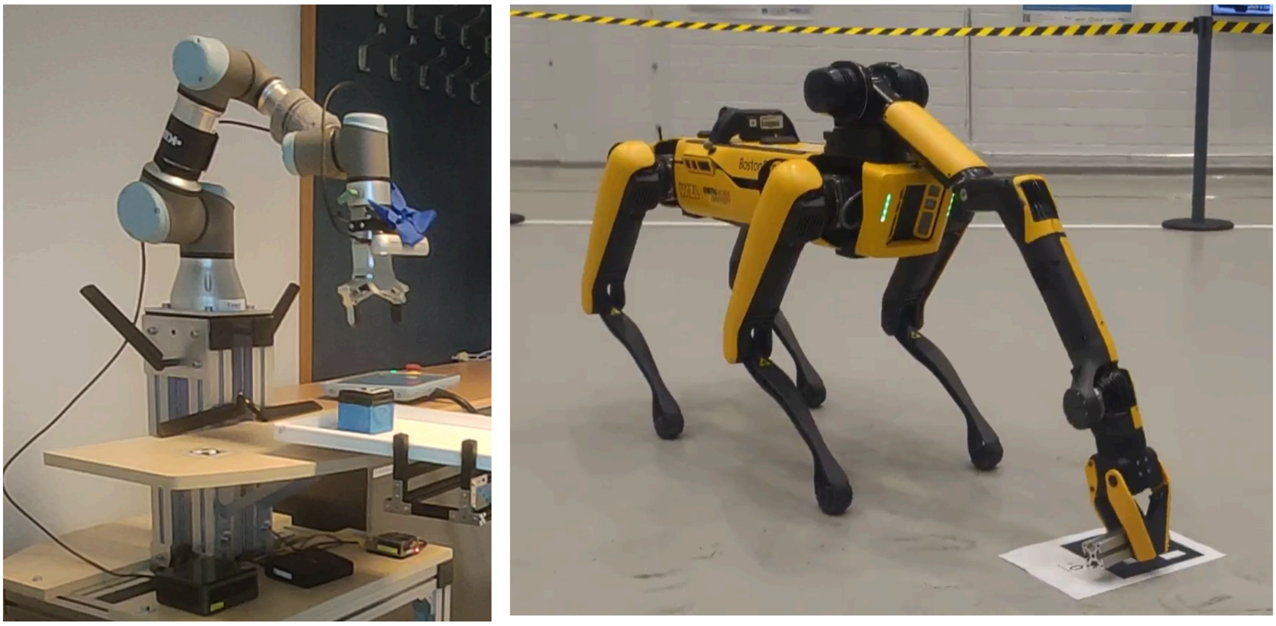

Figure 126: Trials at the 5G sites.

Budapest (Apr–May 2025) UR3 arm plus AMR on a private 5G cell. ROS 2 nodes were containerised in the edge; Bandit broker and GUI ran in a management container. A state-machine blocked depth camera and joint-feedback topics when idle, re-enabling them only for pick-and-place and transport actions, yielding 59 % mean bandwidth savings (from 14% up to 94%).

WZL RWTH Aachen (Jun 2025) Kinova Gen3 arm and Boston Dynamics Spot on the 5G-ICE network. Local driver PCs bridged traffic to an edge host running Bandit services. Enhanced policies silenced arm feedback and high-rate video.

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RESULTS

The project achieved over 30% average bandwidth reduction in real-world robot deployments, with peaks above 90%, enabling denser wireless robotic setups even on constrained 5G/6G networks. Key technical KPIs fulfilled include reduced traffic load, increased robot capacity, and full ROS2 compatibility. The results figure shows potential vs. actual bandwidth and the dynamically saved percentage during the Budapest trial using a robot arm and AMR.

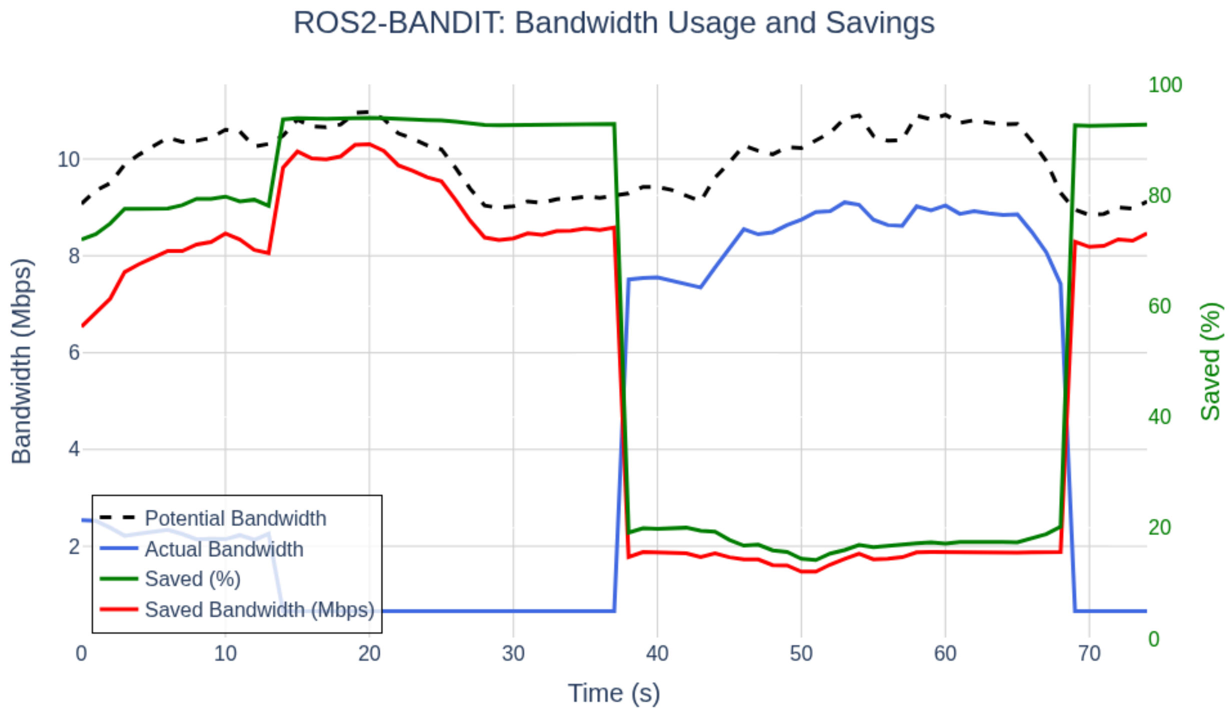

Figure 127: Traffic saving during a pick-and-place task.

5G EMPOWERMENT

Previous network generations could not support high-volume, real-time sensor streams. 5G/6G finally makes this possible by enabling mobile robots to transmit rich data like LiDAR and 3D video continuously with low latency and high reliability. However, many robotic systems still follow wired-world designs that overload real-world wireless links. ROS2-BANDIT addresses this by dynamically filtering data streams, ensuring scalable, efficient communication even on advanced 5G/6G infrastructure.

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PROJECT NAME (ACRONYM)	DR BASED X-G CYBER SECURITY FOR INDUSTRY5.0+ (SCAX)
NAME OF BENEFICIARIES	CISC SEMICONDUCTOR GMBH VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

The SCAX project focused on improving the security of 5G wireless networks by detecting falsified or malicious signals at the physical layer level, where the actual radio waves are transmitted. The team explored free, open-source tools and tested advanced hardware (like software-defined radios and specialized processors) to spot threats. In June 2025, they ran a trial at a smart factory in Linz, Austria (JKU LIT / Silicon Austria Labs), where they successfully tracked a moving device using radio signal direction. Key partners included CISC (a cybersecurity company) and BUT (Brno University of Technology). A major result was showing that their system could detect and locate illegitimate transmitter activity—even in complex factory settings—offering a new layer of protection for future wireless networks.

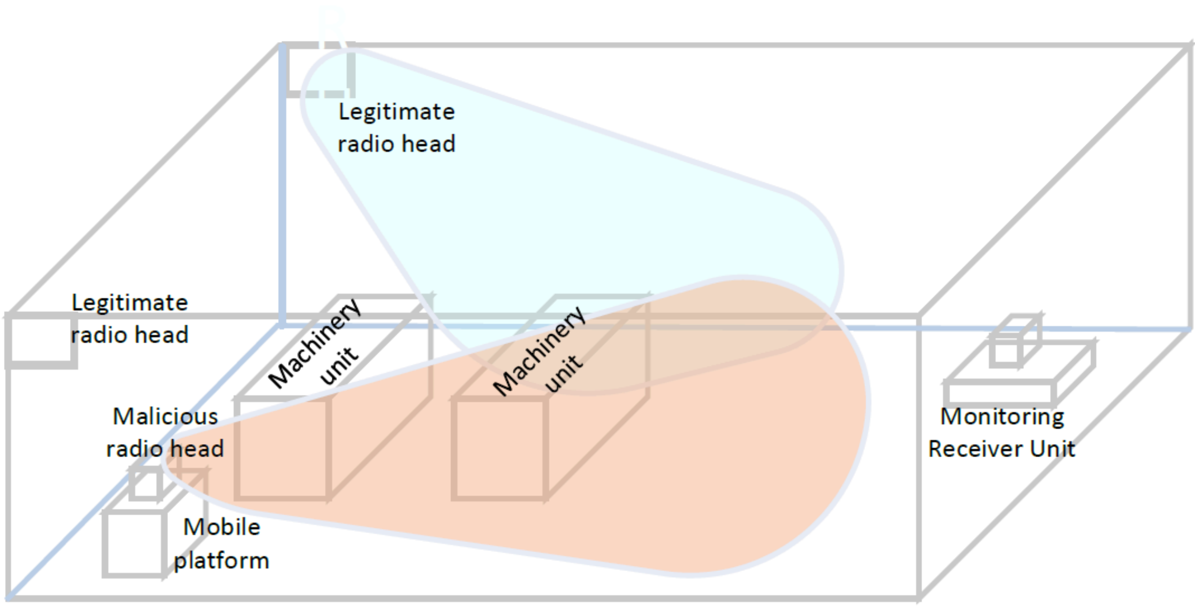

Figure 128.

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ARCHITECTURE

The SCAX project architecture combines smart hardware and software to detect threats in 5G networks. At its core is a custom-built radio receiver with five antennas that listens to wireless signals in the 3.5 GHz band, commonly used for 5G SA. The system analyzes the direction and behavior of incoming signals to spot unusual activity, such as false base stations. It uses advanced signal processing and AI to classify threats, running on flexible hardware platforms like RFSoC (a chip combining radio and processing functions) and software-defined radios (SDRs), which can adapt to different radio signals. All components are designed to work together in real-time, making it possible to monitor, analyze, and respond to security risks in complex environments like factories.

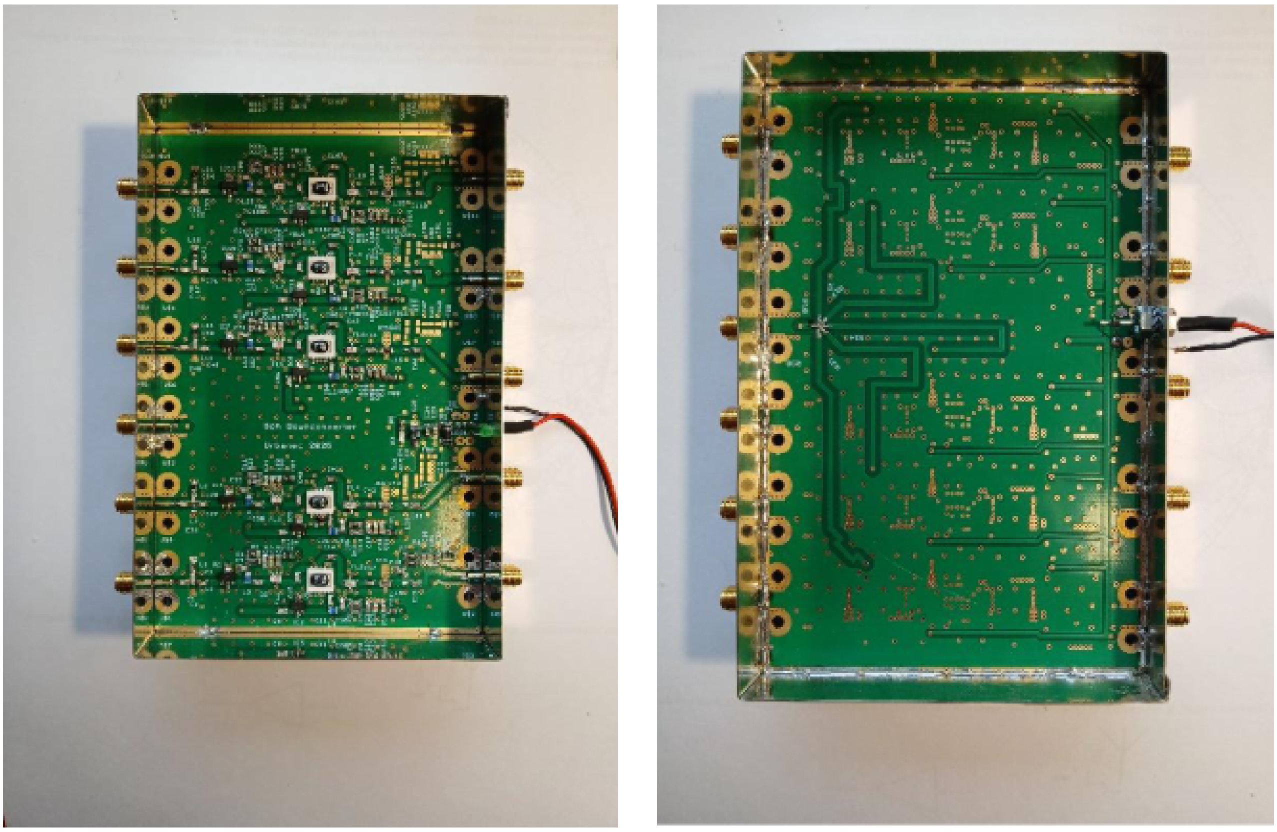

Figure 129: Assembled 5-channel downconverter board for 3.5 GHz band – top (left) and bottom (right).

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TRIAL

The SCAX trial was deployed at the JKU LIT Factory in Linz, Austria, in cooperation with researchers from Silicon Austria Labs. A 5-channel receiver with a uniform circular array was set up to monitor 5G signals in the 3.5 GHz 5G SA band. A mobile robot equipped with a 5G UE device was used to simulate a moving user. The system tracked the robot's position by analyzing signal direction. This setup tested the ability to detect and localize real vs. false transmitters in an industrial environment.

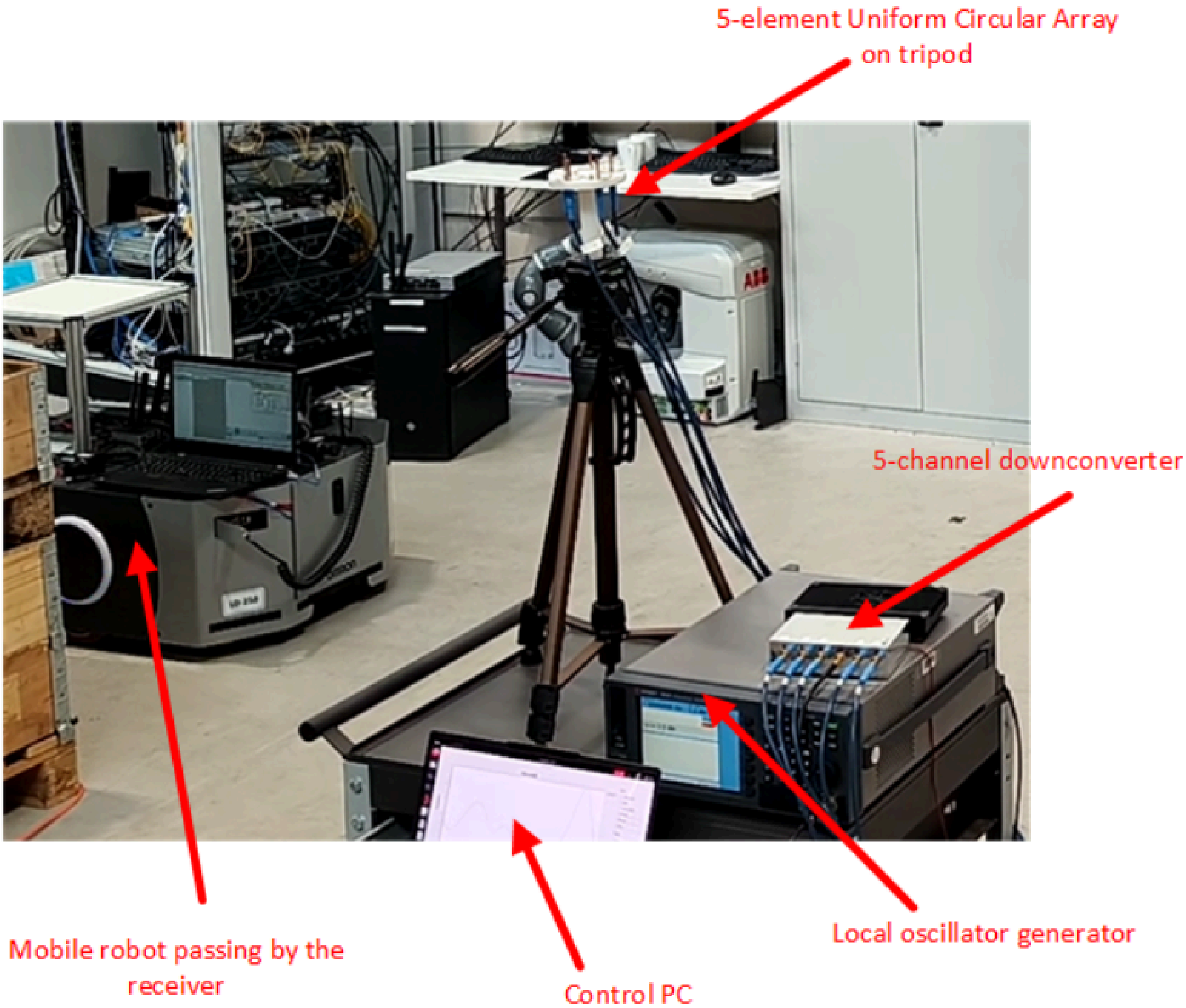

Figure 130.

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RESULTS

SCAX successfully demonstrated detection and tracking of 5G devices using signal direction, improving physical-layer security. Key achievements include a 5-channel receiver prototype, verified in a real factory, and accurate localization of moving transmitters. Performance KPIs met: real-time signal capture, AoA accuracy, and system coherence. Business KPI: strong potential for integration in Industry 4.0 security systems.

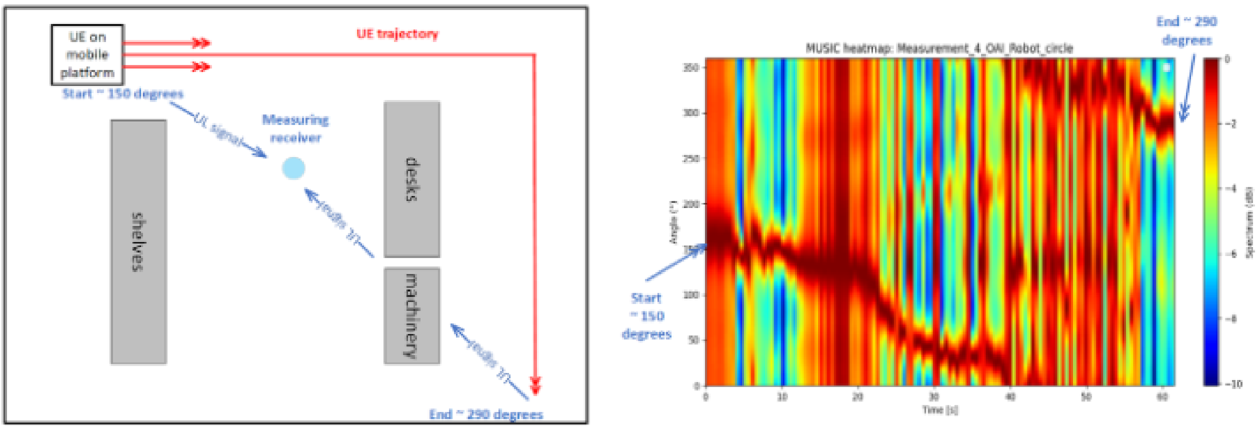

Figure 131.

Tracking the UE mounted on the mobile robot in the factory. Measurement scenario (left) and gathered AoA map (right).

5G EMPOWERMENT

Future technologies will offer major improvements over earlier mobile networks. Key features include:

- Faster speeds for real-time data transfer
- Ultra-low latency, enabling instant communication
- Massive device connectivity, ideal for smart factories and IoT
- Network slicing, allows tailored services for specific needs
- Enhanced reliability and precision positioning in 5G Advanced and 6G

These benefits enable advanced applications like autonomous robots, secure wireless control, and real-time monitoring–capabilities not possible with 4G or earlier networks.

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PROJECT NAME (ACRONYM)	THE REMOTE-CONTROLLED ASSEMBLY PROCESS (TRAP)
NAME OF BENEFICIARIES	UNIVERSITY OF CAMERINO CENTAUROOS
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 31/07/2025
LIST OF INVOLVED PARTNERS	RWTH-IP

OVERVIEW

TRAP (The Remote-controlled Assembly Process) explores the potential of 5G to enable real-time data exchange across digital environments, enhancing efficiency in building processes. The project aims to bridge the gaps between design, production, assembly, and management by creating an integrated workflow where data is seamlessly shared among stakeholders. TRAP envisions a collaborative procedure where designers and engineers (skilled in digital twins and computational design), producers (using robotic 3D printing), and on-site workers (equipped with AR devices) interact simultaneously to ensure a flexible and efficient construction process. Core technologies include Building Information Modeling (BIM), computational design, digital twins, concrete 3D printing, mixed reality, and 5G connectivity. Central to this ecosystem is the BIM-based digital twin, functioning as a dynamic platform for managing, sharing, and coordinating data throughout the construction lifecycle. Led by the University of Camerino (Italy), with support from Centauroos srl, an expert in recycled-concrete 3D printing, the project culminates in the Green5Wall: a modular, dry-assembled structure made of uniquely shaped 3D-printed blocks. It reduces solar radiation, supports greenery integration, and is optimized for storage, transport, and assembly.

