FINAL PROJECT REPORT

Deliverable D9.4

The TARGET-X project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No: 101096614

FINAL PROJECT REPORT

GRANT AGREEMENT	101096614
PROJECT TITLE	Trial Platform foR 5G EvoluTion – Cross-Industry On Large Scale
PROJECT ACRONYM	TARGET-X
PROJECT WEBSITE	www.target-x.eu
PROJECT IDENTIFIER	https://doi.org/10.3030/101096614
PROGRAMME	HORIZON-JU-SNS-2022-STREAM-D-01-01 — SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
PROJECT START	01-01-2023
DURATION	34 Months
DELIVERABLE TYPE	Deliverable
CONTRIBUTING WORK PACKAGES	all
DISSEMINATION LEVEL	Public
DUE DATE	M34
ACTUAL SUBMISSION DATE	M34
RESPONSIBLE ORGANIZATION	Fraunhofer IPT
EDITOR(S)	Janina Gauß
VERSION	Final
STATUS:	V1.0
SHORT ABSTRACT	This final project report provides a summary of the major results and achievements of the TARGET-X project.
KEY WORDS	5G, 6G, trial sites, digital transformation
CONTRIBUTOR(S)	Maximilian Brochhaus, Aneta Gałązka, Marit Zöcklein, Niels König, Lucas Manassés, Pierre Kehl, Manuel Pitz, Benish Khan

Disclaimer

Executive Summary

This final project report contains an overview of the results achieved in the TARGET-X project and provides references to the relevant documents and deliverables.

The achievements span over the four application domains (verticals) Energy, Manufacturing, Automotive and Construction as well as the technology domain. Of relevance are applications and use cases of the 5G and beyond technology for the verticals and end users. Therefore, in all TARGET-X testbeds, the use cases have been described and investigated for the potential benefits for the end users. The benefits are investigated in the methodological assessment framework using key performance indicators (KPIs) and key value indicators (KVIs) from the verticals' users. The presented results include the use cases as well as additional performed trials per testbed. The TARGET-X testbeds have been heavily collaborating with the technology partners to integrate the beyond 5G technology into their testbeds and an overview of the activities is given in this deliverable.

TARGET-X provided Financial Support for Third Parties (FSTP) for 26 projects in the first and 40 projects in the second open call. This resulted in a number of innovations, as reported by 30 out of 40 beneficiaries of the second open call.

Finally, the project has participated in various events, and used a website, LinkedIn channel, and the TARGET-X community for dissemination. The project has actively contributed to conferences e.g., EUCNC, and industry fairs ensuring communication dissemination to technical as well as non-technical audiences across different verticals. A highlight is the TARGET-X trials brochure, providing insights into use cases and trials from both the project consortium as well as prepared by the FSTP projects. Further, the project has published scientific papers and has built a community of supportive partners.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AAS	Asset Administration Shell
BLE	Bluetooth Low Energy
C-ITS	Cooperative Intelligent Transport System
CAM	Cooperative Awareness Message
CPM	Collective Perception Message
CV	Connected Vehicle
DENM	Decentralized Environmental Notification Message
eMBB	Enhanced mobile broadband
FRER	Frame Replication and Elimination for Reliability
FSTP	Financial Support for Third Parties
GEM	Genior Modular
IT	Information Technology
KPI	Key Performance Indicator
KVI	Key Value Indicator
MAF	Methodological Assessment Framework
OEM	Original Equipment Manufacturer
OT	Operational Technology
PMU	Phasor Measurement Unit
QoS	Quality of Service
RAN	Radio Access Network
RedCap	Reduced Capability
ROS 2	The Robot Operating System 2
SDR	Software-Defined Radio
SLAM	Simultaneous Localization and Mapping
SNS JU	Smart Networks and Services Joint Undertaking
TDD	Time Division Duplexing
TSN	Time-Sensitive Networking
URLLC	Ultra-reliable low-latency communication
WP	Work Package

1 Introduction

The TARGET-X project is one of the Smart Networks and Services Joint Undertaking (SNS JU) Phase 1 projects. It is part of Stream D ”Large-Scale SNS Trials and Pilots”. TARGET-X ran for 34 months and started in January 2023. The project costs are more than 14 M€ of which 6 M€ were reserved for Financial Support for Third Parties (FSTP).