ARCHITECTURE

The TRAP project adopts a structured, phased methodology that integrates both digital and physical processes throughout all construction stages. In the design phase, iterative collaboration and data-driven tools are employed to define project goals that align with performance targets and real-world constraints. The production phase incorporates advanced manufacturing methods and embedded sensors to ensure high-quality outcomes, effective cost control, and real-time process monitoring, while Mixed Reality technologies are used to validate outputs and improve logistics efficiency. During assembly, MR tools guide human operators with precision, enhancing accuracy and minimizing errors. Finally, the lifecycle phase enables the continuous digital updating of components to support ongoing asset management and improve long-term operational performance.

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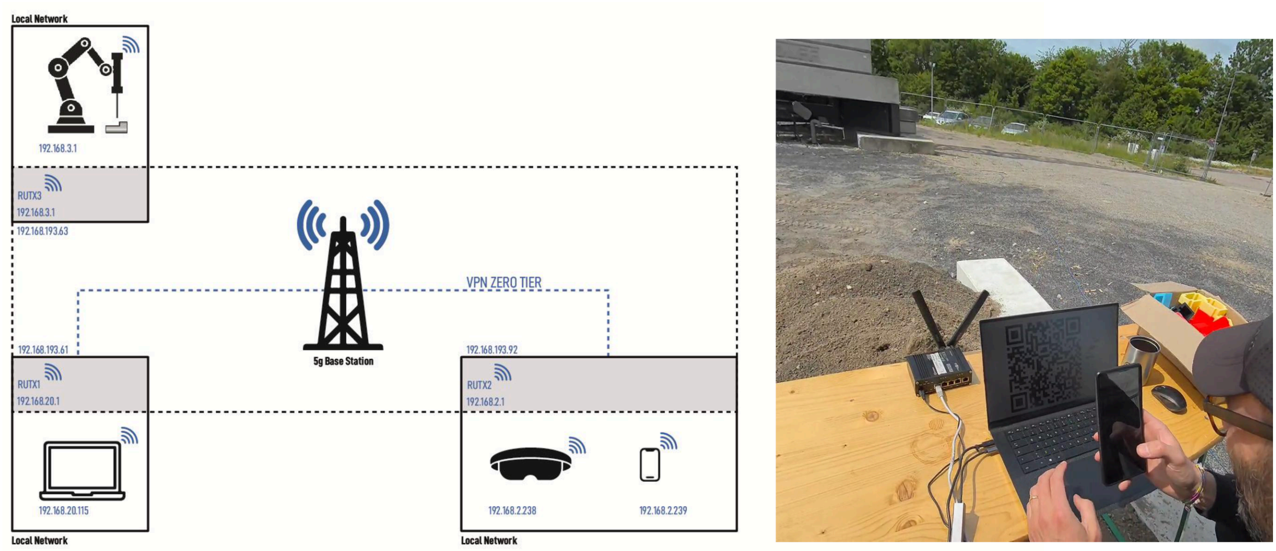

Figure 132.

TRIAL

The test case involves installing the Green5Wall system within a designated steel framework at the test facility provided by the hosting organization. The assembly is performed by the project team using advanced Mixed Reality headsets for hands-free guidance, supported by a robust 5G network that enables real-time video streaming and remote assistance. Comprehensive quantitative and qualitative evaluations are conducted to assess key performance metrics, including the speed and accuracy of assembly and disassembly, along with the efficiency of the re-palletizing process. These findings offer valuable insight into the system's applicability in real-world prefabrication contexts.

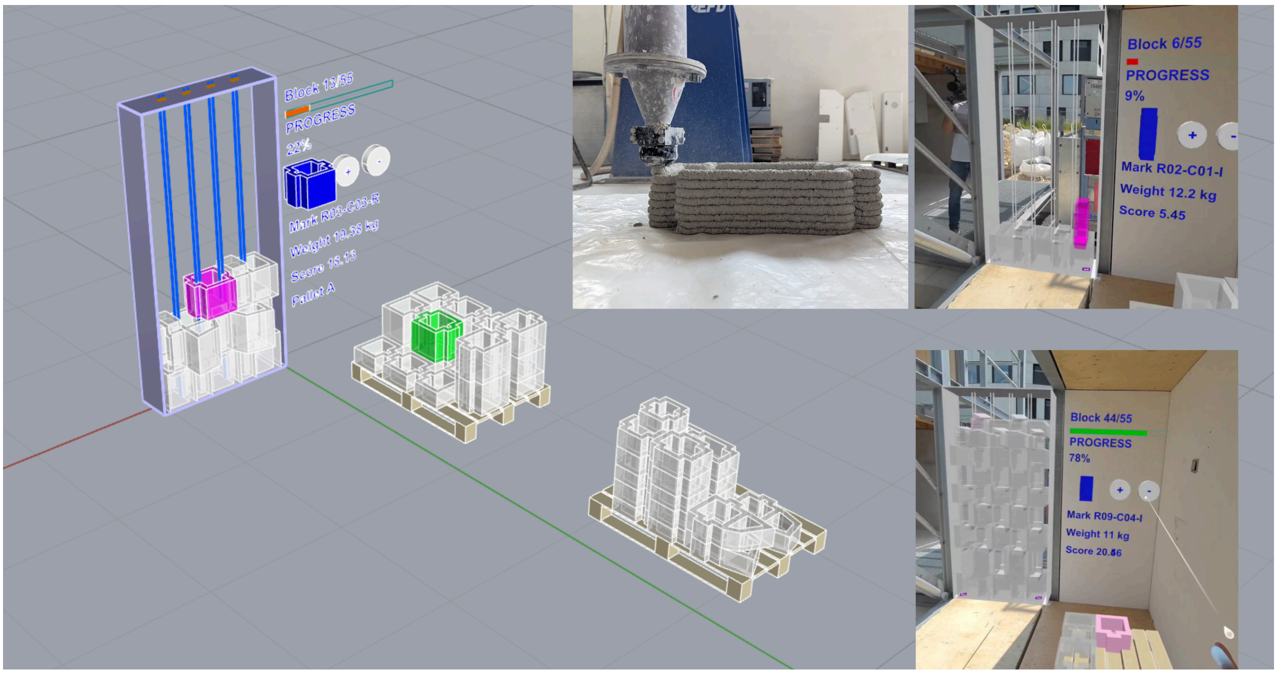

Figure 133.

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RESULTS

The TRAP project successfully demonstrated a 5G-enabled, AI-based platform for predictive maintenance and production optimization in the prefabrication industry. Key achievements include the integration of BIM-based digital twins, real-time data flow from edge to cloud, and high-performance anomaly detection. The system improved process efficiency, reduced downtime, and validated business KPIs such as scalability and interoperability.

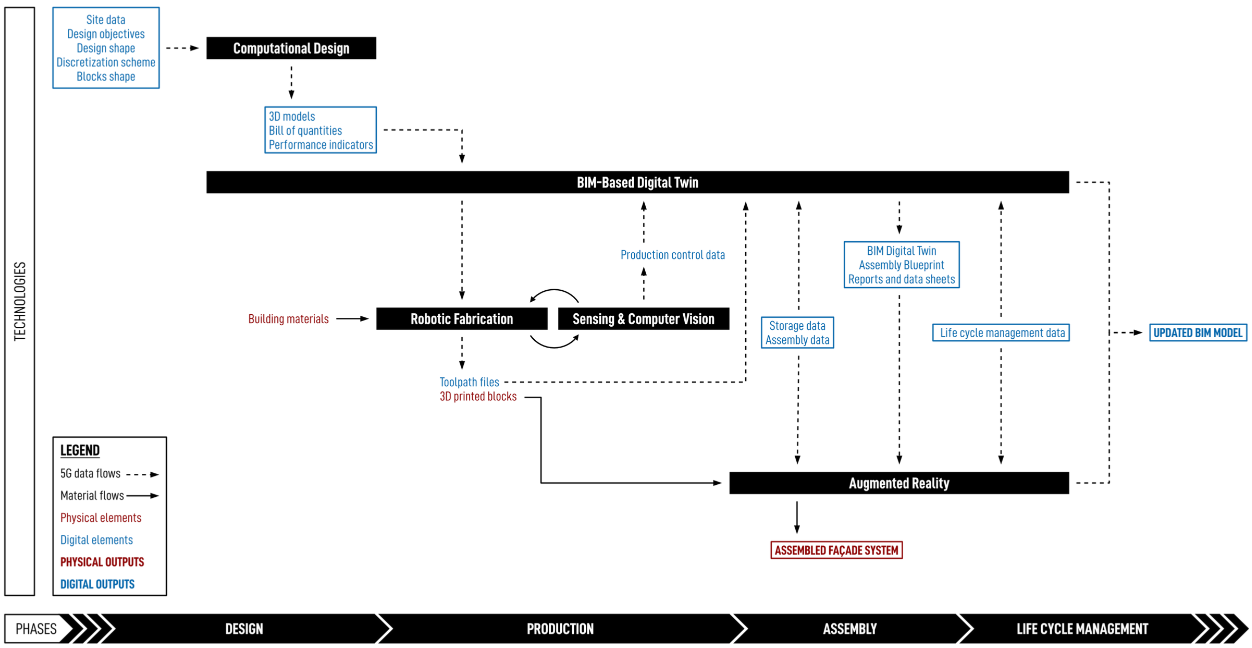

Figure 134.

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5G EMPOWERMENT

5G enables real-time data exchange, low-latency communication, and synchronized control in construction, enhancing digital twins, AI analytics, and robotic workflows. The TRAP project integrates design, simulation, and validation through 5G, using the Teltonika RUTX50 router to connect platforms like Speckle, sensors, and MR devices. Its stability and multi-band support ensure seamless edge-to-cloud coordination even in challenging site conditions.

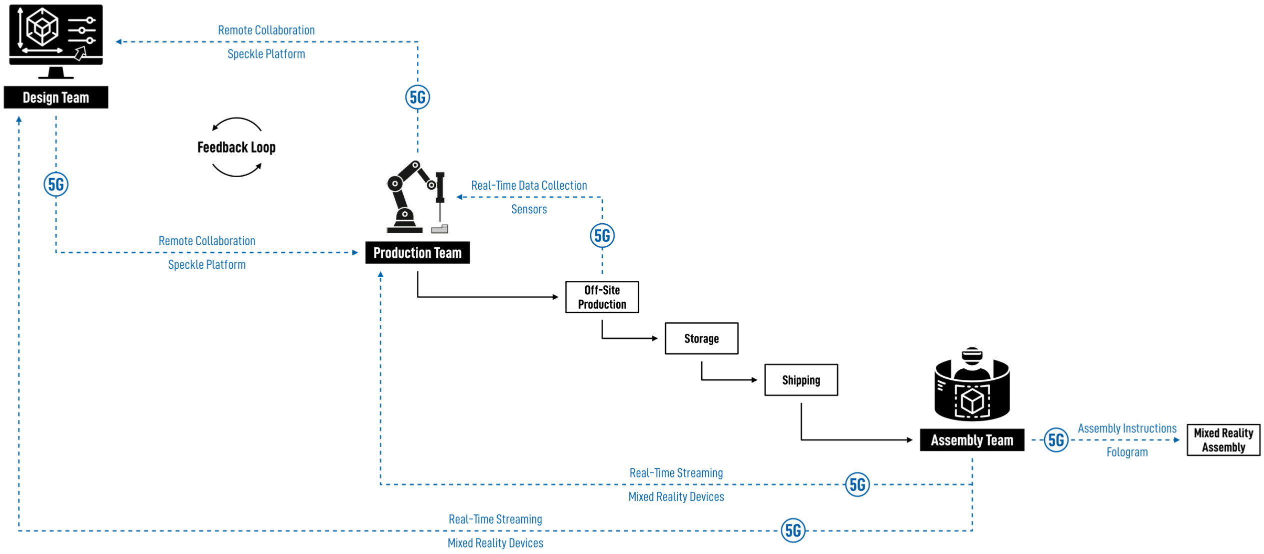

Figure 135.

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PROJECT NAME (ACRONYM)	EDGEPMU EMPOWERING CITIZENS IN ENERGY COMMUNITIES (PMU-EC)
NAME OF BENEFICIARIES	METER SOLUTIONS KISTELEKI ENERGIAKÖZÖSSÉG NONPROFIT KORLÁTOLT FELELŐSSÉGŰ TÁRSASÁG
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 31/08/2025
LIST OF INVOLVED PARTNERS	RWTH

OVERVIEW

The project focuses on collecting high-frequency power quality measurements with edgePMU devices on a low-voltage grid section within the context of the Kistelek Energy Community in Hungary. edgePMU data is enriched with standard measurements (energy consumption, production, voltage levels at prosumer or consumer energy community members) and made available in an anonymized form for interested third parties via a data portal. The edgePMU devices use a local 5G network to send measurements to the server.
With this data available, interested parties, such as a DSO, can smartly intervene in critical situations. For instance, it can remotely control inverters to maintain voltage stability and prevent local power outages. The Target-X project enhances this system with advanced PMU (Phasor Measurement Unit) technology, enabling high-speed measurements and smart protection against grid disturbances. These features are tested in a real-world setting, within a functioning energy community.

Figure 136: Energy commission monitoring with PMU.

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ARCHITECTURE

In this energy-sharing community, each household is equipped with a smart energy meter and a solar inverter. These devices are monitored and controlled by a Modbus RTU interface, which communicates with local gateways via a wireless mesh network. Measured data is sent to the gateways via this network, and the gateways use 5G to forward this data to the server.

The gateways also manage energy storage units to support grid balancing. All units communicate using the standard Modbus protocol. The Target-X PMU device enhances the system with high-frequency data collection for precise protection and fault detection, making the network more robust and ready for future 5G/6G applications.

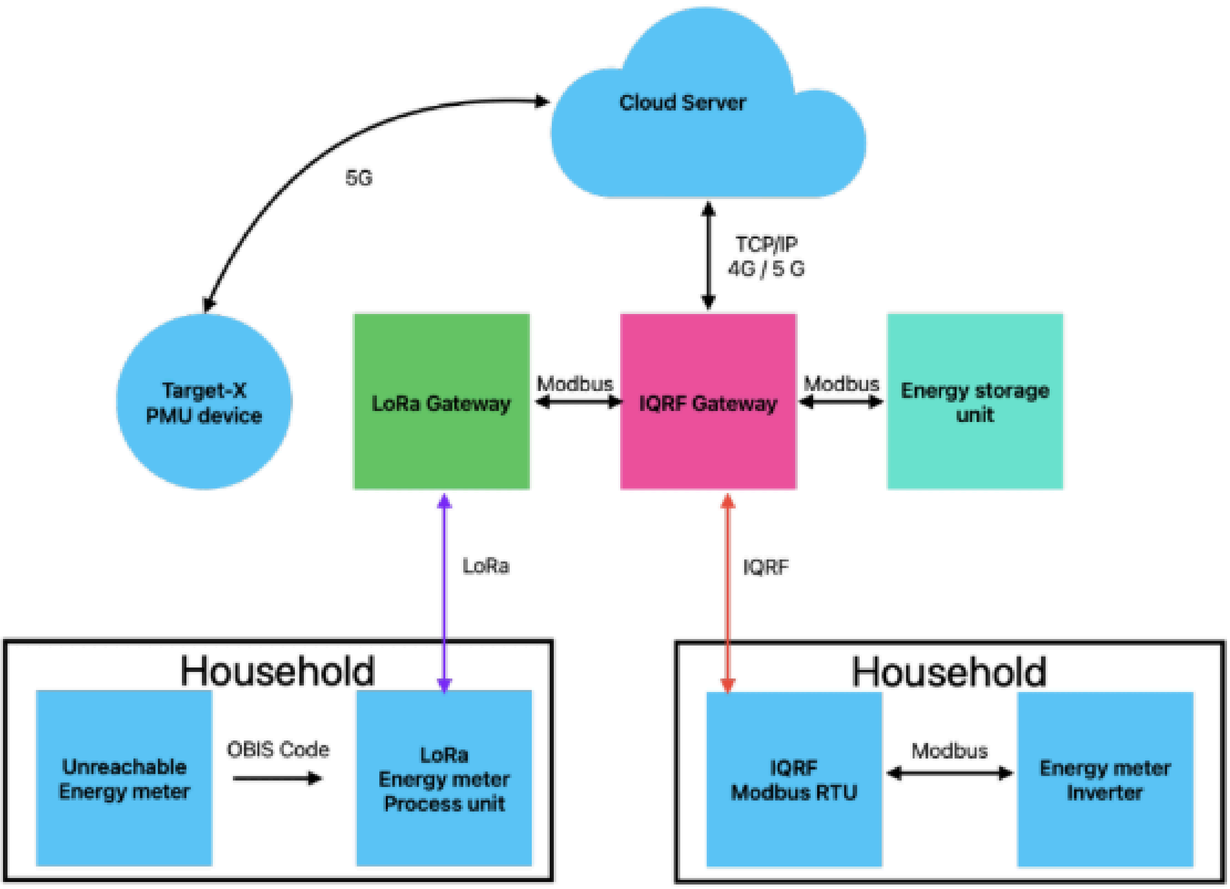

Figure 137: Project architecture

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TRIAL

PMU Integration and Grid Converter

- Designed and built a custom grid converter for safe interfacing with household voltage and current signals
- Converts three-phase grid inputs to extra-low voltage levels compatible with the PMU's ADC
- Enables continuous, high-resolution data acquisition for real-time control and protection
- Successfully field-tested in a live LV grid environment
- Full design and testing methodology to appear in an upcoming IEEE article.

Figure 138: TARGET-X Edge PMU

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RESULTS

Key Outcomes

- Integrated edgePMU devices into the local grid that communicate measurements via 5G
- The setup enables the high-precision monitoring of the entire low-voltage grid (energy consumption, voltage levels by phases)
- The operation will yield reliable data for developing:
  - enhanced fault detection and protection algorithms (to identify and forecast faulty grid sections and design the intervention)
  - enhance the economic optimization models (to avoid, postpone, or optimise grid development activities).

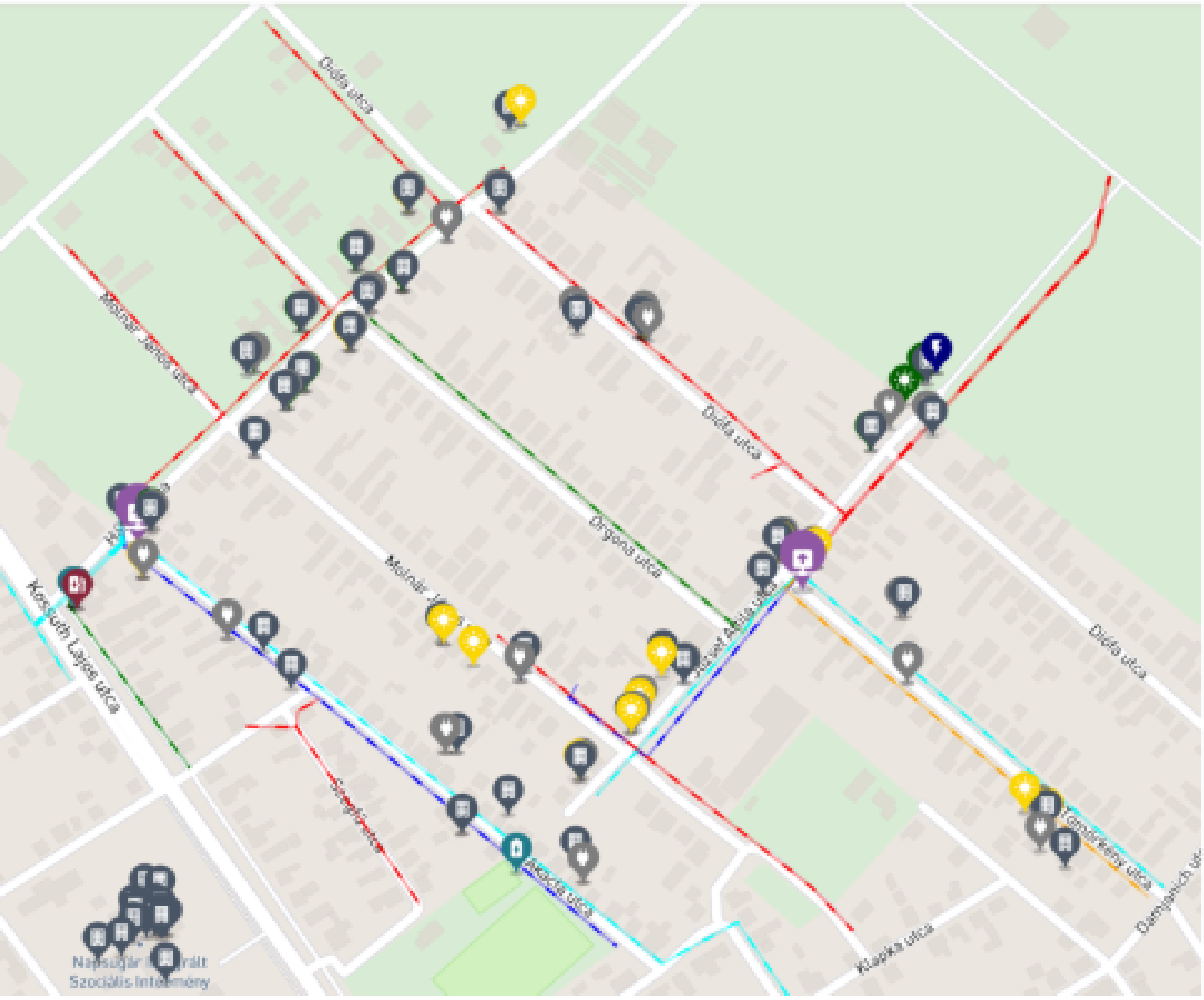

Figure 139: Layout of the monitored energy commission

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5G EMPOWERMENT

5G/6G Empowerment and Added Value

Key advantages of using 5G/6G technologies in this project:
- High data throughput for real-time grid monitoring
- Ultra-low latency, enabling fast fault detection
- Scalable protection logic for low-voltage networks
- Supports predictive maintenance and remote control
- Unlocks capabilities not possible with older networks.

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PROJECT NAME (ACRONYM)	INTERACTIVITY EVALUATION IN BEYOND-5G NETWORKS (INTERACT-B5G)
NAME OF BENEFICIARY	KARLSTAD UNIVERSITY
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	EDD

OVERVIEW

The INTERACT-B5G Project explored how future networks can support real-time interactive services such as online gaming, cloud-based Augmented/Virtual Reality (AR/VR), and Industry 4.0 (I4.0) process automation. These services demand low latency, high stability, and continuous performance, requirements not fully addressed by existing 5G public networks yet.