TARGET-X aims at accelerating the digital transformation in four verticals: Energy, Manufacturing / Robotics, Construction and Automotive. These key verticals jointly integrate beyond 5G technology in large-scale testbeds and evaluate the technology methodologically with user-centric Key Performance Indicators (User-KPIs) and Key Value Indicators (User-KVIs). The FSTP projects act as further innovation drivers.

This is reflected in the project's structure which is shown in Figure 1.1:

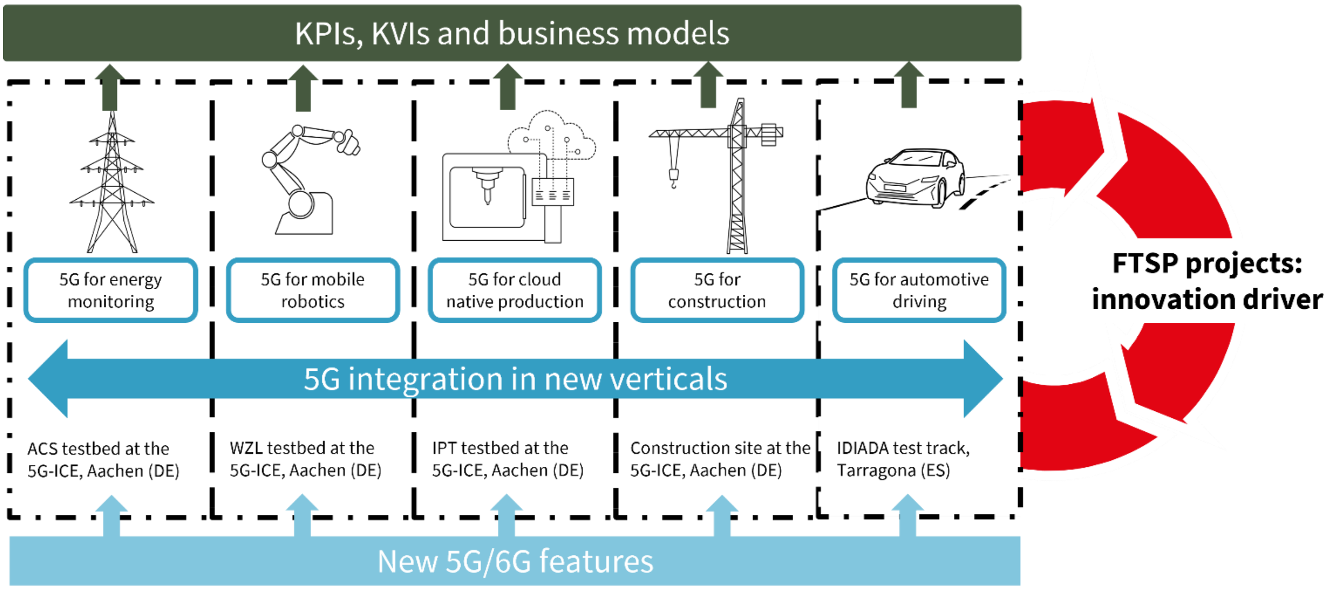

Figure 1.1 Overview of the project's work-package structure and vertical organization

The TARGET-X Work Packages (WPs) can be mapped to the key elements of the TARGET-X structure: WP1 “Methodological Assessment Framework” focuses on use cases and the development of a methodological KPI/KVI assessment. The work packages 2-5 aim at the different verticals: Manufacturing (WP2), Energy (WP3), Automotive (WP4) and Construction (WP5). WP6 (Technology Evolution Beyond 5G) prepares and integrates new 5G/6G features into the testbeds. WP7 facilitates the FSTP projects while WP8 takes care of communication and dissemination. The project management is carried out in WP9.