During the project, Karlstad University ran measurement campaigns in two Beyond-5G (B5G) non-public networks (NPNs): CARL-W (Karlstad, Sweden) and 5G-ICE (Aachen, Germany). Using standardized ITU-T/ETSI methods combined with proprietary and custom tools, the team benchmarked Quality of Service (QoS) and Quality of Experience (QoE) across multiple scenarios.

Key achievements include:

- A large open dataset of QoS/QoE performance across multiple scenarios.
- Demonstrated benefits of edge service placement for latency-sensitive services.
- Validation of enhanced radio scheduling techniques (e.g., pre-scheduling) for improving industrial automation performance.
- Identification of bottlenecks to guide 6G system design.

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ARCHITECTURE

The Project used a measurement-and-analysis setup embedding standardized testing methods.
HW/SW setup

- Clients: 5G-enabled smartphones (Crosscall Stellar-X5 and Core-Z5).
- Servers: ASUS NUC edge units and cloud servers.
- Software: Rohde&Schwarz (R&S) Qualipoc, R&S ROMES, MATLAB/Python scripts.

Figure 140 shows the Project portable setup, including a Crosscall smartphone (client) and an ASUS NUC (server).

Figure 140: The portable setup of the INTERACT-B5G Project (Client: Crosscall device with Qualipoc; Server: ASUS NUC 12WSK).

Testing methods

- ITU-T G.1051 procedure for real-time service interactivity scoring
- ETSI throughput tests
- ICMP ping
- Ericsson's open-source udp-ping for one-way delay analysis

Emulated traffic patterns

- eGaming real-time: Medium-to-high rate downlink/uplink-symmetric flows.
- AR/VR cloud gaming: Low-rate uplink control plus high-rate downlink video transmission.
- Industry 4.0 Process Automation: low-rate low-latency control loop.
- Industry 4.0 Watchdog: low-rate downlink/uplink-symmetric flows.

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TRIAL

Trials were conducted at:

- CARL-W testbed (Karlstad, Sweden): Hybrid 4G/5G standalone/non-standalone setup with indoor/outdoor coverage and edge servers.
- 5G-ICE testbed (Aachen, Germany): 2700 m2 industrial shopfloor with a reconfigurable 5G network, enabling experiments with different radio scheduling mechanisms (dynamic vs. pre-scheduling).

Figure 141 shows an example of the Ericsson radio dots forming the CARL-W testbed and providing 4G/5G indoor coverage at the Department of Mathematics and Computer Science of Karlstad University.

Figure 141: Example of 4G/5G Ericsson radio dots forming the CARL-W testbed and providing non-public connectivity at Karlstad University.

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RESULTS

Results showed that B5G NPNs outperform 5G public networks, reducing latency and improving stability. Among several key insights:

- Edge-placed services lowered response times, enhancing AR/VR and gaming QoS/QoE (see Figure 142 for results obtained in the CARL-W testbed).
- Pre-scheduling significantly boosted the performance of Industry 4.0 services, cutting delay variation and packet loss.
- The dataset created during the measurements in the CARL-W testbed is made available for research, standardization, and industry use.

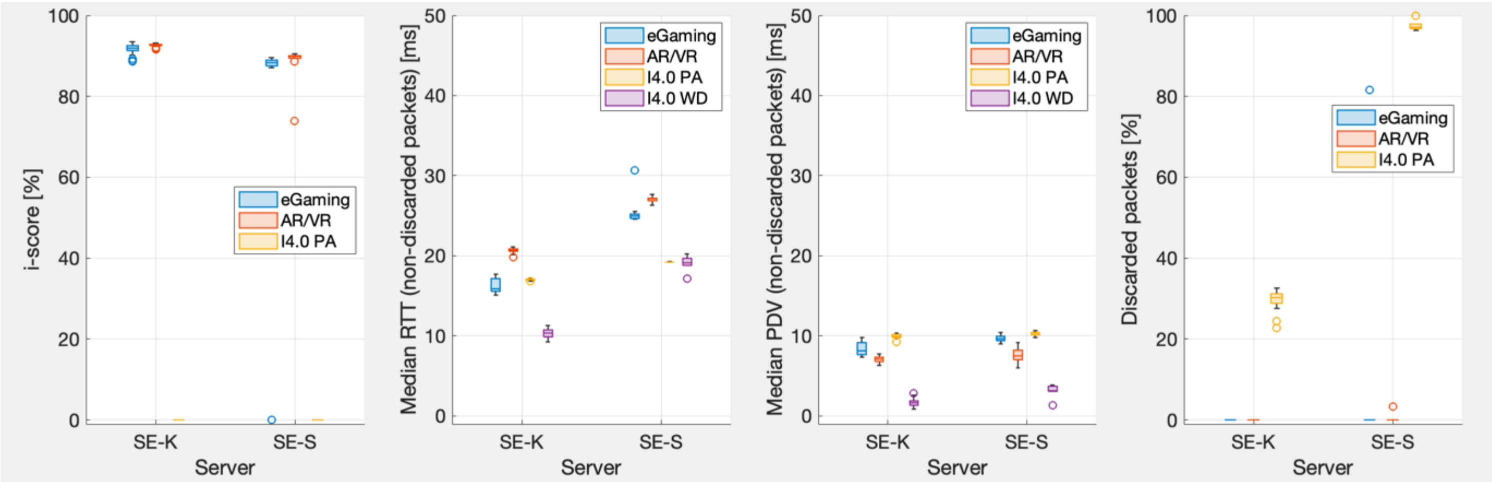

Figure 142: QoS/QoE performance obtained in the CARL-W testbed during the ITU-T interactivity tests, for different traffic patterns and server locations. QoS/QoE metrics: interactivity score (i-score [%]), packet round trip time (RTT [ms]), packet delay variation (PDV [ms]), and discarded packets [%]. Traffic Patterns: eGaming, AR/VR, I4.0 Process Automation (PA), and Industry 4.0 Watchdog (WD); Server location: edge (SE-K) vs. cloud (SE-S).

5G EMPOWERMENT

The Project allowed reproducible trials in controlled testbeds, offering unique insights into how B5G can meet future industrial and consumer needs. It particularly demonstrated how B5G systems provide support to real-time interactive services by lowering latency and increasing service stability and continuity.

Through the Project results, it was also possible to identify current bottlenecks and validate the benefits of advanced system features (e.g., pre-scheduling and edge deployment) on QoS/QoE.

In summary, INTERACT-B5G highlighted how B5G and 6G can unlock new markets and applications.

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PROJECT NAME (ACRONYM)	HARMONIZING DATA-DRIVEN SUSTAINABILITY AC (ECOSYNC)
NAME OF BENEFICIARIES	WEGO SRL, MINERVAS S.R.L.,
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

The Ecosync project aims to address key challenges in EV battery management and sustainability within the electric vehicle sector, leveraging the MinervaS app and Volvero's vehicle-sharing platform. The solution uses real-time data collection via OBD-II dongles and smartphones (4G/5G) to create digital twins of vehicles, optimizing battery usage, promoting eco-friendly driving, and providing tailored charging suggestions. The main pilot was conducted in Vicenza (April 2025) with a Lancia Ypsilon and, as per TPI7, with a Fiat 500e EV at the University of Salerno, focusing on urban driving scenarios using 4G/5G. Key partners include MinervaS, Volvero, and Wego. Achievements include successful TRL6 real-world demonstrations, seamless app integration, robust 5G performance (low latency, high throughput), and the development of an interactive user scorecard for energy efficiency, saved km, and CO_2 savings. The project validates advanced, data-driven, and sustainable mobility services under real 5G conditions.

ARCHITECTURE

The Ecosync project architecture integrates vehicle, smartphone, and cloud components to optimize EV performance and sustainability. Data is acquired in real time from the vehicle through an OBD-II dongle, which connects to the user's smartphone via Bluetooth. The smartphone app (MinervaS) then transmits vehicle and driver data to the cloud platform over 4G/5G networks. The cloud hosts digital twins of vehicles, processes incoming data, and analyzes driver behavior, energy consumption, and charging patterns. Feedback and tailored recommendations are sent back to users in real time, with results displayed in an interactive scorecard within the Volvero app. The architecture ensures robust data aggregation, edge/cloud resource allocation, and seamless integration between hardware and software, enabling dynamic updates, efficient feedback loops, and cross-platform compatibility. The system is designed to be scalable, supporting different vehicles and devices, and exploits the advantages of 5G for low latency and high throughput.

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Main components:
- OBD-II dongle (vehicle data acquisition)
- Smartphone (Bluetooth, MinervaS app, 4G/5G connectivity)
- Cloud/edge server (data processing, digital twin, analytics)
- Volvero platform/app (user interface, scorecard, feedback)

This architecture enables real-time monitoring, sustainability reporting, and actionable eco-driving guidance for EV users.

TRIAL

Trial deployment took place at the University of Salerno (UNISA campus), using a Fiat 500e equipped with an OBD-II dongle and smartphones (iPhone, Samsung, Xiaomi) connected via 4G/5G. MinervaS and Volvero apps enabled real-time data acquisition and feedback. The urban circuit (3.3 km) tested connectivity, driver behavior, and eco-driving in real conditions, demonstrating robust 5G performance and seamless integration.

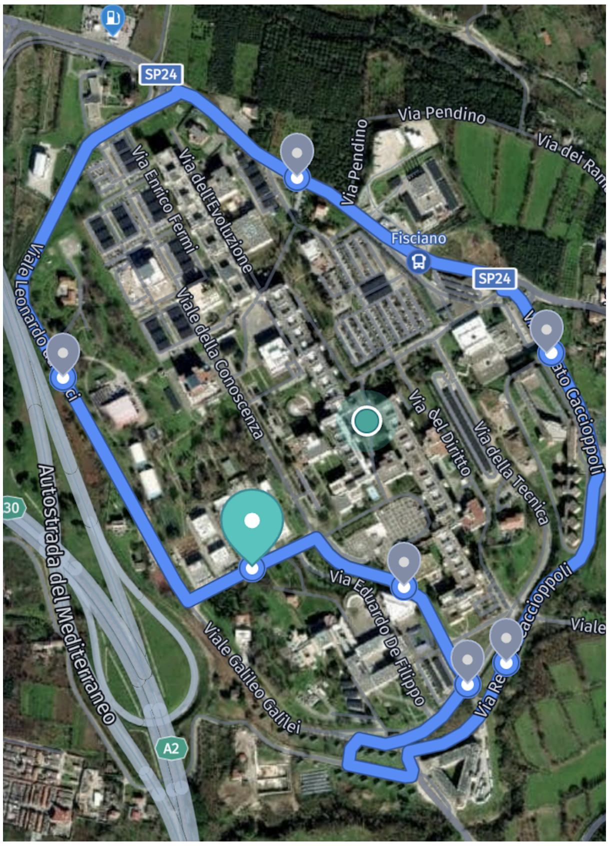

Figure 143.

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RESULTS

Ecosync achieved seamless integration of real-time EV monitoring, 5G connectivity, and driver feedback, validated in urban trials. Key results: low latency, high throughput, improved eco-driving, user scorecard, and potential for CO_2 savings. The project demonstrated TRL6 with robust data-driven KPIs, supporting new business models for EV sharing.

Test ID: 1 - iPhone, 2 - Samsung, 3 - Redmi // N - Normal, R - Range, S - Sherpa // 4 - 4G, 5 - 5G										
Date	Hour	Driving Profile	Test ID	Cell	Network	MQTT			API - elaboration	API - Maps
						Size 90th Percentile	Throughput	Latency	time spent	time spent
17/04/2025	14:39:30 - 14:45:03	Normal	3N5	Xiaomi	5G	10 B	1 msg/s	66,66 ms	596,4 ms	59,6 ms
17/04/2025	14:39:30 - 14:45:03	Normal	2N5	Samsung	5G	10 B	1 msg/s	55,73 ms	653 ms	49,8 ms
17/04/2025	14:39:30 - 14:45:03	Normal	1N5	iPhone	5G	10 B	1 msg/s	62,09 ms	696 ms	2 ms
17/04/2025	14:50:32 - 14:56:05	Range	3R5	Xiaomi	5G	10 B	1 msg/s	64,8 ms	597 ms	179,4 ms
17/04/2025	14:50:32 - 14:56:05	Range	2R5	Samsung	5G	10 B	1 msg/s	58,17 ms	576,4 ms	178,4 ms
17/04/2025	14:50:32 - 14:56:05	Range	1R5	iPhone	5G	10 B	1 msg/s	63,49 ms	3,74s	7 ms
17/04/2025	15:00:14 - 15:05:24	Sherpa	3S5	Xiaomi	5G	10 B	1 msg/s	59,9 ms	756,3 ms	74,1 ms
17/04/2025	15:00:14 - 15:05:24	Sherpa	2S5	Samsung	5G	10 B	1 msg/s	61,11 ms	618,9 ms	56,3 ms
17/04/2025	15:00:14 - 15:05:24	Sherpa	1S5	iPhone	5G	10 B	1 msg/s	78,18 ms	1.24s	6 ms
17/04/2025	15:09:20 - 15:14:16	Sherpa	3S4	Xiaomi	4G	10 B	1 msg/s	67,1 ms	623,7 ms	224,3 ms
17/04/2025	15:09:20 - 15:14:16	Sherpa	2S5	Samsung	5G	10 B	1 msg/s	57,31 ms	635,9 ms	920,9 ms
17/04/2025	15:09:20 - 15:14:16	Sherpa	1S4	iPhone	4G	10 B	1 msg/s	61,13 ms	625 ms	6 ms
17/04/2025	15:19:09 - 15:24:30	Range	3R4	Xiaomi	4G	10 B	1 msg/s	-	724,9 ms	126,5 ms
17/04/2025	15:19:09 - 15:24:30	Range	2R5	Samsung	5G	10 B	1 msg/s	72,42 ms	655,3 ms	329,2 ms
17/04/2025	15:19:09 - 15:24:30	Range	1R4	iPhone	4G	10 B	1 msg/s	97,75 ms	640 ms	9 ms
17/04/2025	15:28:10 - 15:32:40	Normal	3N4	Xiaomi	4G	10 B	1 msg/s	67 ms	582,8 ms	230 ms
17/04/2025	15:28:10 - 15:32:40	Normal	2N5	Samsung	5G	10 B	1 msg/s	62,44 ms	2,55s	2 s
17/04/2025	15:28:10 - 15:32:40	Normal	1N4	iPhone	4G	10 B	1 msg/s	62,34 ms	586 ms	4 ms

Figure 144.

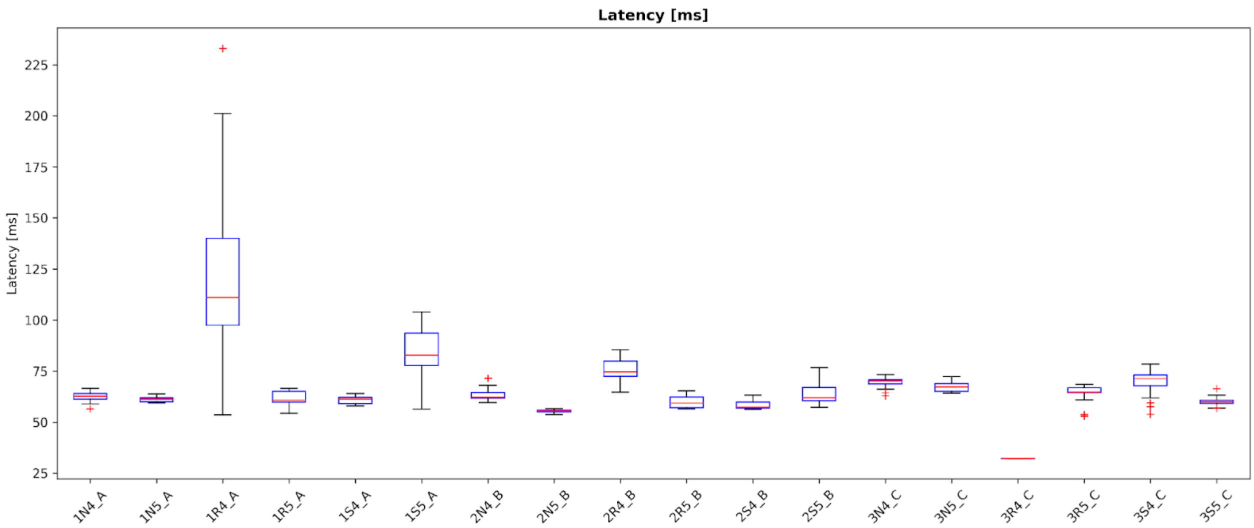

Figure 145.

5G EMPOWERMENT

5G enables ultra-low latency, high throughput, and reliable real-time data transfer, essential for EV monitoring and feedback in Ecosync. Unlike 4G, 5G supports dynamic updates, adaptive routing, and cloud-edge computing, allowing instant driver guidance and improved energy efficiency. These benefits pave the way for scalable, data-driven mobility and future-ready EV sharing, which previous generations cannot deliver.

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PROJECT NAME (ACRONYM)	VISUAL INERTIAL ODOMETRY AND RTK-GNSS MAPPING (VINS RTK MAPPER)
NAME OF BENEFICIARY	LINK ROBOTIK TEKNOLOJILERI MAK SAN VE TIC A.S.,
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	I2CAT

OVERVIEW

The real-time digital twin generation system uses a monocular camera, an inertial measurement unit, and RTK-GNSS to obtain the pose of the vehicle (localization), and meanwhile, it uses 3D Lidar measurements to generate a 3D point cloud map of the environment. The system can be mounted on the top of a car and communicate with a 5G cloud server. The 3D mesh files are generated on the cloud server, which can be used in a simulation environment to replicate the surroundings.

Figure 146: A picture from the test car and VINS-RTK-Mapper

Figure 147: Hardware box of the VINS-RTK-Mapper

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ARCHITECTURE

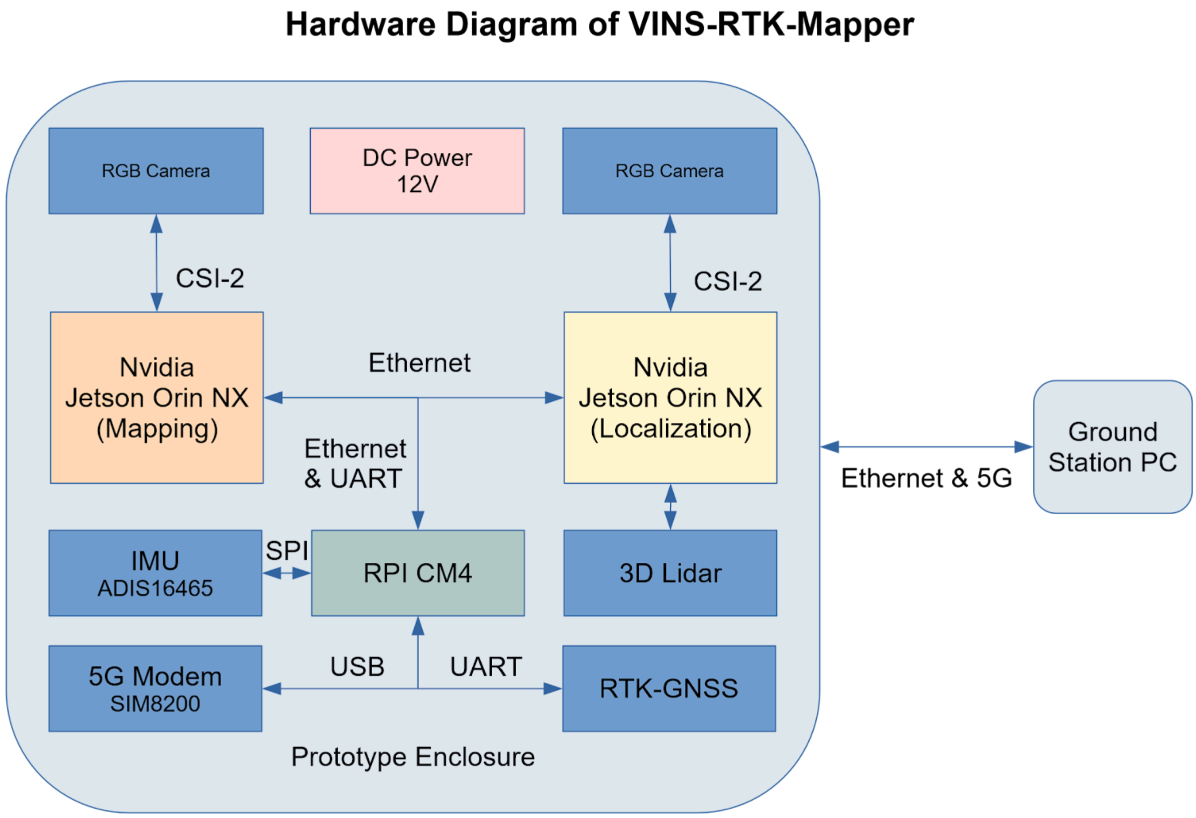

Figure 148: Hardware diagram

Figure 148 shows the hardware architecture of the VINS-RTK-Mapper device.

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TRIAL

1. A prototype box of VINS-RTK-Mapper is mounted on the top of the car by using vacuum suction cups, as shown in Figure 149. The prototype box includes all the hardware and software required for generating a digital twin, such as IMU, camera, RTK-GNSS receiver, 5G modem, processor modules, battery, etc. The 3D lidar is mounted on the top of the prototype box and connected by using a cable to the box.

Figure 149: Prototype attached to Test Vehicle

2. The process is started over the GUI screen of the prototype, which runs on the laptop inside the car. The GUI can show the current map and the pose of the vehicle. Also, the Start and End buttons will control the digital twin generation process. Another button named Process will start the surface construction process, and the Save button can fetch the output files from the server to save them into the storage device, e.g., flash drive, SSD. The user can use the files in the simulator environment for viewing or testing, etc.

3. The connection between the ground station laptop PC and prototype box is established over Ethernet (it can also be over a 5G network), and on the GUI, the process can be started and ended.

4. After the process is started, the car will be driven manually at a speed of about 20-40 km/h, and the software will process the sensory data and show the output.

5. Then, after the process is finished, the 3D map data is stored in a storage device and sent to the cloud server.

6. The post-processing software in the cloud server generates the simulation map files, and the output of the process is the digital twin of the environment, which can be viewed in the simulator software.