Figure 1.1 gives an overview of the testbeds in TARGET-X. They aim at evaluating and validating the 5G and beyond technology. The Energy testbed “5G for energy monitoring” is located at the 5G-Industry Campus Europe in Aachen, Germany, and uses the RWTH-ACS main building EON Energy Research Center as a testbed for energy monitoring. The Robotics testbed “5G for mobile robotics” uses the RWTH-WZL state-of-the-art mobile assembly laboratory that is also part of the 5G-Industry Campus Europe in Aachen, Germany. The Cloud Native Production testbed “5G for cloud native production” is located at the machine hall of the Fraunhofer Institute for Production Technology IPT, the central coordinator of the 5G-Industry Campus Europe. Both, the robotics and the cloud native production testbeds are associated with the Manufacturing vertical. The Construction testbed "5G for construction" implements a living lab on a reference construction site that is also part of the 5G-Industry Campus Europe. The Automotive testbed "5G for automotive driving" is located at the Applus IDIADA test track in Tarragona, Spain, that covers 370 hectares and a mobile communication infrastructure.

This document is the final project report of TARGET-X and gives an overview of the project's achievements. It describes the relevant results and provides references to all deliverables, papers, and further output of the project. Some of these outputs can also be found on the TARGET-X website https://target-x.eu/ and in the project's community on Zenodo https://zenodo.org/communities/targetx/. Additionally, it provides insights into the results of both open calls for FSTP, the selected and executed projects and their highlights.

1.1 Objective of the document

The objective of this final project report is to summarize the achievements and overall progress of the TARGET-X project across the various work packages and verticals. This includes the achieved results and references to the relevant deliverables.

The objectives of the document align with the objectives of the TARGET-X project:

1. To demonstrate and validate industrial 5G/6G technologies and architectures in large-scale pilots in four different verticals.
2. Investigating 5G/6G and peripherical technologies across the whole value chain (devices, connectivity, service delivery) to identify, assess and propose new 5G/6G features targeting connected industries.
3. Enabling future use cases by self-adapting communication networks
4. Dynamic allocation of communication and computation resources across Information Technology (IT) & Operational Technology (OT)
5. KPI and Key (Societal) Value Indicator (KVI) generation from real business cases validated on large scale trial sites
6. Enhance the 5G/6G ecosystem in the manufacturing & robotics, automotive, energy, and construction verticals
7. To disseminate and communicate the outcome of the TARGET-X project and contribute to standards, the scientific and industrial domains, and the subsequent SNS phases.

1.2 Structure of the document

The Deliverable at hand is structured according to the overall structure of TARGET-X. The first chapter introduces the overall concept of TARGET-X. The following chapter 2 relates to WP1 "Methodological Assessment Framework" that targets use case descriptions and methodological assessment with User-KPI and User-KVI. In the next chapters 3-7, the TARGET-X testbeds that represent the WP2-5, describe their key results and lessons learned of the project with a focus on lessons learned regarding 5G and beyond. Unlike previous deliverables, this report is structured by testbed and trial rather than by vertical and use case. Vertical specific lessons learned can be found in the respective vertical deliverables, that are also referenced in the sections. The sections further include information about the FSTP projects mentored. Chapter 8 "Technology evolution beyond 5G" focuses on the technological developments and achievements incorporating lessons learned from a network perspective. Chapter 9 summarizes the activity on cybersecurity. In the following chapter 10, the FSTP process and insights are summarized. Chapter 11 provides insights on the innovations in the project. This is followed by a description of the communication and dissemination efforts in chapter 12. Chapter 13 concludes the document with a summary.

1.3 Relation to other activities

This deliverable is the final report of the TARGET-X project. It is related to all the activities carried out in the project. It summarizes the achievements of the project. A list of all related deliverables can be found in the References.

2 Use cases and methodological KPI/KVI assessment framework

2.1 Use Case Overview

Within TARGET-X, a total of 12 use cases have been developed as the core use cases of the project [TAR23-D11]. In addition, a variety of further use cases have been developed in the FSTP projects. One of the key objectives of TARGET-X was to transfer 5G technology into industry, thereby accelerating the digitalization of the European economy. This goal was addressed by the development of a Methodological Assessment Framework (MAF) for the evaluation of the value proposition of the TARGET-X use cases. An overview of the developed use cases is provided in Table 1**Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 1 Overview of TARGET-X Use Cases.

Use Case Name	Testbed	Work Package	Deliverables
Inline Quality Assurance for Machining	Manufacturing	2	D2.5: Report on Working Demonstrators and Validation Implemented for 5G/6G Technologies in Manufacturing
Environmental Condition Monitoring	Manufacturing	2	D2.5
Trace and Tracking of Workpieces	Manufacturing	2	D2.5
Edge-Controlled Automation with Mobile Manipulation	Robotics	2	D2.5
Energy Monitoring and Energy Consumption Awareness	Energy	3	D3.6: Energy Pilot Analysis
Cooperative Perception	Automotive	4	D4.4: Integration and Validation Outcomes
Digital Twin	Automotive	4	D4.4
Predictive Quality of Service for Tele-operated Vehicles	Automotive	4	D4.4

5G for Automation of Deconstruction Processes	Construction	5	D5.3: Report on Living Labs and Task Assessment
5G for Mixed Reality Supported Deconstruction Planning	Construction	5	D5.3
5G for Energy Analytics	Construction	5	D5.3: Report on Living Labs and Task Assessment
5G for Safety Assistant System	Construction	5	D5.3

For each of these listed use cases, User-KPI and/or User-KVI have been defined to capture each use case's value proposition from both techno-economic and societal perspectives. The prefix "User" has been purposely selected to illustrate the focus on the potential benefit for the end user of a certain use case. The User-KPI and User-KVI are part of the MAF which is explained in the next section in detail.

2.2 Methodological KPI / KVI Assessment Framework

The MAF developed in TARGET-X serves two main purposes. On the one hand, it builds a bridge from Network KPI (which describe the critical characteristics of a network, such as latency or throughput) to a value proposition that is achieved through the implementation of the use case. In this way, the MAF can be used to build a common ground of understanding and simplify communication between experts in the different domains of networking and the domain in which 5G is applied (e.g., manufacturing). On the other hand, the MAF employs specific User-KPI and User-KVI to gain transparency regarding the value proposition of a specific use case. In this way, a data-driven- calculation of key indicators (User-KPI & User-KVI) is used to make an estimation of a use case's benefit. The MAF is pictured in Figure 2.1 and it is extensively described in [TAR24-D12].

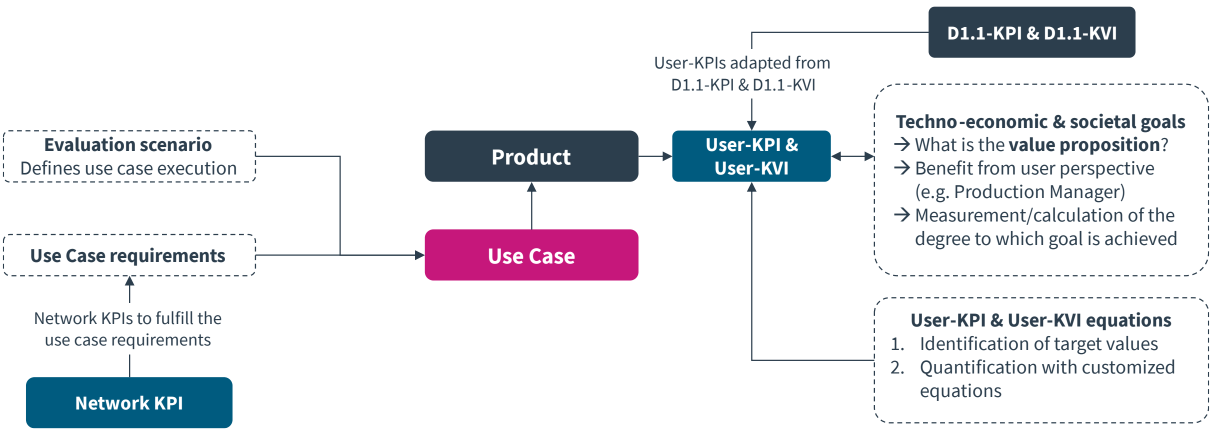

Figure 2.1 Methodological Assessment Framework of TARGET-X

The basic principles behind the MAF have also been validated by activities of the TARGETX WP1 team in the 5G Alliance for Connected Industries and Automation (5G-ACIA). In those activities, a Whitepaper has been compiled, based on a use case evaluation following the principles of the MAF [5GAC25]. In this way, additional feedback from IT and OT experts was collected from outside the TARGET project consortium, further validating the principle which the MAF was constructed upon. The MAF has also been transferred into a web-based software tool that contains the evaluation results of the use cases.