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The use case is completed.

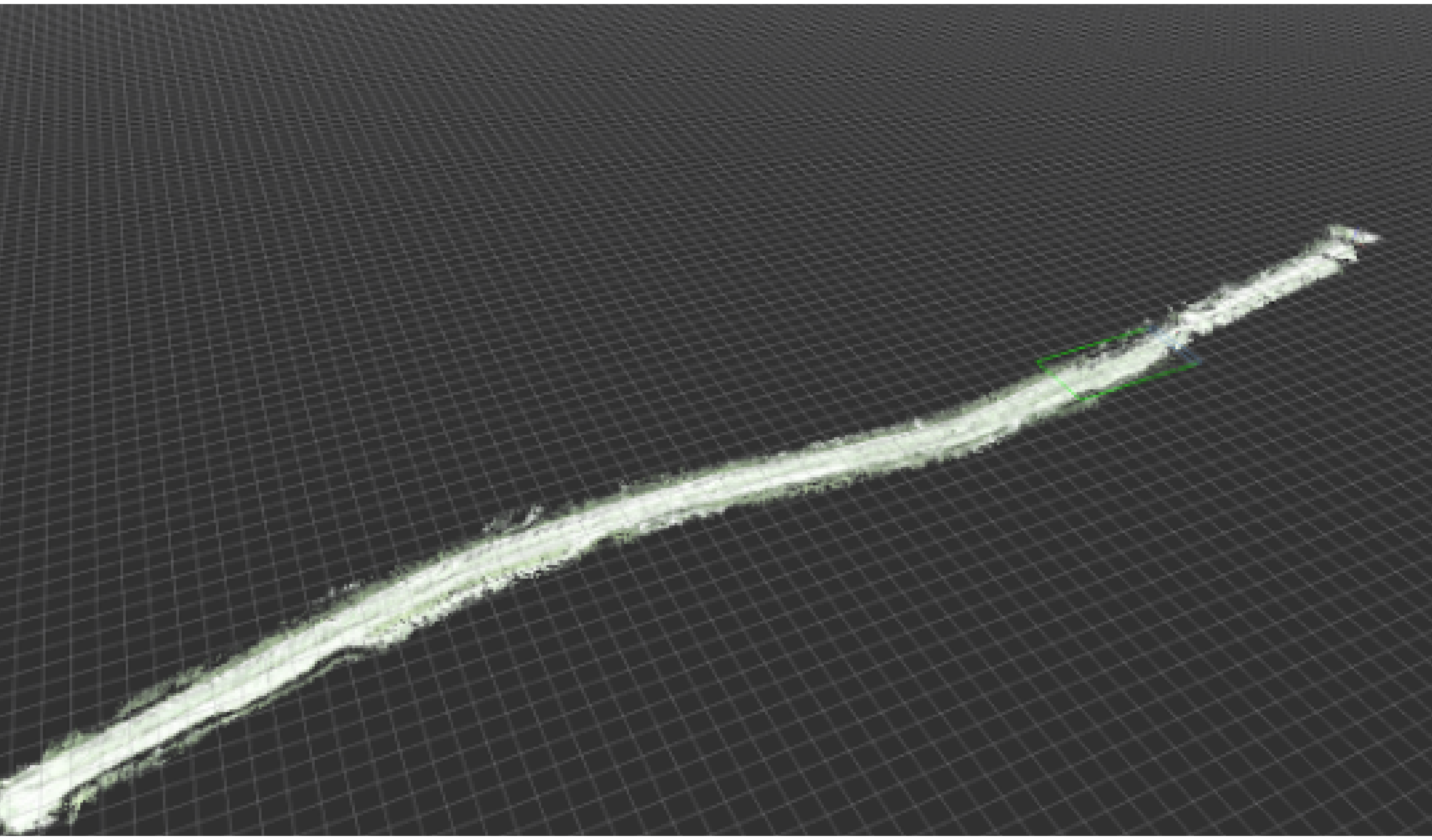

Figure 150: Example mesh generated in Bilisim Valley Technopark (Turkey)

Figure 150 shows an example mesh file generated over 1600 meters of path.

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RESULTS

The Vins RTK's prototype and Vins RTK Development plan were presented in 5G Techritory in Riga in the Startup Showcase in late October 2024, where it was highlighted for its integration with 5G-enabled positioning infrastructure and compatibility with 5G platforms. Some discussions with 6G-SNS stakeholders are also made.

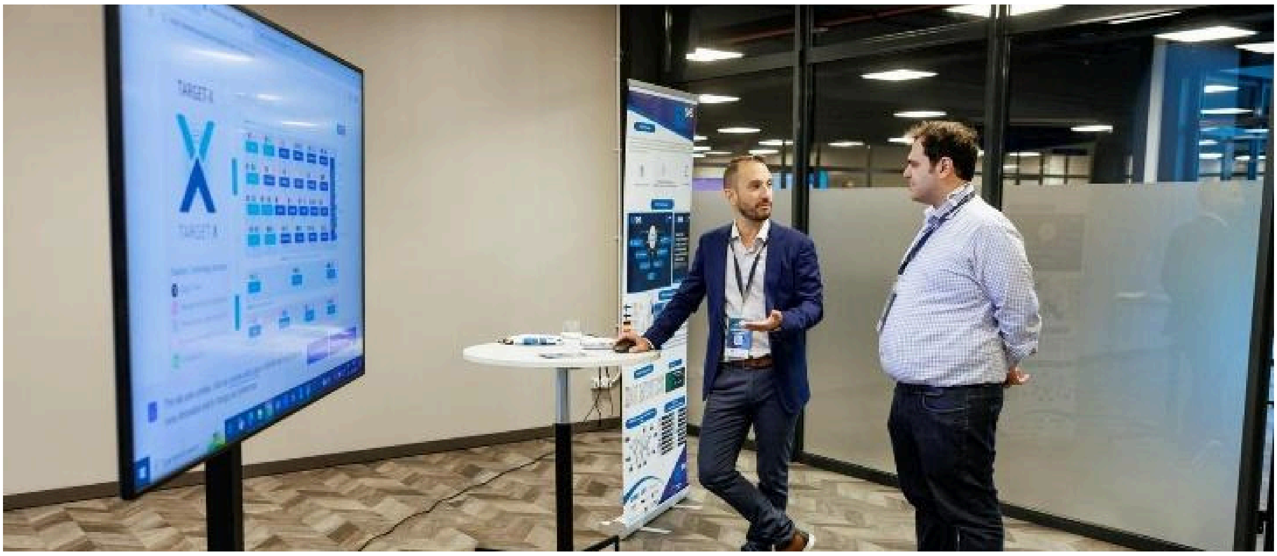

Figure 151: 5G Techritory – Discussion with 6G Smart Networks and Services Industry Association Project Manager

Figure 152: 5G Techritory – Discussion with 6G Smart Networks and Services Industry Association Project Manager

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The solution was presented at ViennaUP 2025 in May 2025, attracting attention from urban mobility stakeholders with ÖBB and EIT Urban Mobility Central.

Figure 153: Presentation at ÖBB Open Innovation Factory

Also, a presentation on the Road to Global side event in ViennaUp 2025 was maintained, and afterwards, some contacts for future opportunities were maintained. We started a PoC project with Adastec company, which is developing an Automated Driving Software Platform for commercial vehicles.

Figure 154: Presentation at Road to Global Event

Link Robotics also participated in the Start-up Arena held in Automatica Munich as part of the TARGET-X project and did a presentation for their Vins RTK Mapper by-product as part of the dissemination, showcasing their prototype and solution on stage.

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Figure 155: Automatica Munich Start-up Arena - Project Output Prototype

Figure 156: Automatica Munich Start-up Arena - Project Pitching

We are actively exploring support channels under EIT Urban Mobility, aiming to align with their goals in smart infrastructure, connected mobility, and data-driven city planning. In parallel, we are preparing for participation in EU CCAM (Connected, Cooperative & Automated Mobility) initiatives to scale our technology through collaborative pilots across European cities.

Our participation in Target-X Open Call #2, developments, and testing was also disseminated as a success story by EEN Istanbul titled " Access to TARGET-X Cascade Funding Call Grant".

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5G EMPOWERMENT

During the last period of the project, the hardware and software are tested on a test road in the Bilisim Valley Technopark in Kocaeli, Turkey. The real-time experiments show that the prototype could generate the coloured point cloud map over a 1.6-kilometer path. The map is converted to OBJ 3D Mesh format by using the Marching Cubes algorithm.

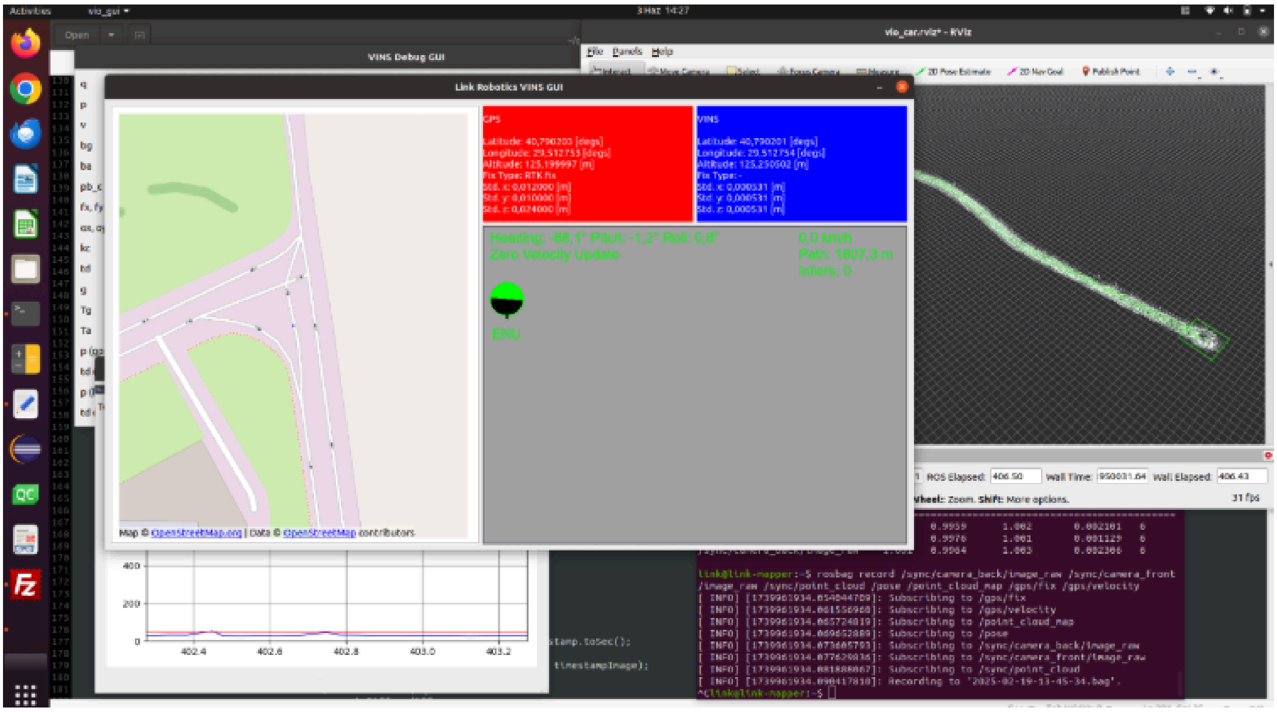

Figure 157: A screenshot taken at the end of the experiment

In Figure 157, the real-time generated map can be seen covering over 1600 meters of path. The mapping rate is 1 Hz while the localization rate is 20 Hz. The system could receive the RTCM corrections over an LTE network, and a Real-Time Kinematics (RTK) fix could be achieved with about 1-2 centimetres. RTCM is an abbreviation of Radio Technical Commission of Maritime Services.

Network Tests

In the final tests in Bilisim Valley, the network was 4G LTE. Since the network in the tests in the Idiada Test Center was 5G, a comparison between the two was necessary.

The cloud server used in the tests in Turkey was a Google Cloud server located in the United Kingdom. Since the network was public, ports for testing were not open, and the throughput tests could not be performed. So, only latency plots are shown.

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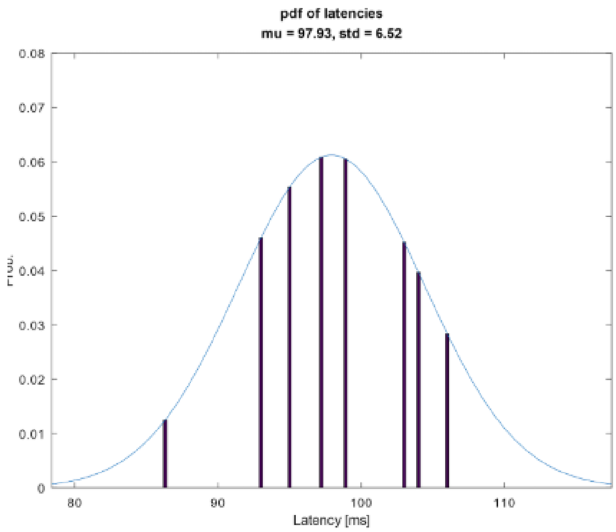

Figure 158: Latency experiments done in Turkey (LTE network)

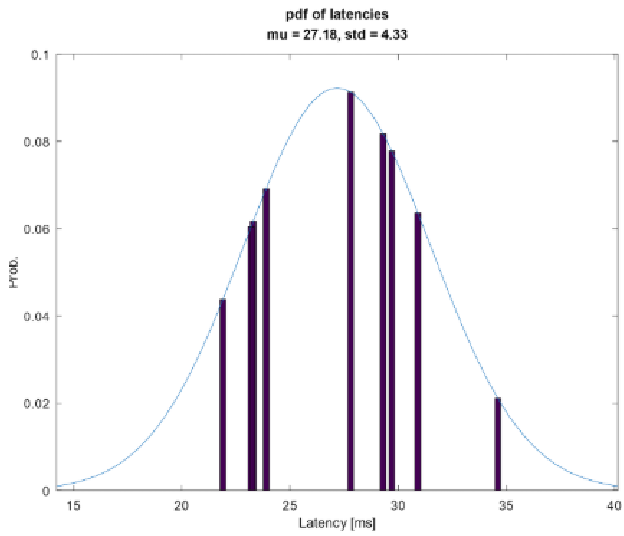

Figure 159: Latency experiments done in Spain (5G)

In Figure 158, the average latency in the 4G network was about 98 ms, while the average latency in the 5G network in Spain was about 27 ms, as shown in Figure 159.

It can be concluded that the network and cloud server combination in the experiments at IDIADA was giving better latency with a 5G private network.

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PROJECT NAME (ACRONYM)	ADVANCING SUSTAINABLE ENERGY WITH AI (ECOPREDICT)
NAME OF BENEFICIARIES	ARTIO.TECH P.C. KLIMAMICHANIKI ANONYMI ETAIRIA EMPORIAS KAI MELETON KLIMATISMOU KAI ENERGEIAKON EFARMOGON
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

EcoPredict aims to revolutionize energy sustainability by combining advanced AI and 5G technologies. The project's core objective is to maximize the self-consumption of renewable energy and improve energy efficiency in buildings. It achieves this through (1) a bespoke deep learning methodology for renewable energy modeling, (2) integration of 5G for real-time data acquisition and control, (3) deployment of a predictive energy management service model, and (4) demonstration in a fully equipped building with PV panels, heat pump, and a network of sensors measuring energy generation and consumption.

The project runs for 9 months and is led by ARTIO.Tech and Klimamichaniki, supported by mentors from RWTH Aachen University. Key milestones include:

- MS1 (Oct 2024): Delivery of the Individual Mentoring Plan.
- MS2 (Apr 2025): Deployment of the AI/ML methodology, 5G integration, and sensor network.
- MS3 (June 2025): Market Uptake Report and final presentation at the TARGET-X networking event in Aachen.

A major achievement includes the real-world deployment of an AI-powered predictive energy management system in a live-building environment.

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ARCHITECTURE

The EcoPredict architecture integrates IoT sensors, edge gateways, and a cloud-based AI engine. In a multi-floor building, Z-Wave multisensors collect temperature, humidity, and CO_2 data, while Qubino smart relays and Modbus-connected energy meters monitor energy consumption and device operation. Each floor transmits data via Beetabox edge gateways over 5G to the cloud. The cloud engine hosts advanced ML models that process real-time data and generate energy management recommendations. PV data, heat pump status, and weather forecasts are also integrated through APIs and MQTT over 5G, enabling dynamic control and predictive optimization.

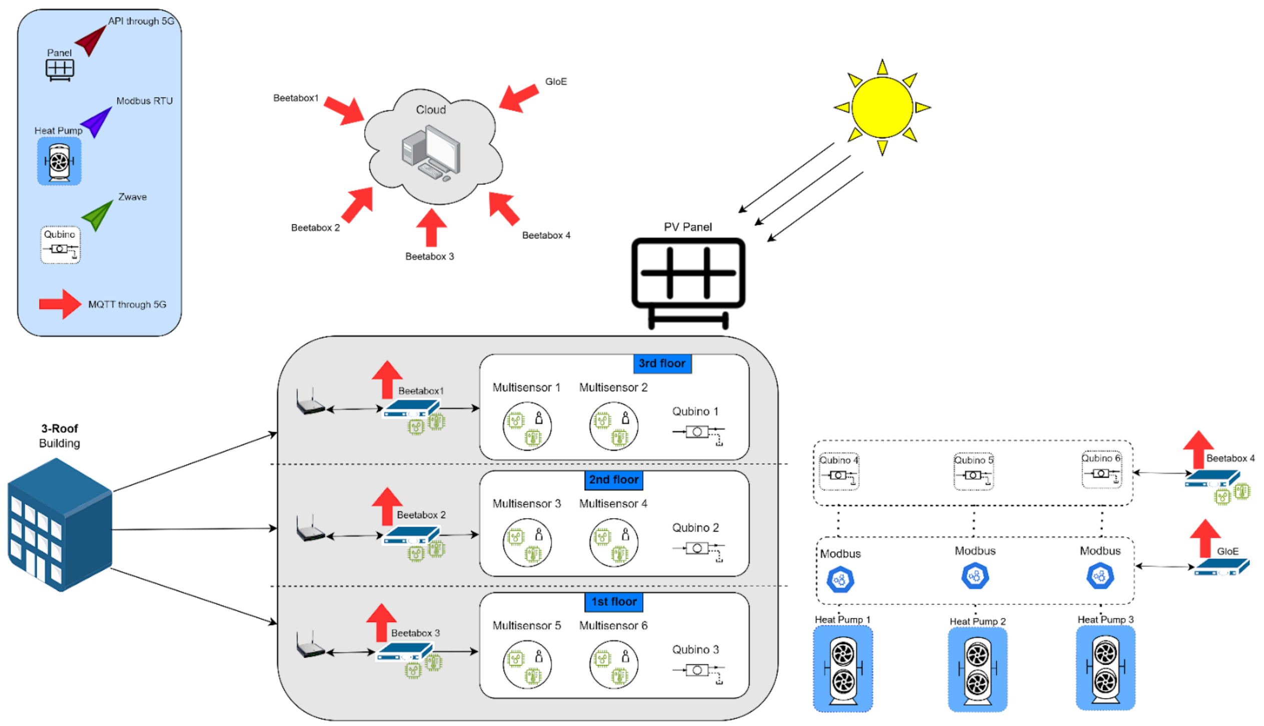

Figure 160.

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TRIAL

The EcoPredict trial is deployed in a multi-floor commercial building in Greece, equipped with PV panels, heat pumps, and real-time monitoring infrastructure. The setup includes multisensors (Z-Wave), energy meters (Modbus), and smart relays (Qubino) installed across all floors. Data is transmitted via Beetabox edge gateways over 5G to a cloud-based ML engine for predictive energy optimization and control. Deployment photo provided below.

Figure 161.

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RESULTS

EcoPredict achieved a 9.96% energy reduction during real-life deployment with LLM-based recommendations, maintaining comfort in 87% of intervals. The top figure shows reduced heat pump use in Zone 1. The platform also introduced a Bayesian Optimization framework for PID control, achieving 45% better temperature tracking and up to 7% less energy use than rule-based methods, as shown in the second figure. Results confirmed robustness under real and simulated spring tests.

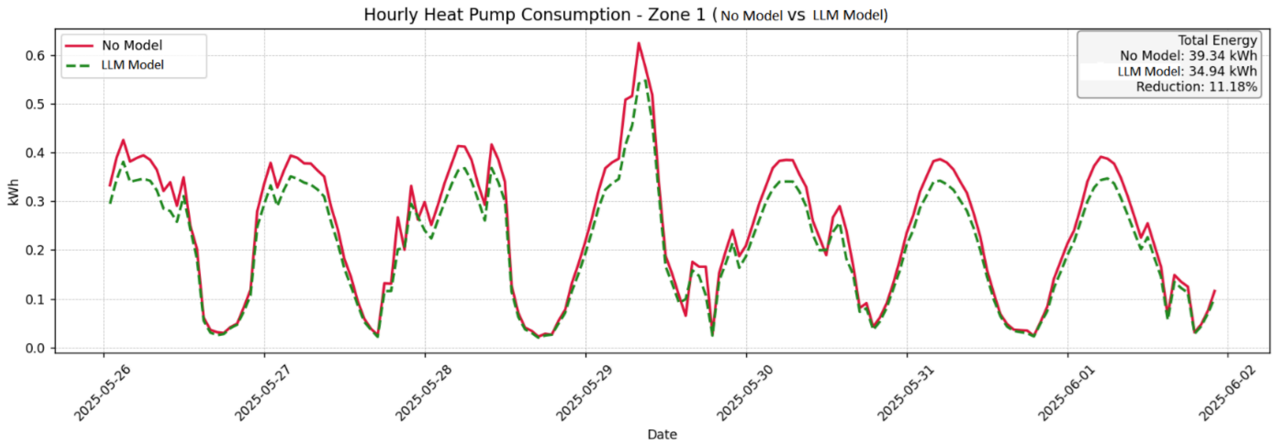

Figure 162.