2.3 Results & lessons learned

The MAF has been applied to the TARGET-X use cases, indicating a positive value proposition achievable through the implementation of the use cases. The evaluation results are described for each use case individually in their respective sections of the deliverable at hand. The value propositions presented here are the explicit value propositions of the use cases.

Through the development and application of the MAF, valuable lessons could be learned over the course of the project:

- The developed MAF enables the capturing of the value proposition of different 5G-based use cases in a domain-agnostic way
- The MAF paths the way from Network KPI to user benefits (value propositions)
- For a uniform assessment of 5G-based use cases, a small set of User-KPI and User-KVI is sufficient
- It is important to establish comparability between different verticals by focusing on a limited selection of aspects, e.g., process capability (c_p and c_{pk}) that have significant impact
- The positive impact of 5G can be shown with both measurement data as well as expert estimations as input parameters
- One of the advantages of the MAF is its versatility and broad applicability; however, this sometimes compromises the accuracy of the analyses performed using the model
- One of the key challenges for the evaluation of the use cases was their increasing technical maturity, since not all use cases could be evaluated as planned

The evaluation results of the use cases described in Sections 3-7 can be condensed to the following quintessential result: The use of 5G makes processes (use cases) more efficient through timely and reliable communication while at the same time the insights into the processes are increased, so that more can be learned about them. This suggests, in particular, potential for scaling up industrial 5G applications, enabling greater output to be achieved across the board with less input (material, energy, manpower, etc.). At the same time, however, it should be noted that a detailed economic analysis of the use cases was not possible, as many uncertainties remained regarding the costs and potential savings. Instead, a detailed economic analysis was carried out with an external partner of the project at an automotive OEM, where it was shown that a 5G-based use case implemented there had a net present value of €1.2 million with a payback period of 5 years and an ROI of 130% [5GAC25].

Overall, the MAF successfully achieved its objective of providing a generic framework to capture the value proposition of 5G-based use cases across the project's verticals.

3 Energy

3.1 Motivation

The energy testbed within the TARGET-X project aims to further integrate 5G technology into the energy domain. This can either be for grid monitoring or increased energy awareness. These two cases have different requirements. The grid monitoring case depends on high sampling rates and high time tagging accuracy, whereas the energy awareness case requires a high energy metering accuracy. The testbeds for both types of use cases are located at the 5G-Industry Campus Europe at RWTH Campus Melaten in Aachen. Both use cases focus on a 5G-enabled, synchronized measurement devices that can be used for local grid monitoring or, in other verticals, to measure the energy consumption of machines such as those on construction sites.

Grid Monitoring

The grid monitoring case is carried out at the RWTH-ACS institute building and other locations within Europe. The locations are partially provided by FSTP project and project partners. For the measurements, the 5G-edgePMU is used. It focuses on the voltage behaviour of the local low-voltage grid. The measurement data from all test sites are sent to an edge cloud-like infrastructure that can visualize the data and handle short- and long-term storage. A more detailed description of the energy testbed is given in deliverables D3.1 [TAR23-D31] and D3.4 [TAR24-D34] as well as with the results in D3.6 [TAR25-D36].

Energy Awareness

The energy awareness use case utilizes the construction and robotics testbed. In the testbeds, different processes at the sites have been evaluated from an energy perspective. To achieve that, energy as well as current and voltage measurements are needed. This is accomplished by utilizing the Meter-X device build as a weatherproof box for inline measurements.

The Energy vertical has the following objectives:

1. It will demonstrate the 5G/6G potential for creating energy and facility awareness and making possible data-driven energy-related functionalities fostering sustainability across different sectors.
2. It will develop a modular and open architecture for acquisition and post-processing of data, that will be implemented and demonstrated thanks to 5G functionality.