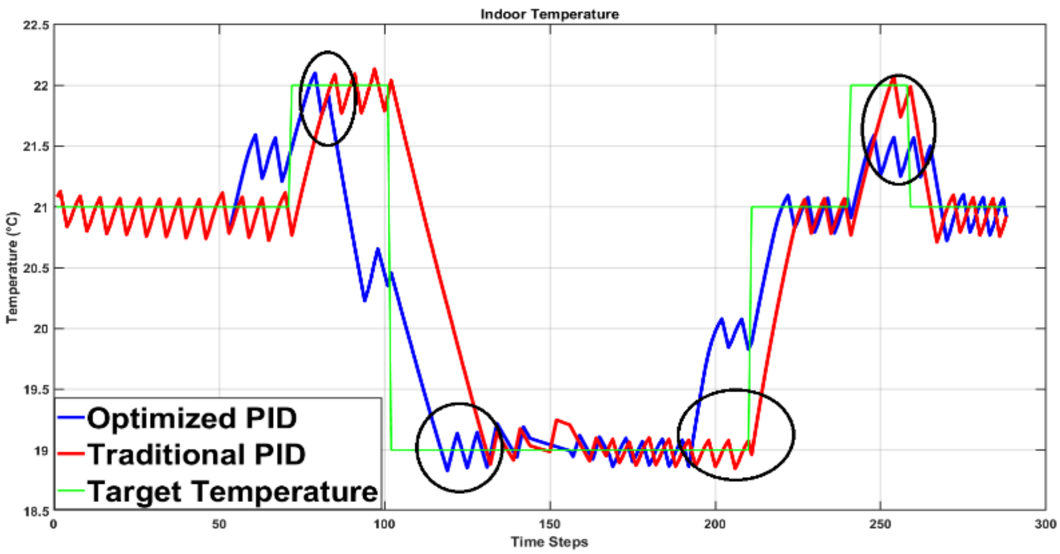

Figure 163.

Publications:
1) https://www.mdpi.com/2075-5309/15/13/2303
2) https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=11073464

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5G EMPOWERMENT

5G enabled EcoPredict to achieve real-time energy optimization by providing ultra-low latency and high-speed communication between sensors, edge devices, and the cloud. Unlike previous generations, 5G supported the fast transmission of large sensor datasets and allowed for instantaneous deployment of ML-based recommendations, ensuring precise control and efficient energy management in dynamic building environments.

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PROJECT NAME (ACRONYM)	OPEN WIRELESS TIME-SENSITIVE NETWORKING FOR 5G-INTEGRATED INDUSTRIAL SYSTEMS (OWTSN)
NAME OF BENEFICIARIES	R3 SOLUTIONS GMBH TECHNISCHE UNIVERSITÄT BERLIN
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

In OWTSN, R3 Solutions, and TU Berlin collaborate on developing a TSN interface (iTSN) for industrial wireless networks and integrating it into 5G cellular systems for designing end-to-end deterministic wireless networks, using open-source, Linux-based components. This enables the use of the emerging industrial standard IEEE 802.1 Time-Sensitive Networking (TSN) on wireless medium and facilitates connecting wireless TSN devices to 5G/6G systems with additional QoS profiling. Through experiments in both real-life testbeds and emulated setups (June 2025), we demonstrate significant improvements in bounded latency and jitter for mixed-criticality traffic in time-synchronized hybrid networks. Our main contributions include:

- An open-source TSN framework (wTSN) for scheduling, configuration, and management of hybrid TSN and Wi-Fi networks.
- A high-precision clock synchronization method across wired and wireless domains (horizontal) and between networks and operating systems (vertical).
- Different priority-aware traffic scheduling approaches in hybrid wireless networks.
- A detailed investigation of QoS mapping between 5G and TSN networks.

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ARCHITECTURE

Figure 164 shows our reference architecture with interconnected TSN listeners and talkers (Nodes 1–3) and a wireless subnetwork (AP, STA 1–2). The latter forms a virtual TSN bridge, aligned with the 3GPP approach to integrate TSN and cellular networks. The network is synchronized using our hybrid clock-synchronization method. Mixed-criticality traffic can be scheduled on wired-wireless transition links (Links 1–3) or within the virtual bridge (W Links 1–2) over the wireless interface. Our open-source TSN framework manages TSN stream requests, computes schedules, and maintains the network via a hybrid TSN controller (CUC/CNC iTSN) and additional wTSN agents on the endpoints.

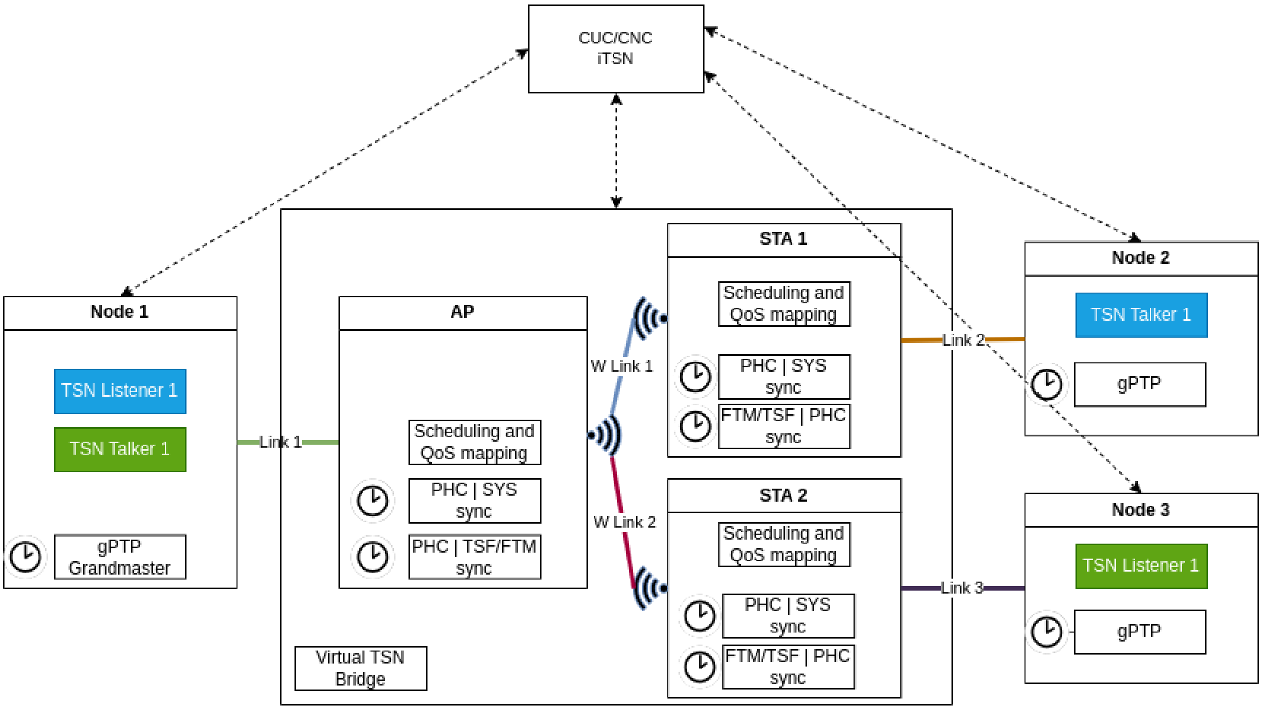

Figure 164: Reference architecture for OWTSN.

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TRIAL

We conduct experiments in a hybrid wired-wireless demonstrator (Fig. 165) built in the R3 Solutions test environment. As the hardware platform, we use R3's Edge X product family, based on NXP processors and Wi-Fi equipment. In parallel, we develop our open-source iTSN framework and additional scheduling approaches in an emulation environment set up by TU Berlin. Experimental settings and parameters are aligned across both deployments.

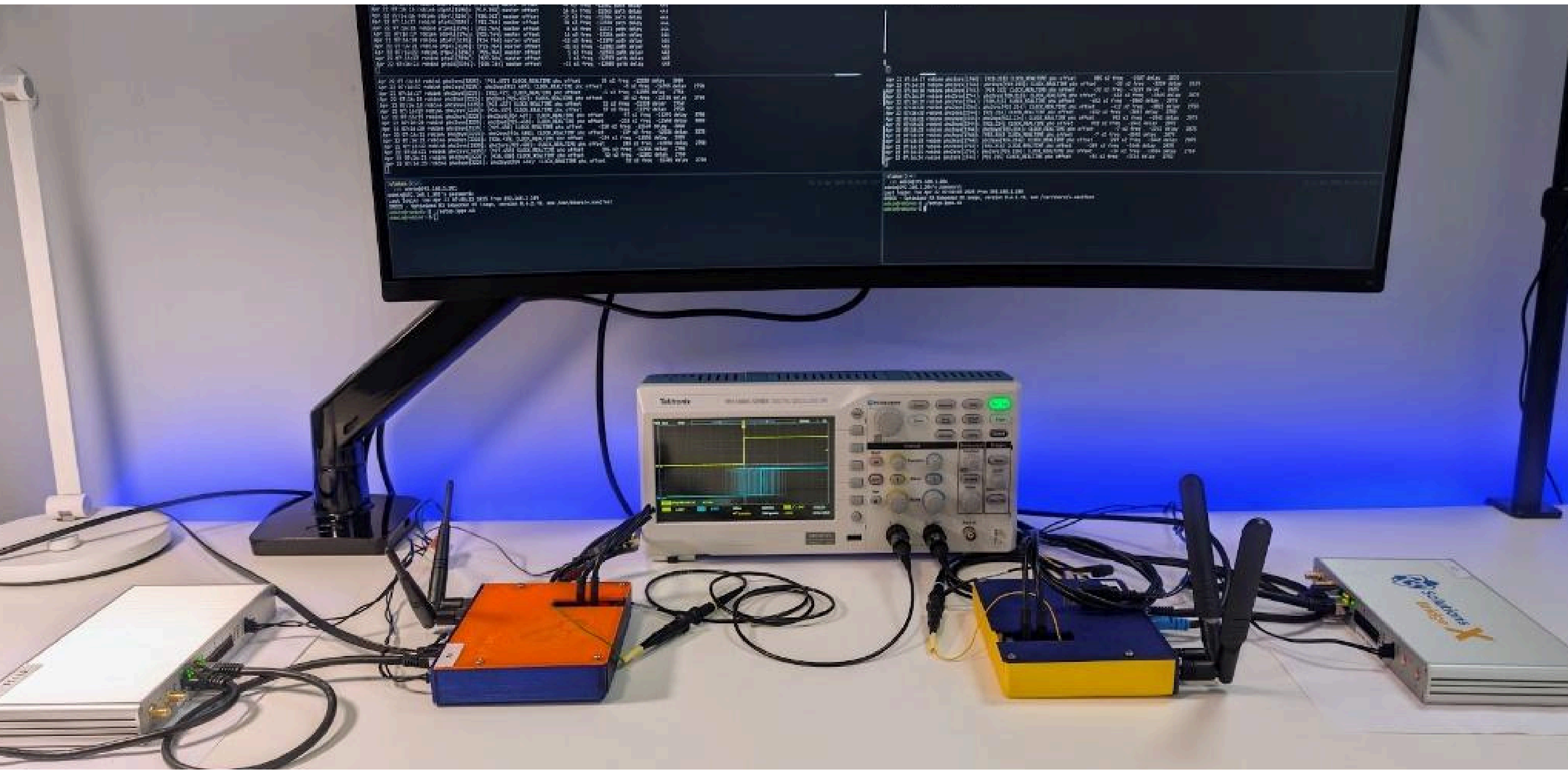

Figure 165: Hybrid wired-wireless demonstrator.

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RESULTS

We first evaluate clock synchronization between the AP and STAs. Figure 166 shows oscilloscope pulses measuring the delay between rising edges at wireless nodes, achieving sub-1µs (P90) accuracy over the air.

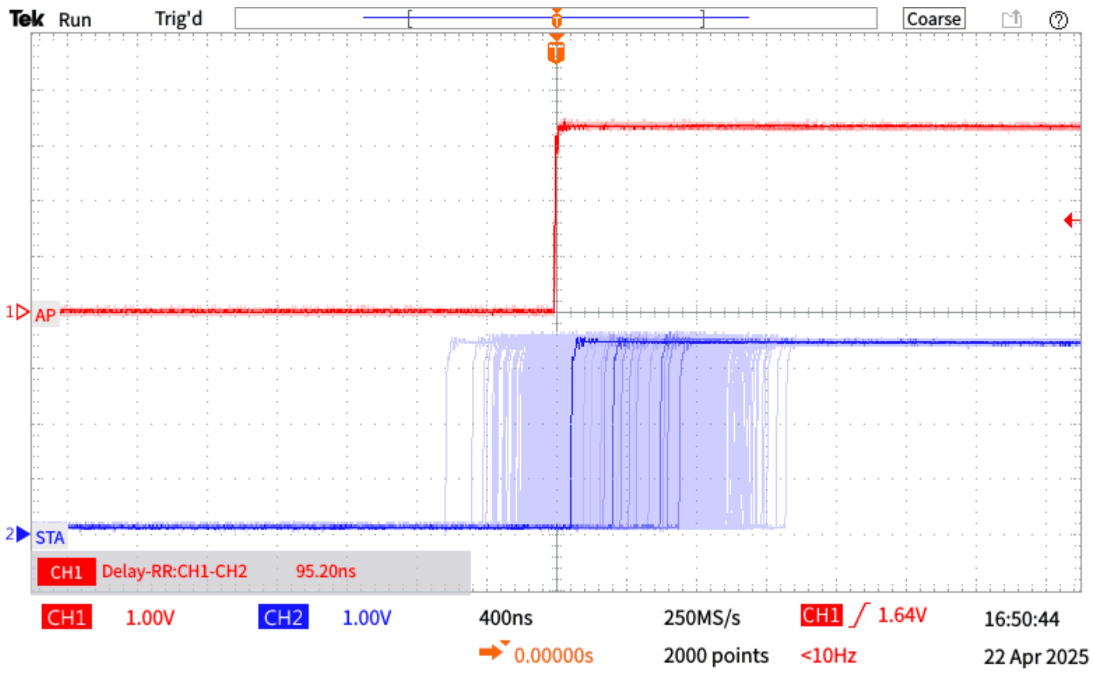

Figure 166: Clock-synchronization performance over the air.

Figures 167 and 168 show AP transmission timelines for high- and low-criticality streams in 5 ms cycles. In Fig. 167, unscheduled streams show no clear pattern. Figure 168 illustrates traffic shaping, with frames sent in designated slots and latency bounded under 10 ms.

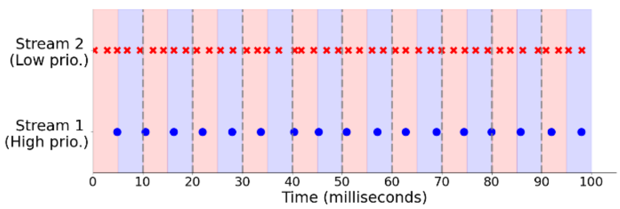

Figure 167: Tx timeline without scheduling.

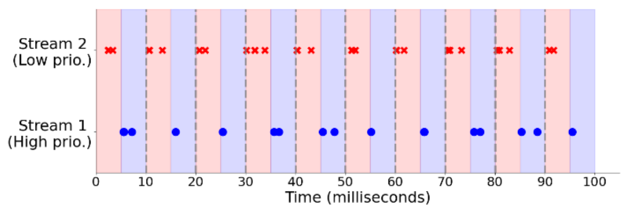

Figure 168: Tx timeline with scheduling.

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5G EMPOWERMENT

OWTSN introduces novel clock-synchronization and scheduling methods for hybrid TSN and Wi-Fi networks, enabling integration with 5G/6G systems under low-latency and jitter constraints. Our open-source iTSN framework provides a configuration and management layer across wired and wireless domains. Further analysis highlights needed adaptations to align traffic requirements for end-to-end QoS across TSN and 5G/6G networks.

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PROJECT NAME (ACRONYM)	5G - ENHANCED QUALITY CONTROL TOOL FOR COMPOSITES (5G-EQCT)
NAME OF BENEFICIARY/RIES	TRYGONS S.A. ITHERMAI B.V
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

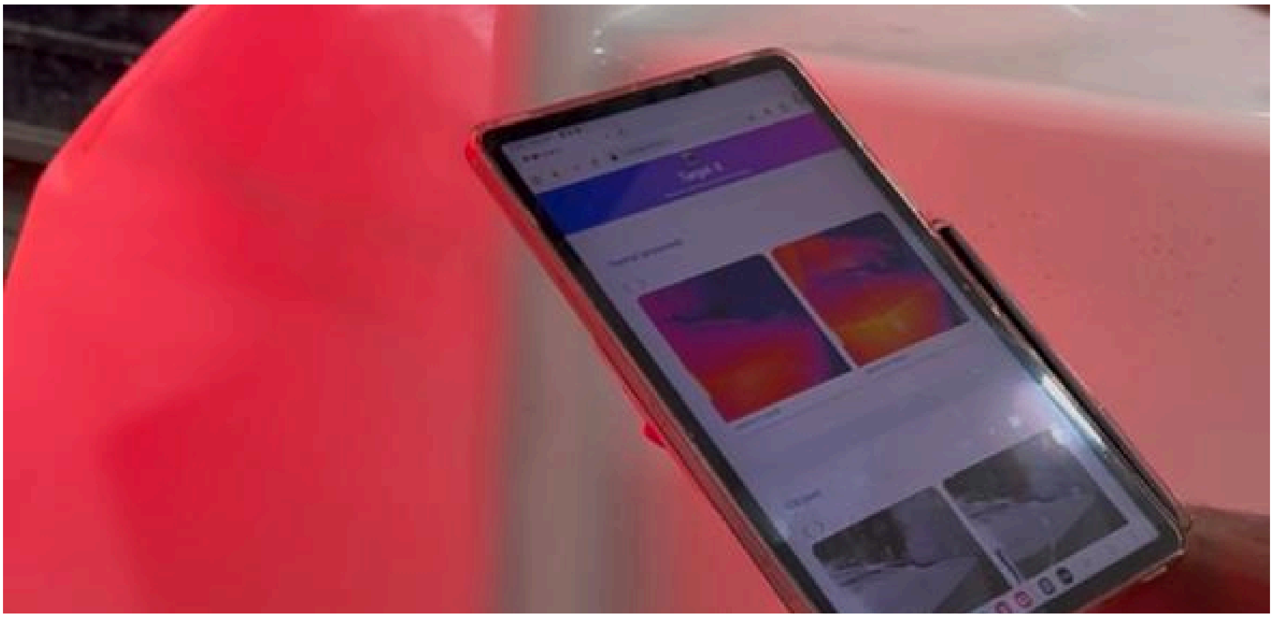

Figure 169: Clock-synchronization performance over the air.

The 5G-EQCT project developed a portable, AI-powered system for quality control in composite manufacturing, utilizing RGB and thermal imaging, real-time analysis, and 5G connectivity. This system was piloted at TRYGONS, where it successfully detected both surface and subsurface defects in large composite parts, including hidden air inclusions (key milestone).

The project involved iterative testing for system refinement in February and March 2025, followed by full validation trials in April and May. Key partners included TRYGONS (end-user and pilot site) and iThermAI (AI model development), with Fraunhofer IPT and Target-X mentor providing crucial technical advice and continuous evaluation.

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ARCHITECTURE

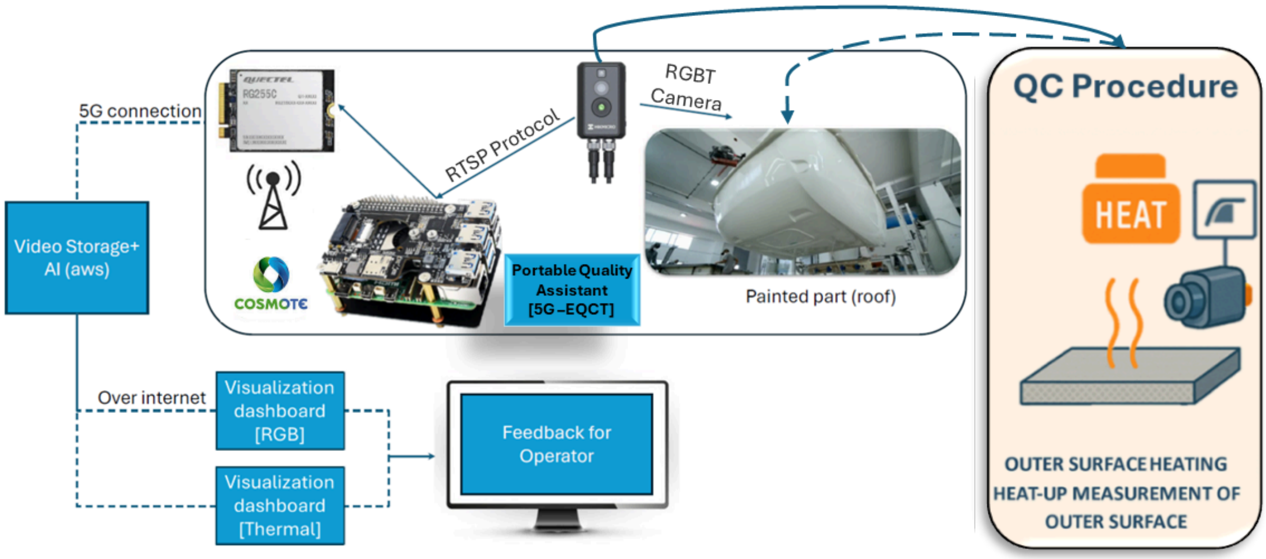

Figure 170: Clock-synchronization performance over the air.

The 5G-EQCT system consists of an RGBT camera paired with infrared (IR) lamps, mounted above the composite surface. The IR lamps briefly heat the part to reveal subsurface defects such as air inclusions. A Raspberry Pi with a Quectel 5G module streams both RGB and thermal video to a cloud-based AI engine developed by iThermAI. The AI model detects surface issues via the RGB stream and subsurface anomalies via the thermal stream, with results displayed in real time on a live dashboard. This portable, modular, and scalable architecture enables easy integration across different production lines and environments, with 5G ensuring high-speed, low-latency connectivity, with plans for future versions to explore edge AI integration.

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TRIAL

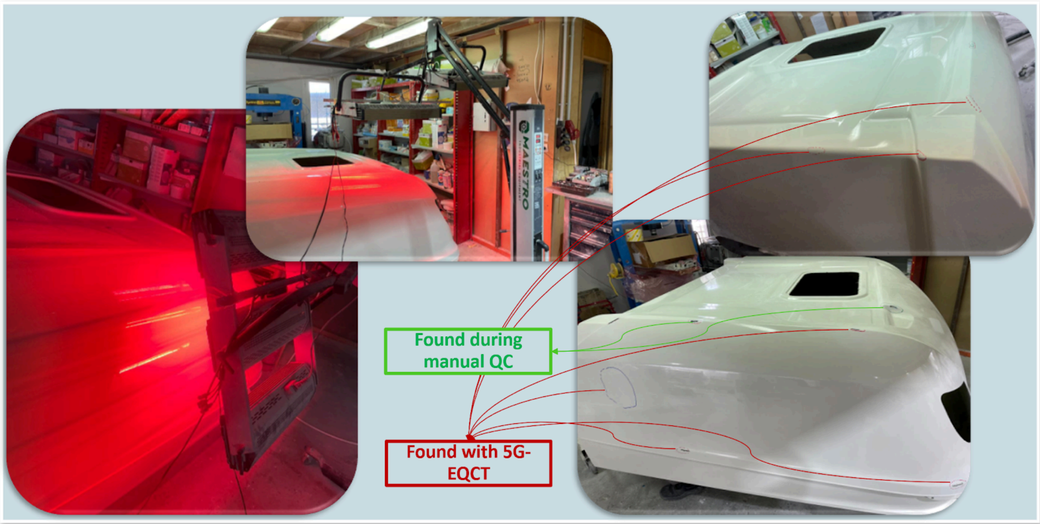

Figure 171: Prototype Validation Process

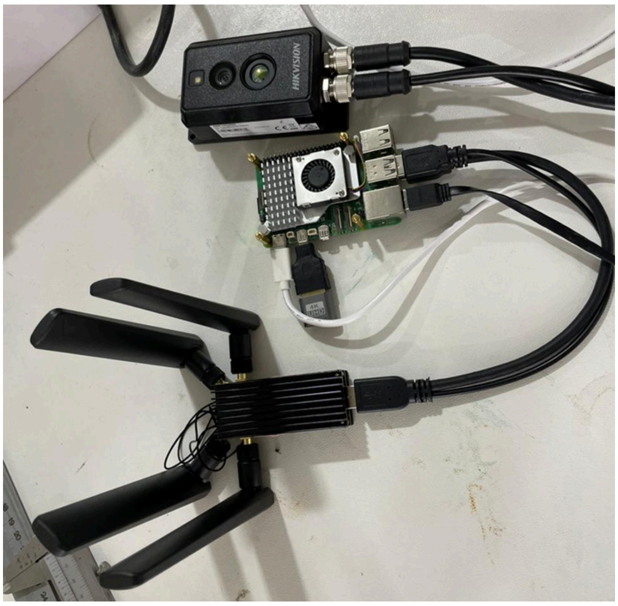

Figure 172: Prototype Setup

The trial setup involved mounting an RGBT camera and infrared heating lamps above composite parts using a fixed support frame. A Raspberry Pi acted as the local controller, connected to a Quectel RM500UEA-based 5G dongle for cloud communication. The system streamed synchronized RGB and thermal video to an AI model for defect analysis. Results were visualized in real time through a dashboard, accessible on the operator's preferred portable device (tablet, smartphone, or laptop), enabling immediate defect marking and faster, but more importantly, informed decision-making.

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RESULTS

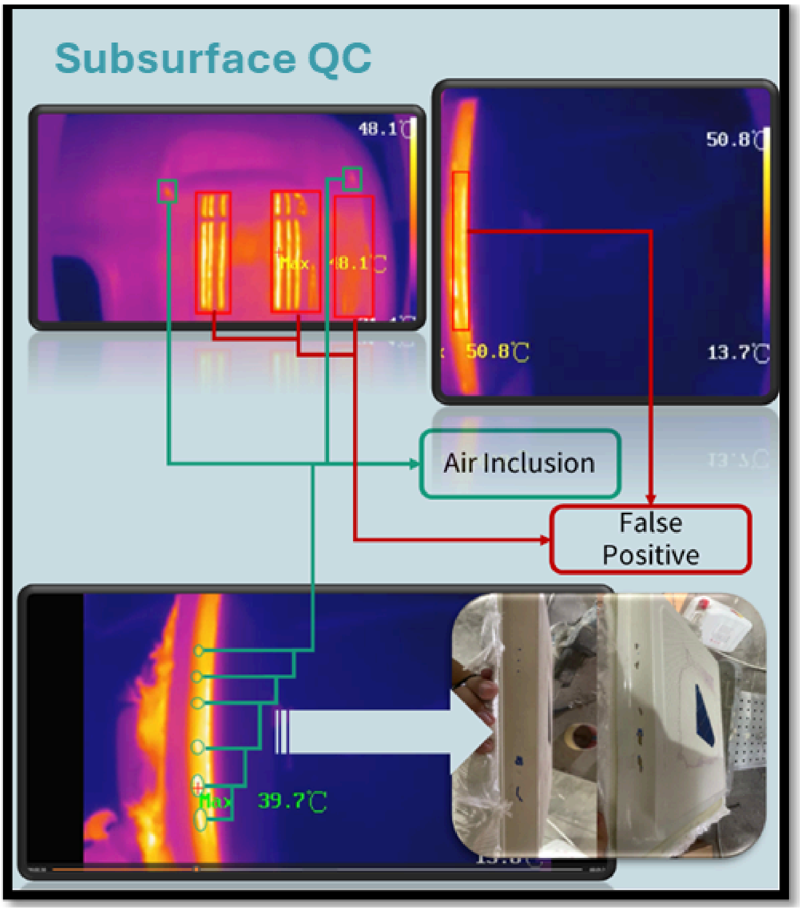

Figure 173: Subsurface QC results

The project successfully validated a real-time AI-powered quality control system for detecting surface and subsurface defects in composite parts. Key achievements include over 76% surface defect detection accuracy and more than 60% detection of subsurface issues, significantly outperforming traditional manual inspection (30%). The solution reduced quality control time by more than 50%, while also lowering operator workload. Business-wise, a draft commercial plan was developed and market outreach initiated. The pilot also resulted in a strategic decision to decouple the solution into two tools, enhancing usability and market adaptability.

5G EMPOWERMENT

5G enabled real-time RGBT video transmission from the shop floor to a remote AWS-based AI engine for defect detection. Its high bandwidth and low latency ensured immediate processing and feedback, handling continuous imaging data transfer without delays, making real-time quality control feasible. Results are shown in real-time on any number of dashboards given the server-based solution, showing alerts to operators. This mobile deployment eliminates the need for local computing infrastructure.

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PROJECT NAME (ACRONYM)	PILOT OF A RETROFIT SYSTEM FOR MACHINE AUTOMATION (PIRGOS)
NAME OF BENEFICIARIES	MOBACT MONOPROSOPI E.P.E. WINGS ICT SOLUTIONS SA
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	CCR, RWTH-IP

OVERVIEW

PIRGOS addresses a longstanding gap in construction by offering a modular, retrofittable kit that brings automation, guidance, and intelligent control to heavy machinery via advanced sensors, edge computing, and 5G/6G connectivity. Born from Mobact's field experience and WINGS's deep technical expertise, PIRGOS delivers centimeter-level positioning, real-time mapping, human safety, and obstacle detection, while preserving operator familiarity through an intuitive touchscreen interface.

Figure 174.

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ARCHITECTURE

PIRGOS's architecture fuses GNSS+RTK, LiDAR/IMU, and dual-camera data in real time on an NVIDIA Jetson edge device to produce a georeferenced 3D mapping result. A touch-based in-cab control panel displays live telemetry (battery, position, orientation, velocity, bucket altitude) alongside front/rear video and map views, while a cloud dashboard supports remote monitoring, KPI analytics, and mission planning. WINGS ICT developed the data-fusion pipeline and UI; Mobact shaped the use cases and ran field deployments.

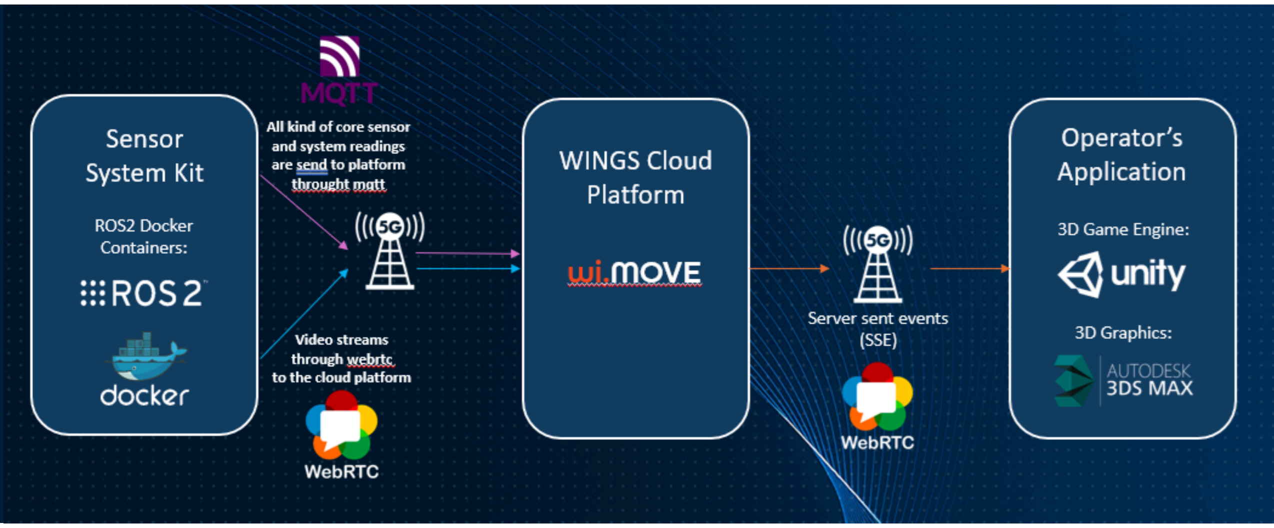

Figure 175.

TRIAL

Between 2 and 4 June 2025, the PIRGOS team deployed the full retrofit kit on a Bobcat at the RWTH Aachen campus testbed. Over the three-day trial, we rigorously evaluated the system's high-precision 3D mapping capabilities, validated the in-cab user interface, and assessed end-to-end robustness under controlled lab-to-field handover scenarios–demonstrating seamless transitions between operational modes and reliable, centimeter-level accuracy.

Figure 176.

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RESULTS

- Reduced CO_2 emissions by limiting idle time and unnecessary machine operations through digital precision.
- Improved site safety, especially for personnel near active machinery, by eliminating the need for manual grade checking through full digital supervision and real-time awareness tools.
- Increased productivity, as pre-programmed work schedules and remote monitoring reduce delays and facilitate task coordination.
- Optimized energy use, supported by continuous system status feedback and targeted execution through health and diagnostic monitoring.
- Minimized construction waste, enabled by accurate execution of excavation and grading operations, reducing the need for material rework or corrections.

5G EMPOWERMENT

For our experiments, we utilized the dedicated 5G campus network at Aachen, which consistently outperformed the commercial 5G setup in terms of latency stability under a full-load scenario of 40 Mbps. Round-trip times (RTTs) on the campus network typically ranged between 20 and 35 ms, with noticeably lower variance and fewer outliers compared to the commercial network, where RTTs spanned 35–75 ms, with occasional spikes exceeding 250 ms. These results underscore the suitability of controlled 5G campus networks for industrial automation scenarios that require low and predictable latency. Nevertheless, to meet the stringent demands of future industrial applications—such as ultra-low latency and higher throughput—further technological advancements beyond 5G will be essential, given that 6G standards are still under development.

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PROJECT NAME (ACRONYM)	POWER GRID OBSERVABILITY WITH PMU DEVICES AND 5G (EDGEPMU-5G IOT)
NAME OF BENEFICIARIES	INDA D.O.O. ELEKTRO GORENJSKA D.D.
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-ACS

OVERVIEW

The project aims to enhance control of critical points in the electricity distribution system through the integration of edgePMU devices and the development of a real-time communication and IoT system using 5G technology.

Its purpose is to validate the concept and functionality of such a system under real-world conditions.

Project partners include INDA d.o.o., Elektro Gorenjska d.d., and RWTH Aachen University.

To achieve the project's objectives, edgePMU devices will be installed at low-voltage transformer stations operated by Elektro Gorenjska. This setup will allow evaluation of how real-time monitoring of electrical parameters can improve identification, analysis, and response to network disturbances.

Key achievements in initial milestones by TPIs:

- TPI1: Technical specifications of the edgePMU defined; sample units built
- TPI2: 5G communication module analyzed
- TPI3: In-field test environment established
- TPI4: Pilot installation and initial evaluation begun.

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ARCHITECTURE

The main goal of the edgePMU device and its system is to simplify field data acquisition and access, reduce the need for manual setup and control, separate short- and long-term data storage, and store metadata with the measurements. This supports data reuse in future projects and enables new data-driven use cases.

The architecture consists of three layers (see Figure 177):

- Edge cloud services (top layer)
- Secure VPN-based 5G connection
- Field devices (bottom layer)

Measurement data is streamed from the device to the edge cloud via an MQTT-based Broker Service.

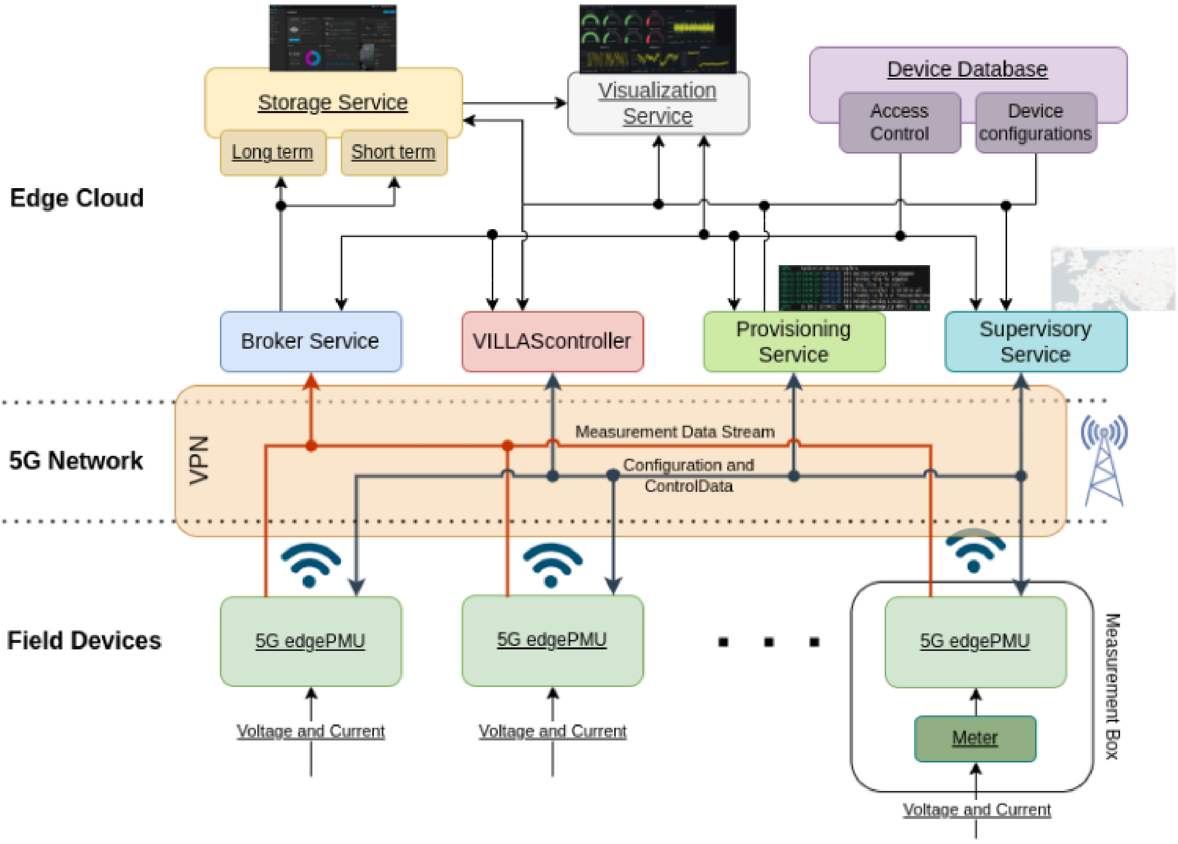

Figure 177: General architecture of the edge cloud and field side for the energy vertical

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TRIAL

After identifying potential sites, locations were inspected to assess suitability for edgePMU installation. Focus was on physical layout and technical conditions for integration. Available connection points were required to install edgePMUs in parallel with existing measurement systems, avoiding interference. This setup enables direct validation of edgePMU performance.

Figure 178: Transformer station - installation site.

Figure 179: edgePMU device without top cover.

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Figure 180: Installation of the edgePMU device in parallel with existing metering devices.

RESULTS

The project aimed to test edgePMU devices using 5G in a real environment. This was achieved with a successful installation in a low-voltage transformer station. The device provides precise measurements to be compared with standard meters. Data is temporarily stored locally and accessed via 5G. Cloud transfer is not yet functional, but can be enabled with a software update. The system meets expectations, with further development needed.

Figure 181: Measurements on edgePMU device on site.

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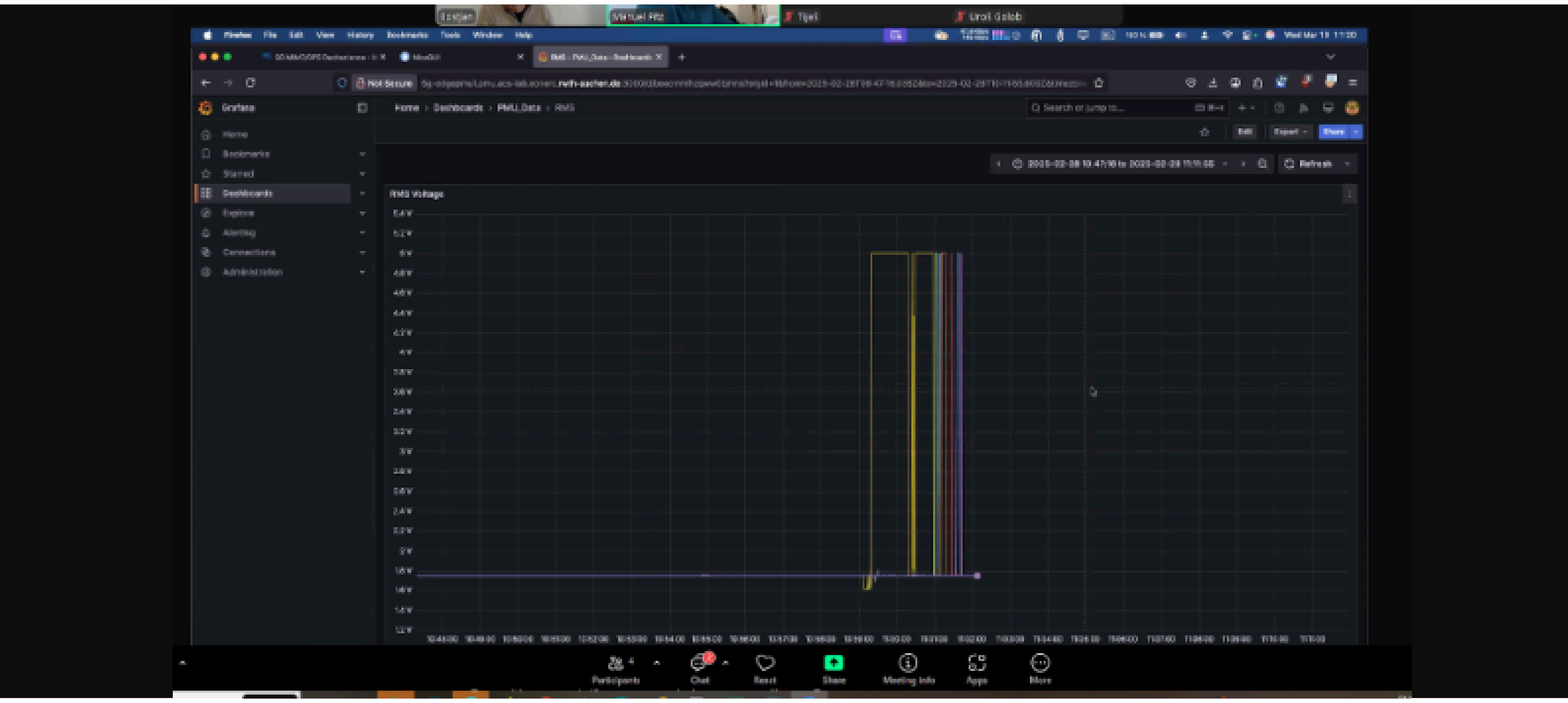

Figure 182: Graphical tool used at edgePMU device to monitor measurements.

5G EMPOWERMENT

The use of 5G technology is a key project feature, enabling high-volume data streaming and cloud processing –unlike current solutions with local processing. The new approach allows simultaneous monitoring of multiple sites, enabling faster anomaly detection and response. The 5G-based system design was confirmed as feasible, but full validation was not completed and requires further development work.

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PROJECT NAME (ACRONYM)	EXTENDED COOPERATIVE AI POWERED 5G HEATMAP TOOL (X-CRAIG)
NAME OF BENEFICIARY	Espacio SOA SL
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	EDD

OVERVIEW

The X-CRAIG project has developed and made publicly available (via an open-source license in the Espacio SOA GitHub repository) the tools for easy, low-cost, and fast 5G indoors heatmapping using mobile or COTS devices.

For this project, Espacio SOA has received support and cascade funding from the Target-X EU Project and its mentor Ericsson, who has guided, provided experienced support, and an external point of view to the project works.

The X-CRAIG project is composed of three complementary subsystems:

- Backend server and web interface – for storing, accessing, showcasing, and extrapolating 5G indoor measurements.
- Android app – the main measurement tool, which uses augmented reality and relative displacements to estimate the user's indoor position.
- Raspberry Pi module – equipped with a HAT and a professional 5G card, used for golden rule measurements and bias correction.

Users can organize measurements by rooms (locations) and temporal sessions, and use them to train and further extrapolate results to other areas using AI techniques.

The service is currently available in trial mode at https://measurements.espaciosoa.com.

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ARCHITECTURE

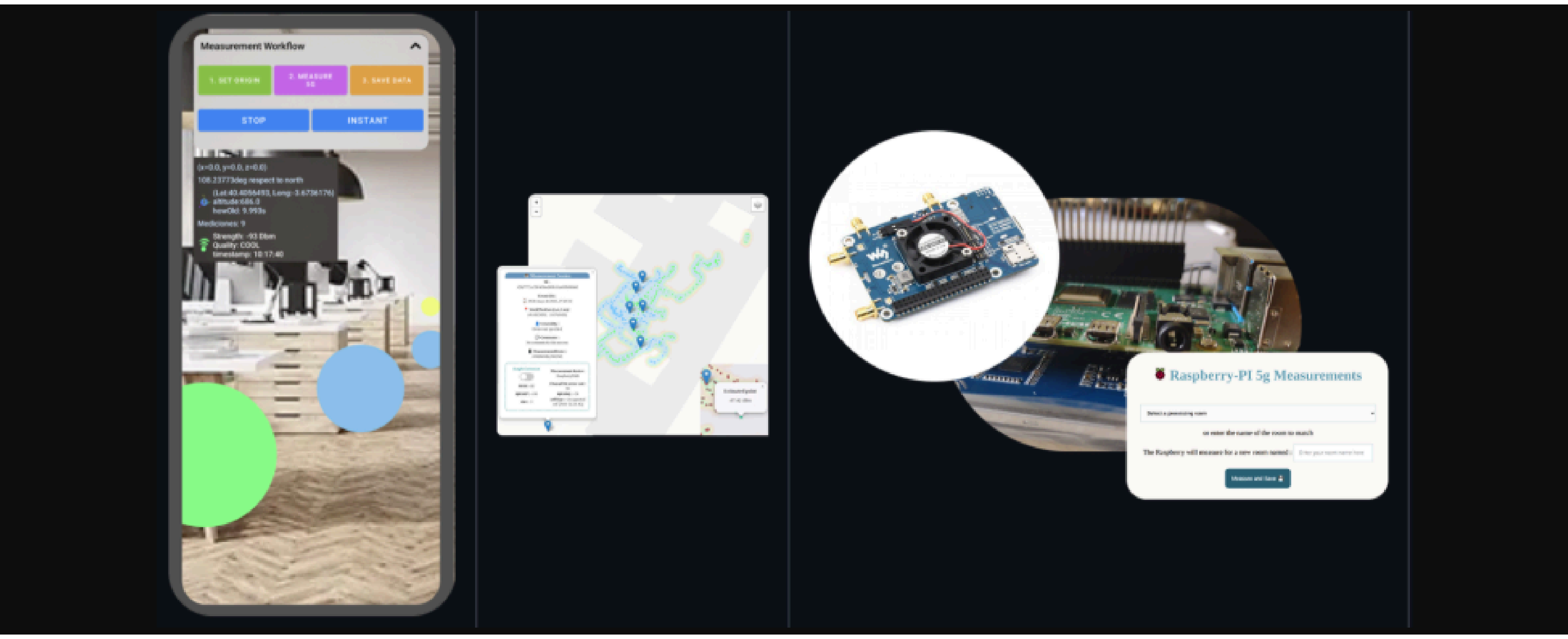

Figure 183: X-CRAIG Components.

The Android app consists primarily of a single augmented reality (video see-through) screen that allows users to measure points in their surroundings and visualize them as coloured spheres.

The backend server centralizes the storage of 5G measurements and displays the measured points and their properties on a 2D world map. The application enables interactive plotting of various signal characteristics, as well as performing interpolation and AI-based estimations of cell signals in surrounding areas.

Finally, the Raspberry Pi module consists of a Node.js application that communicates via serial port with a 5G module, allowing the extraction of information regarding cell signal quality through AT commands.

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TRIAL

The project was tested and validated in an office building in the tech district of Madrid, Julian Camarillo

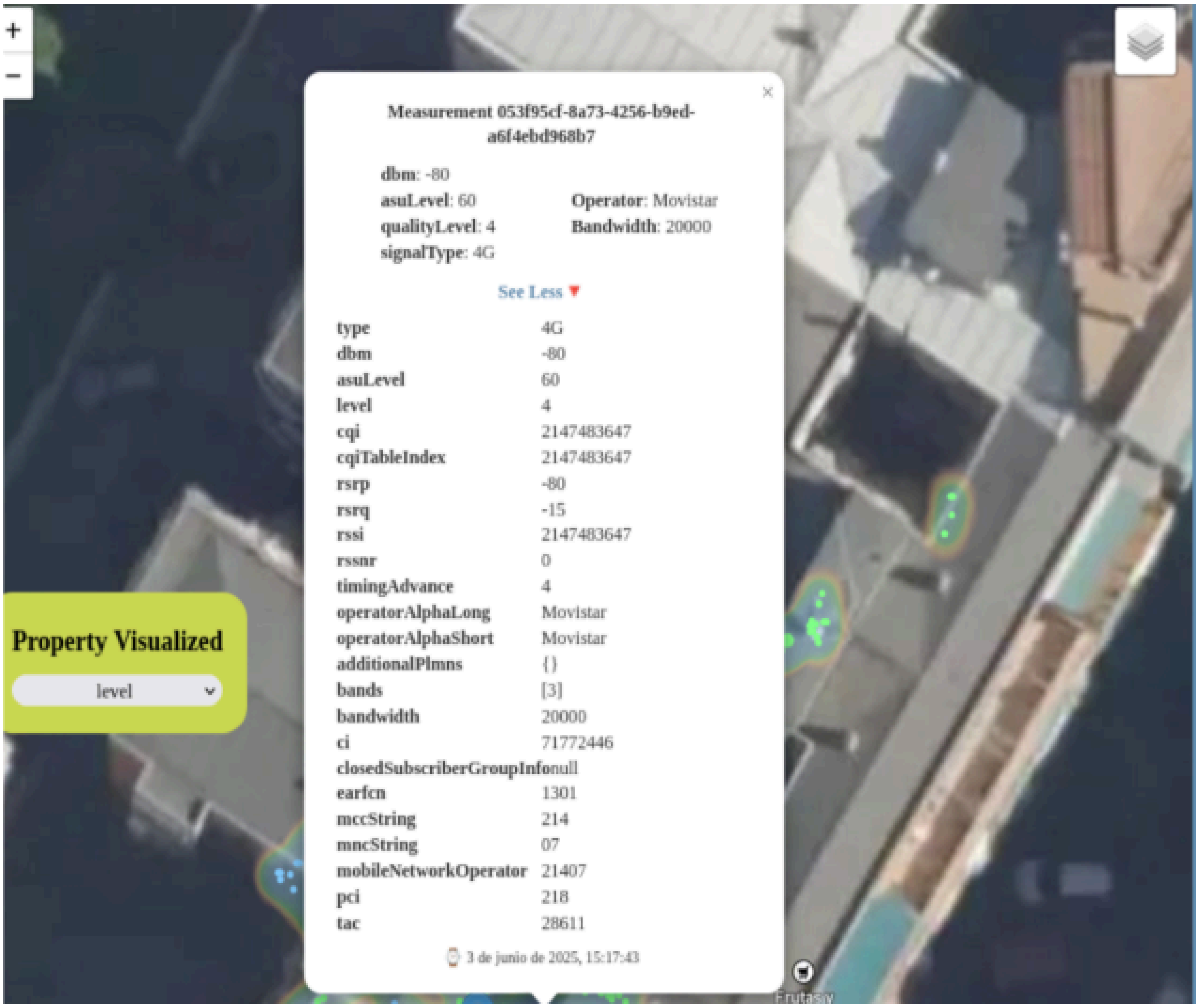

Figure 184: X-CRAIG Available Measurements.

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RESULTS

The X-CRAIG project has been conceived with scalability and ease of use in mind. To achieve this, it adopts a cloud-based architecture, uses state-of-the-art non-relational databases (MongoDB), and has successfully passed a stress test with 100 simulated users online.

Through the web interface, the user can correct the origin point and also apply the Raspberry Pi bias adjustment.

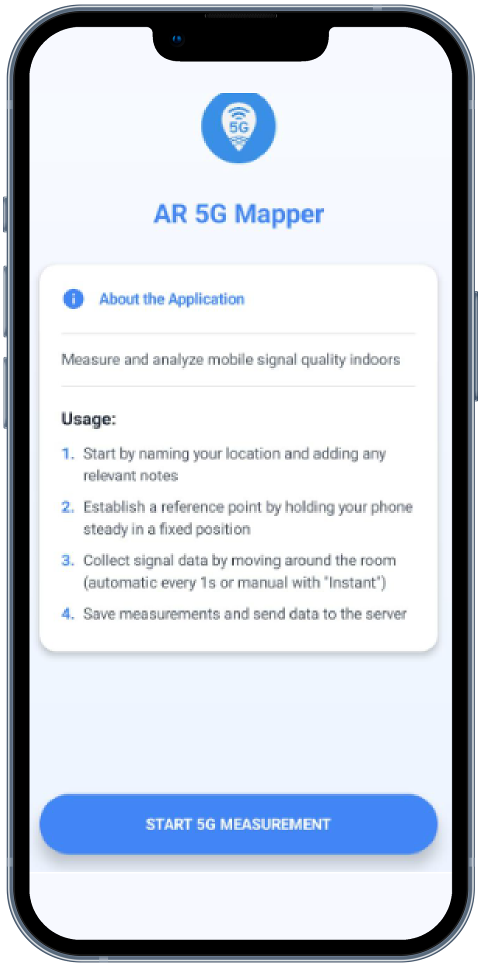

Figure 185: X-CRAIG Measurement App

5G EMPOWERMENT

Thanks to advances in smartphone technology and augmented reality tools, it is now possible, through X-CRAIG, to perform indoor measurements without dedicated equipment, at a fraction of the usual cost.

All the code has been released as open source to the community, while Espacio SOA's business value will rely on advanced features to be offered beyond the current ones (e.g., Wi-Fi support, more powerful AI algorithms, and enhanced estimations).

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PROJECT NAME (ACRONYM)	LOCAL-POSITIONING-SYSTEM EMBEDDED IN THE 5G ECOSYSTEM (LPS-5G)
NAME OF BENEFICIARIES	UNIVERLAB S.R.L DOMINA S.R.L
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	IPT

OVERVIEW

The LPS-5G system aims to develop a centralized, modular, and scalable platform capable of integrating and processing data from diverse sources, including 5G, RFID, UHF/SHF readers, and cameras. The objective is to create a unified data architecture supported by standard APIs (REST, MQTT) that enables real-time, synchronized, and accessible data exchange. A key focus is on implementing advanced data fusion algorithms that combine sensor and video inputs to achieve high-precision localization and object detection, prioritizing sources based on reliability and accuracy. The system also includes the design of a user-friendly web dashboard for monitoring and visualizing movement and safety-related alerts in industrial environments. Emphasis is placed on leveraging open-source software and cost-effective technologies to ensure adaptability and long-term sustainability.

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ARCHITECTURE

The LPS-5G system architecture integrates 5G smart tags, AI-based computer vision, and MEC (Multi-access Edge Computing) to deliver high-precision, real-time indoor localization in complex industrial environments.
Smart tags equipped with IMU (Inertial Measurement Unit) sensors use 5G communication modules for data exchange, enabling continuous position estimation and rapid transmission of movement data. These tags interact with AI-powered cameras that perform advanced object detection, ensuring situational awareness even for personnel without wearable tags.
MEC nodes process localization and safety data locally, minimizing latency and ensuring immediate alert delivery. Anti-collision algorithms coordinate signals from multiple tags to prevent interference and ensure data accuracy.

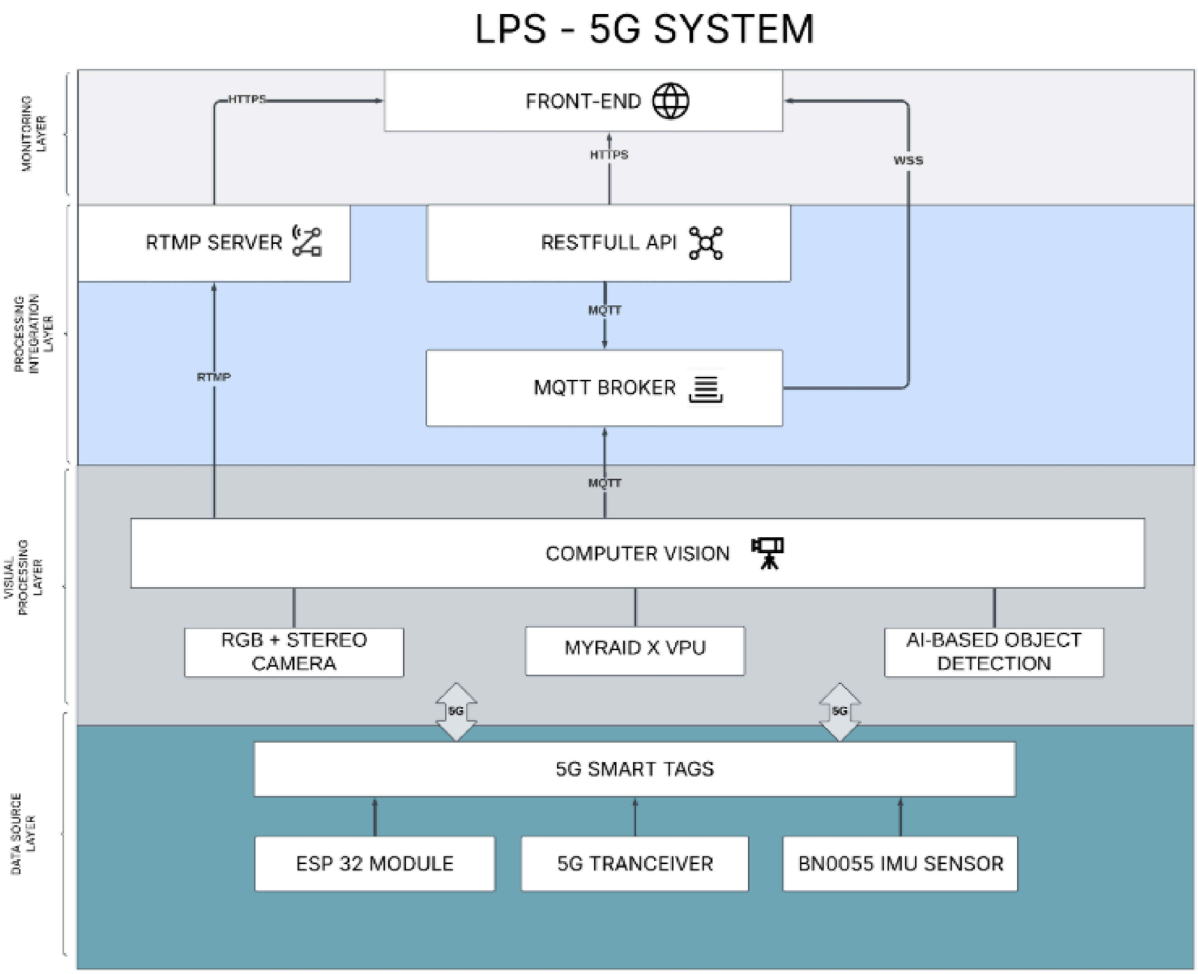

Figure 186: LPS-5G system Architecture

The architecture supports standard communication protocols for interoperability and seamless integration with existing industrial systems. Secure 5G encryption and cloud connectivity ensure protected, scalable data handling in compliance with privacy and operational requirements.

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TRIAL

LPS-5G trial in BICT S.r.l, Italy: The LPS-5G system was successfully tested in Italy across lab and industrial environments. It used 5G sensors, stereo cameras, and ArUco tags to simulate real safety scenarios with machines and forklifts. The system reliably triggered alarms and ensured precise operator localization.

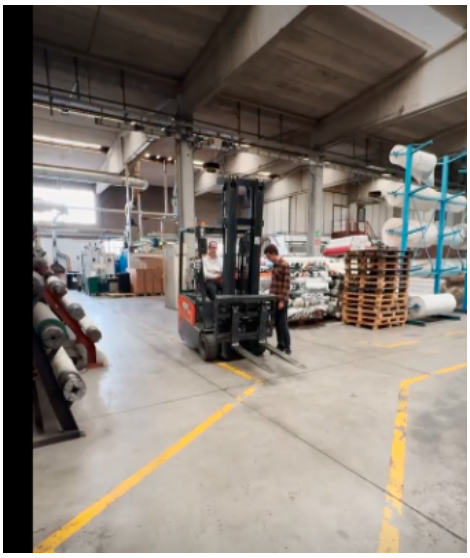

Figure 187: Collision Risk Detection Forklif and Operator

The LPS-5G system was tested at Fraunhofer IPT using a private 5G network, validating its adaptability. A local MQTT broker processed data securely, confirming effective communication in a controlled lab setting.

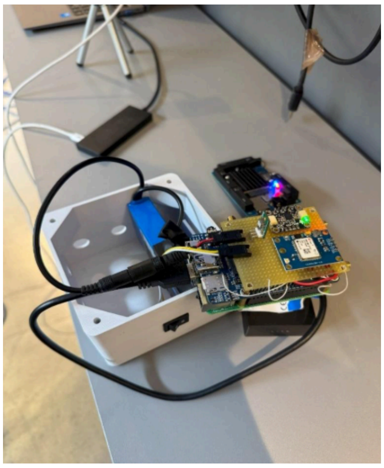

Figure 188: Testing LPS-5G System over Private 5G Network

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RESULTS

The LPS-5G system demonstrated strong performance and reliability during testing. It achieved an average latency of 0.68 seconds, enabling real-time monitoring and safety alerts. Dual localization using computer vision and 5G-based inertial sensors ensured high accuracy, with effective thresholds (30 cm for machinery, 2 m for forklifts) for collision prevention.

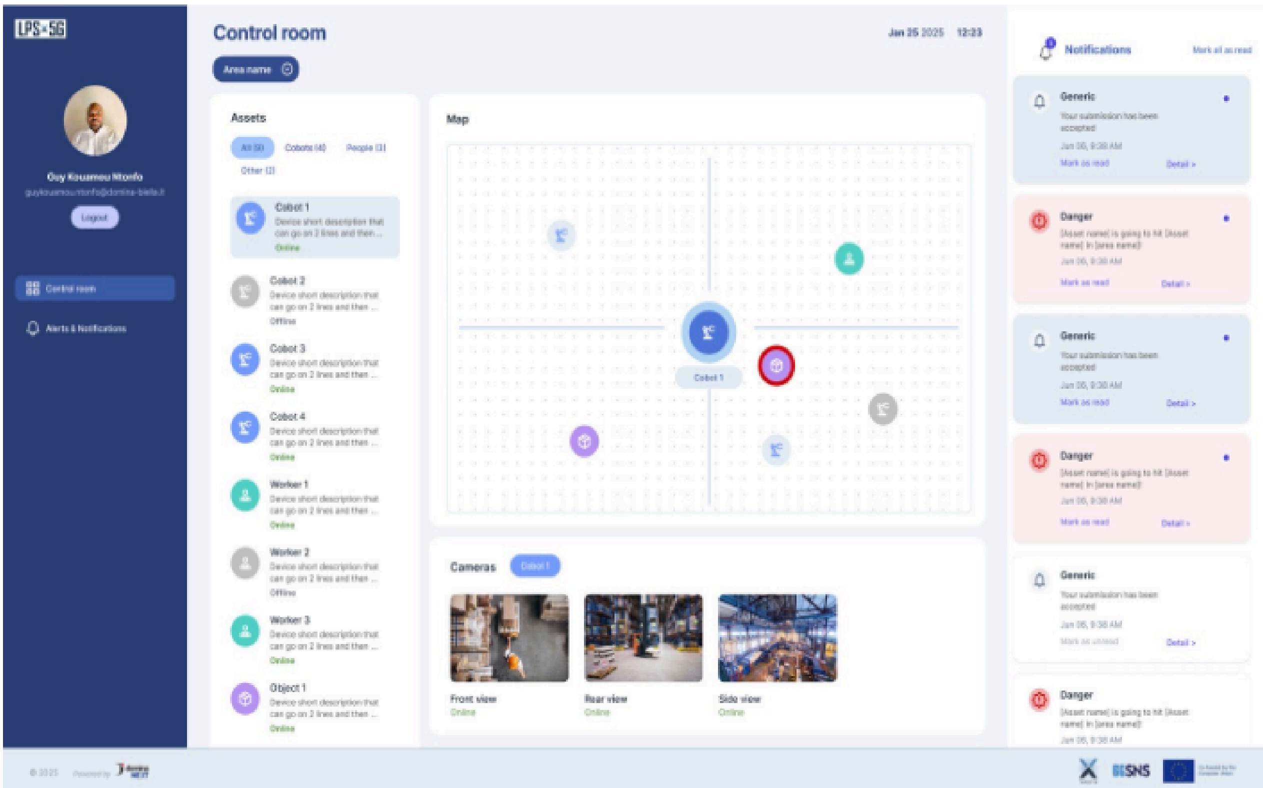

Figure 189: Dashboard monitoring collisions alerts

The system maintained 100% uptime and published data at 10 Hz, with data freshness aligned to latency. Security and privacy were ensured through secure transmission and authentication, supporting regulatory compliance. These results validate LPS-5G as a robust, real-time localization solution for industrial safety.

5G EMPOWERMENT

The LPS-5G system leverages 5G to deliver low-latency, high-bandwidth data transmission, ensuring real-time positioning and safety alerts. 5G connectivity allows seamless integration of smart tags, inertial sensors, and AI-powered cameras, enabling high-frequency data publishing (~10 Hz) and consistent data freshness (~0.68s latency). It supports robust communication, scalability across industrial environments, and reliable operation even in complex, high-mobility scenarios, enhancing worker safety and system responsiveness.

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PROJECT NAME (ACRONYM)	GRISP.IO ROS2 TOPIC SNIFFER (GRTS)
NAME OF BENEFICIARY	DIPL.-PHYS. PEER STRITZINGER GMBH
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

From Oct 2024 to Jun 2025, Dipl.-Phys. Peer Stritzinger GmbH, together with WZL | RWTH Aachen University, developed the GRiSP.io ROS2 Topic Sniffer (GRTS), a solution that simplifies and secures data communication among industrial robots, autonomous vehicles, and drones using ROS2. GRTS intelligently manages data flow, significantly reducing network congestion by compressing and prioritizing messages in real time. Trials demonstrated up to 70% lower bandwidth usage and reliable sub-30 ms latency, even during network disruptions. The solution seamlessly supports robots switching between Wi-Fi, private 5G, and satellite connections. Today, GRTS is available as an easy-to-use commercial application hosted at app.grisp.io/fluxros, enabling effortless local or cloud-based smart routing for ROS2 robots.

ARCHITECTURE

GRiSP.io ROS2 Topic Sniffer (GRTS) is organized into three layers. First, each robot runs a lightweight ROSiE bridge, enabling automatic discovery of communication endpoints and efficient handling of sensor data. Next, sensor messages are packaged and securely transmitted over an encrypted tunnel, which intelligently adapts to network conditions such as congestion or signal quality. Finally, a central Hub service hosted securely in the cloud or at the network edge manages incoming data streams, applying policies for prioritizing, compressing, or selectively dropping data in real time. Operators can visualize network health and robot performance through intuitive dashboards. The solution integrates seamlessly with existing robot fleets and supports hybrid local and cloud routing, automatically selecting the optimal network between Wi-Fi, private 5G, and satellite links.

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TRIAL

Trials involved mobile emulated robots streaming high-resolution video and sensor data over a dedicated 5G network slice. GRTS managed bandwidth dynamically, reducing video data peaks by 70% while ensuring stable latency under 30 ms. Satellite tests confirmed rapid adaptation despite high latency. Operators easily adjusted policies from mobile devices, observing effects immediately through real-time dashboards.

RESULTS

GRTS reduced network usage by 70%, minimized data loss during high-bandwidth streams, and maintained stable latency below 30 ms even with disrupted connectivity. Seamless robot roaming between Wi-Fi, private 5G, and satellite networks was achieved with near-instant policy updates. The solution is now commercially accessible at app.grisp.io/fluxros

5G EMPOWERMENT

5G technology enables GRTS to dynamically prioritize critical robot communications with ultra-reliable, low-latency connections. Network slicing and adaptive bandwidth management ensure performance even during high data loads or mobility events—benefits that previous wireless technologies couldn't deliver, unlocking new industrial automation and drone inspection use-cases.

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PROJECT NAME (ACRONYM)	INTEGRATION OF ETHERCAT WITH ROS2 ON 5G-ENABLED EM (ROS2 ON 5G EMBEDDED SYSTEMS)
NAME OF BENEFICIARY	SIA ITSOLUTIONS & PROGRAMMING
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	RWTH-WZL

OVERVIEW

The project aimed to integrate EtherCAT, a real-time industrial Ethernet protocol, with ROS 2 on a 5G-enabled embedded system to enable high-performance, low-latency communication for robotic and industrial automation applications. By combining the deterministic behavior of EtherCAT with the ROS2 modular robotics framework and the high bandwidth (eMBB) and ultra-reliable low-latency communication (URLLC) of 5G, the project delivers a scalable solution for advanced robotics use cases.

The development focused on implementing EtherCAT slave support on the Hilscher netX90 platform, integrating motor control via the CiA402 profile, and enabling ROS2 communication through a gRPC-based middleware. The system was deployed on a mobile robot running a custom Yocto Linux distribution with ROS2 nodes, navigation stack, and SLAM. A remote control application (AmurCore) was used over 5G with a VLAN for real-time teleoperation and monitoring.

The pilot use-case involved testing real-time motor control, map navigation, and remote access over 5G using the Quectel RM500U modem. The trial validated system stability, communication reliability, and responsiveness in both indoor and outdoor environments, demonstrating readiness for industrial robotics applications.

ARCHITECTURE

The Beerbot firmware adopts a modular, layered architecture to ensure scalability and maintainability across hardware, firmware, and communication components. The system is built on the Hilscher netX90 SoC, using dual Cortex-M4 cores to implement Field-Oriented Control (FOC) for precise motor control. The firmware layers include:

- Hardware Abstraction Layer (HAL): Interfaces with timers, ADCs, PWM, and sensors.
- Motor Control Layer (MCL): Implements FOC logic, motion states, calibration, PI loops, and transformation modules.
- Application Layer: Uses cifXApplication for EtherCAT communication (CiA402) with ROS 2 integration via beerbot_diff_control.

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The firmware integrates with ROS 2 running on a Qualcomm RB3 board, communicating via gRPC for efficient and low-latency messaging. Robot discovery and communication use AmurCore software and protobuf-serialized Controls and Sensors messages.

5G connectivity is ensured using the Quectel RM500U-EA modem, supporting both URLLC and eMBB technologies in SA/NSA modes, which allows for low-latency robot teleoperation and transmission of all necessary data for debugging. It is paired with a Waveshare 5G USB adapter for connection to the USB port.

The Yocto Project is used to build a custom Linux distribution, extending a Qualcomm base image with ROS 2, EtherCAT support, systemd services, and SLAM navigation. All services launch automatically, ensuring autonomous control with rich telemetry and diagnostics.

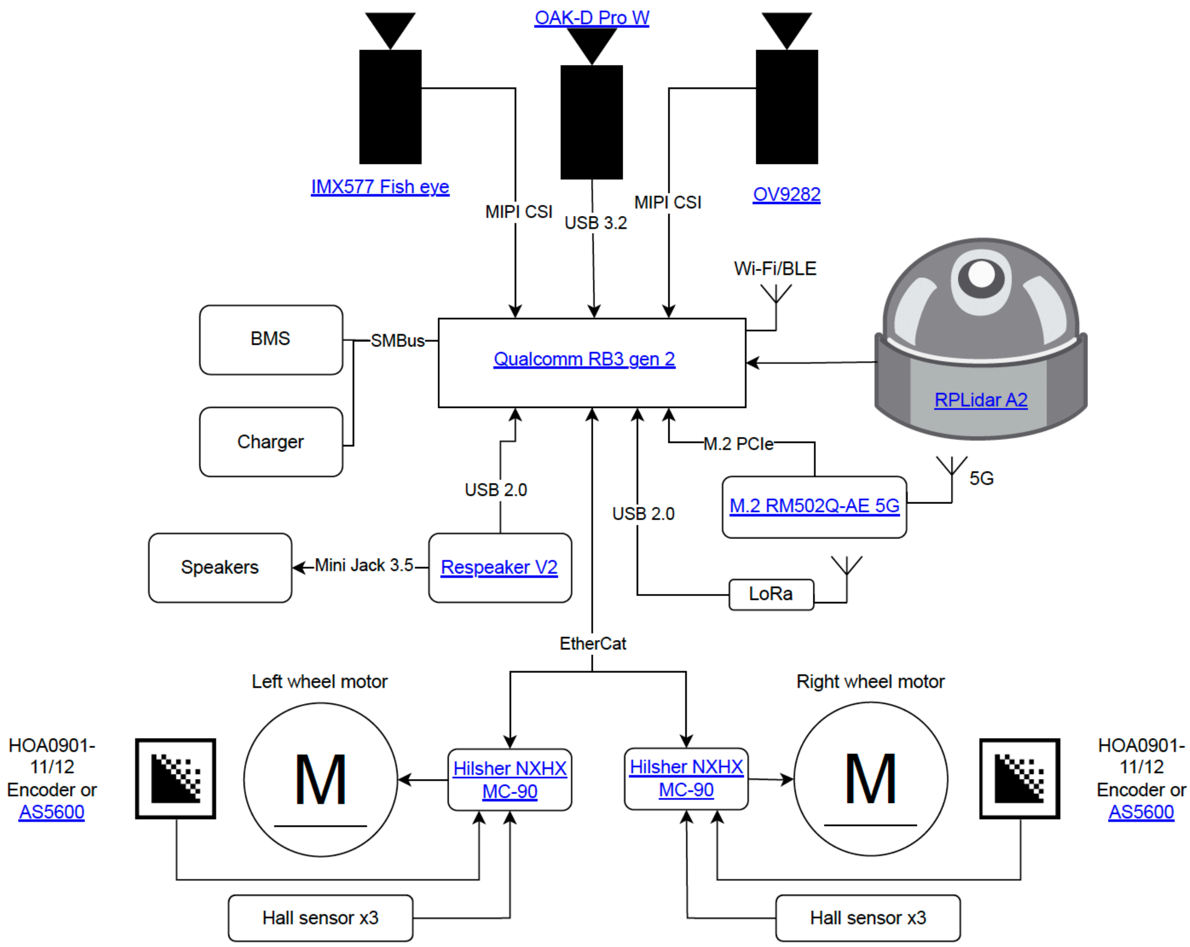

Figure 190.

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TRIAL

The trial deployment was built on our developed robot, outside of the TARGET-X testbeds.
Our robot uses the EtherCAT firmware on the Hilscher netX90 board, connected to Qualcomm RB3, which uses the Quectel RM500U-EA modem for connecting to 5G networks. Motor controlling through the CiA402 profile; this configuration was validated on the real robot. Motor control node integrated with ROS2, and communicating via gRPC for controlling purposes. EtherCAT and 5G module drivers were integrated into a custom Yocto image. A remote-control node and SLAM stack ensured real-time navigation, tested in indoor/outdoor scenarios over 5G.

Trial Sites: IT Solutions, Daugavpils

Photos:

Figure 191.

RESULTS

The project integrated EtherCAT with ROS 2 on embedded platforms equipped with 5G connectivity, enabling the development of real-time, scalable robotic systems. It achieved low-latency closed-loop control, remote operability, and a modular design suitable for both industrial and mobile robotics applications. The results demonstrate strong potential for adoption in sectors such as automation, logistics, and telemedicine. The project successfully addressed key Industry 4.0 KPIs, including system integration, latency reduction, and scalability.

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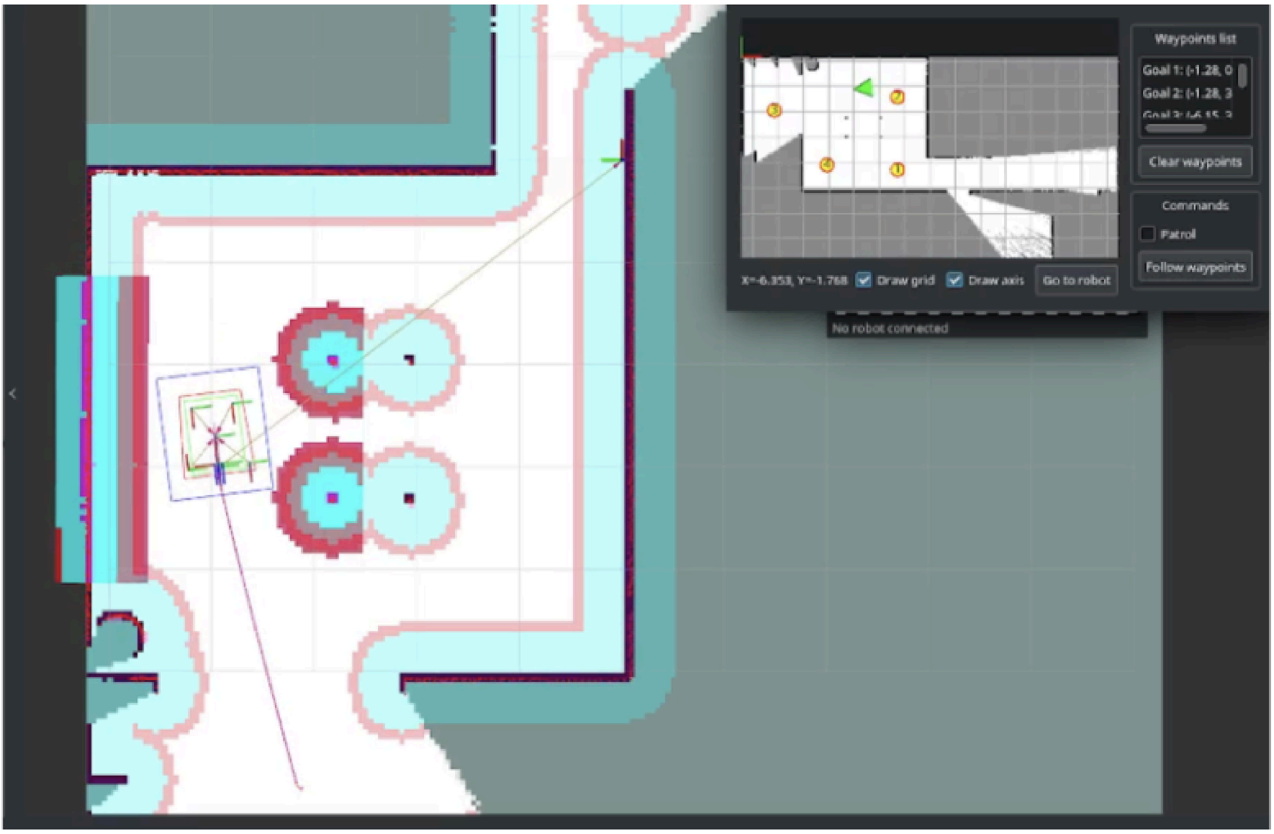

Figure 192: Example of navigation controlling via AmurCore

5G EMPOWERMENT

5G enables ultra-low latency, high-speed, and reliable wireless communication, supporting real-time control, remote operability, and high scalability in robotics. Unlike 4G, it allows low latency which is ideal for teleoperational use cases. Also, 5G Networks use light broadband, that allows data from sensors to be transmitted in raw bags for debug. This opens new possibilities for smart factories, telemedicine, and mobile robotics–where precision, modularity, and long-range control are critical.

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PROJECT NAME (ACRONYM)	DYNAMIC INTERIORS WITH REAL-TIME TWINS (INTELLIMAT)
NAME OF BENEFICIARIES	ARCOLOGY SYSTEM LTD RESOURCEKRAFT LTD
DATES OF THE SUPPORT PROGRAMME	TARGET-X 2nd Open Call 01/10/2024 - 30/06/2025
LIST OF INVOLVED PARTNERS	CCR

OVERVIEW

IntelliMat is a modular, sensor-integrated interior system developed under the EU-funded TARGET-X programme to enable real-time spatial tracking, cloud-based digital twins, and circular fit-out reuse in commercial buildings. Built around a ceiling-mounted SmartGrid, the system embeds Bluetooth 6 receivers and reflectors into walls, doors, and fixtures, enabling their position and status to be tracked with high accuracy.

Data is streamed via 5G to a cloud dashboard for live layout management, predictive maintenance, and lifecycle traceability. The project is led by Arcology System, with RTLS development by ResourceKraft. Pilot deployment began in June 2025 at the High-Performance Building Alliance (HPBA), a UNECE Centre of Excellence.

A key achievement was the successful pivot from Bluetooth CTE to Channel Sounding, improving accuracy fivefold and demonstrating IntelliMat's readiness for circular, data-driven interiors.

Figure 193.

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ARCHITECTURE

The IntelliMat system is built on a ceiling-mounted modular framework known as the SmartGrid. This aluminium grid provides the physical and spatial infrastructure for interior walls, doors, lighting, and services, all designed to be plug-and-play and fully reconfigurable. Embedded within these modular components are Bluetooth 6 receivers or reflectors, which communicate with fixed initiators installed at key points in the ceiling structure. Using a new Bluetooth Channel Sounding method, the system calculates precise location data based on the round-trip signal time between these devices—without requiring manual calibration or alignment.

All spatial data is transmitted in real time over a dedicated 5G uplink to a cloud-based digital twin platform. This allows users to visualise current layouts, track the use and movement of interior components, and overlay environmental data from embedded sensors. The architecture is designed to be scalable, IT-independent, and circular-ready. It supports predictive layout changes, asset reuse, and compliance with EU digital product passport requirements—making IntelliMat a fully integrated physical and digital platform for intelligent interiors.

TRIAL

Trial deployment took place in June 2025 at the High-Performance Building Alliance (HPBA) in Enniscorthy, a TARGET-X testbed and UNECE Centre of Excellence for circular construction.
The IntelliMat system was tested in a real-world modular ceiling environment, using tripod-mounted Bluetooth 6 initiators and plywood-mounted receivers simulating modular components.
Testing focused on spatial accuracy, signal stability, and 5G cloud integration, validating IntelliMat's ability to deliver real-time positioning and layout data without fixed infrastructure.

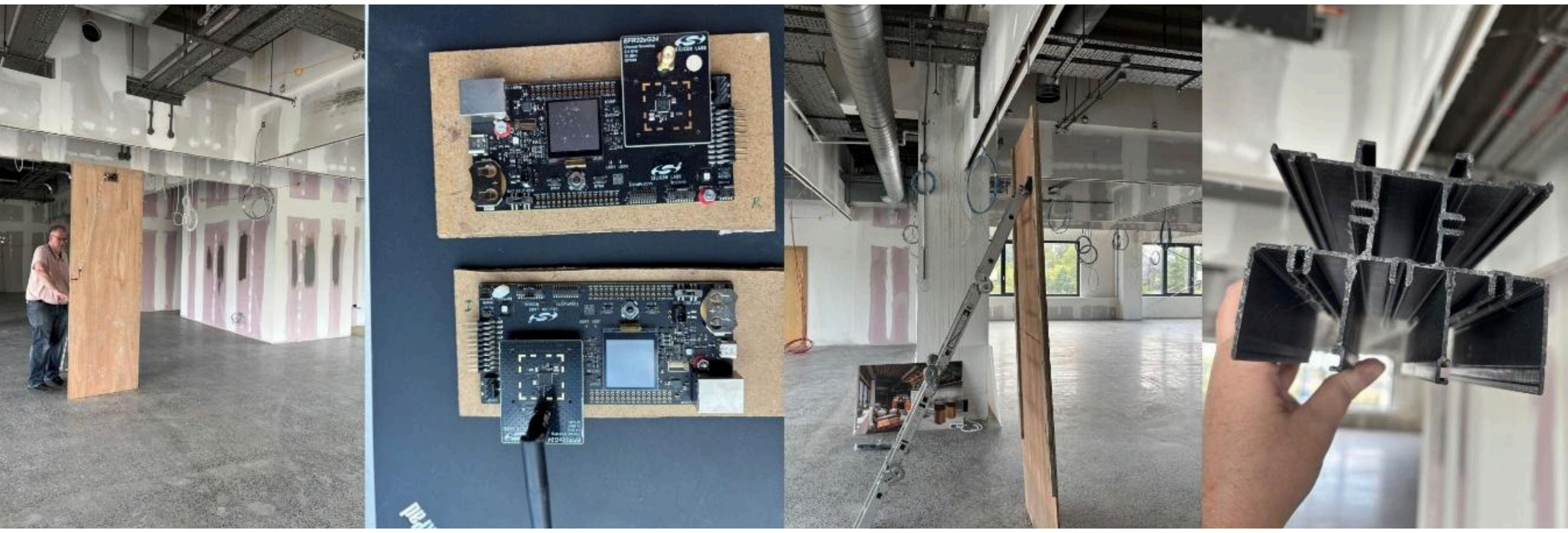

Figure 194: IntelliMat trial at HPBA showing Bluetooth 6 devices deployed in SmartGrid ceiling setup for real-time tracking and 5G integration

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RESULTS

The pivot to Bluetooth Channel Sounding delivered major performance gains, reducing location drift from ±3 m (CTE) to ±150–300 mm across the grid—even in obstructed environments. Field trials at HPBA validated the system's accuracy, resilience, and ease of deployment using 5G uplink. Components were successfully tracked and mapped in real time.
The cloud interface enabled live spatial layouts and metadata management, proving IntelliMat's readiness for scalable, circular deployment and integration with smart building systems.

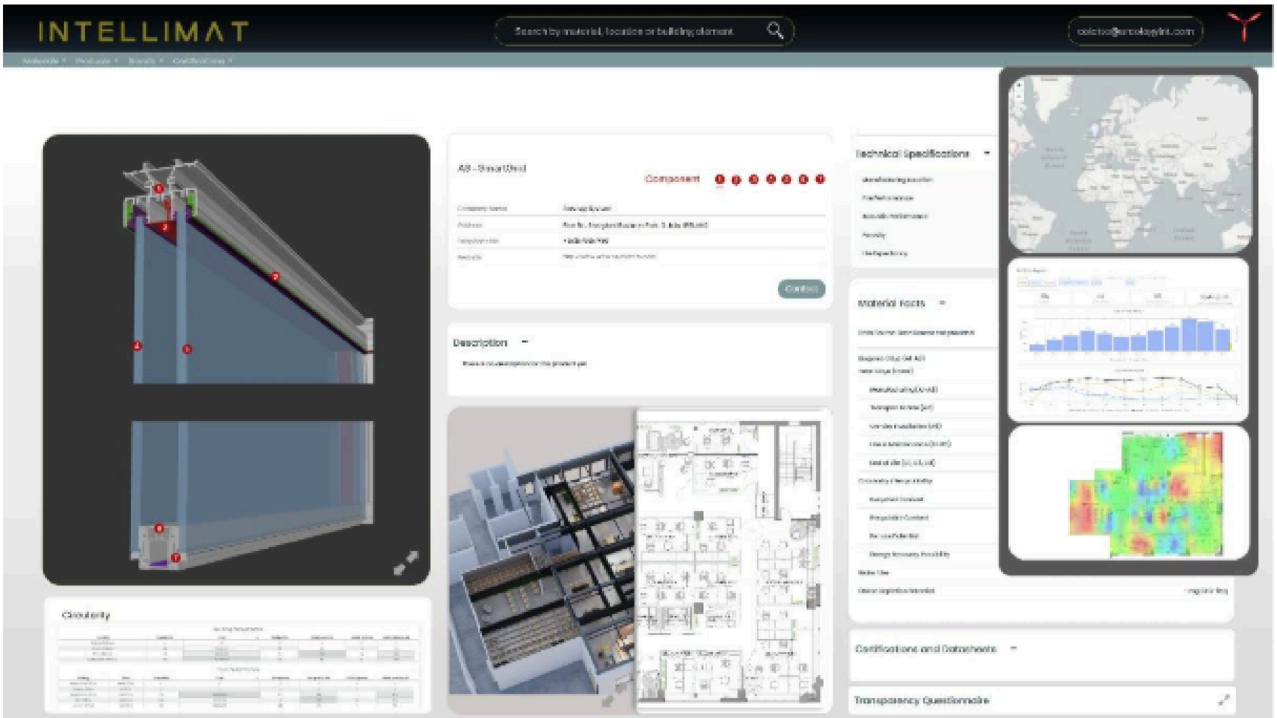

Figure 195: IntelliMat dashboard showing real-time layout tracking, material component status and sensor integration

5G EMPOWERMENT

IntelliMat leverages 5G to enable real-time tracking, layout reconfiguration, and cloud synchronisation of modular building components—all without relying on local IT infrastructure. 5G's low latency and high data throughput allow spatial and sensor data to be streamed continuously from site to cloud, supporting predictive layout updates, circular asset reuse, and remote diagnostics.

Unlike Wi-Fi or 4G, 5G enables seamless, secure deployment across large-scale interiors with zero configuration, unlocking spatial intelligence at a system-wide level.

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TARGET-X

CONSORTIUM PARTNERS

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ERICSSON

CONSTRUCTION ROBOTICS

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