3.2 Grid Monitoring in a European Grid

Within this trial the 5G-edgePMU is deployed in different parts of the European power grid. With its capability of synchronized measurements, the results can then be compared. The 5G-edgePMU transmits the 25 measurements per second to a storage system located at RWTH Aachen. This trial was achieved together with project partners and two FSTP projects. The deployment of the 5G-edgePMU in the Aachen testbed is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

The following locations are now deployed with a 5G-edgePMU device

- Aachen Germany

- Barcelona Spain
- Kistelek Hungary (FSTP Project)
- Kranj Slovenia (FSTP Project)
- Milano Italy

Figure 3.1 5G-edgePMU deployed in the RWTH Aachen testbed

Key results

- The 5G-edgePMU was deployed in five countries.
- It was shown that the 5G-edgePMU can utilize 5G SA and 5G NSA for connectivity.
- The developed remote control and management platform was used to remotely configure the field devices.
- A frequency comparison within the five countries shows a very close tracking of the grid frequency, as it is expected. This showcases the synchronization precision of the 5G-edgePMU.

3.3 Energy Awareness in a Laboratory Environment

Within this trial, a 5G-enabled energy measurement device was deployed. The hardware stack is based on the Meter-X but in this case for stationery use in a fixed installation. The three measurement points are distributed within three rooms. Each with a specific load type. The test point in the mechanical workshop monitors equipment like lathe, drill press and CNC machine. The device deployed in the electronics lab supervises loads like switches, soldering stations, as well as a fridge. Finally, in the server room the major loads are different types of servers as well as real time simulation hardware. This trial uses a local 5G SA deployment that is limited to the laboratory environment. The deployment is shown in Figure 3.2.

Figure 3.2 5G-enabled energy measurement in energy testbed. Mechanical workshop (left), electronics lab (center) and server room (right).

Key results

- The three energy measurement devices have been deployed successfully in the laboratory environment.
- The measurements are collected and visualized in a local edge cloud environment
- New insights about the different load types were gained.
- Within this trial the impact in Germany by the Spanish power outage in 2025 was measured. A clear dip in the grid frequency could be observed.

3.4 Energy Awareness on a Construction Site

Energy awareness on a construction site requires a mobile and easy to use device for energy measurements. The Meter-X device that was developed within TARGET-X allows for non-electricians to connect different devices under test in a construction environment. In this trial the Meter-X is connected to a GEDA 1200 Z/ZP material lift and the energy consumption of the lift is analyzed. The setup is shown in Figure 3.3.

Figure 3.3 GEDA 1200 Z/ZP lifter with Meter-X on the Reference Construction Site

KPI/KVI Evaluation

For this trial, an evaluation based on User-KPI and User-KVI was conducted. The selected User-KPI and User-KVI for the evaluation have first been described in D1.2, Section 3.5.3.3 and Section 3.5.3.4 [TAR24-D12]:

User-KPI:

- Completeness of process and product data
- Timeliness of process and product data

The measurements with Meter-X showed that the developed solution can significantly increase the completeness and timeliness of measurement data, as no data would exist without the solution. The connection of Meter-X to a 5G network enables real-time analysis of the data, so that high quality data with high granularity (7 phase measurements per one second) is available for analysis purposes. Therefore, the considered use case offers high value regarding completeness and timeliness of energy measurement data.

User-KVI:

- Global Warming potential, GWP
- Water consumption, WCon
- Ozone depletion, ODep
- Photochemical ozone formation, PhOz
- Consumed electricity per kilogram of transported mass, E

The acquired energy measurement data was employed to calculate the environmental footprint of an exemplary construction operation on the construction site following the LCA method. For this purpose, the GEDA 1200 Z/ZP lifter was equipped with Ytong stones and lifting operations were carried out. At the beginning, the empty lift was raised once and then lowered again. This operation was repeated once more. Then the lift was loaded with two Ytong blocks at a time and raised and lowered twice in succession. This procedure was repeated step by step, with two more Ytong blocks being loaded onto the lift each time, until there were 12 Ytong blocks on the lift at the end. In total, the lift was moved up and down 14 times. The energy that was consumed during these lifting operations was measured with MeterX and used for the calculation of the environmental User-KVI. In total, 0.213 kWh were consumed during the operations (idle times excluded).

The following values listed in **Fehler! Verweisquelle konnte nicht gefunden werden.** were calculated for the User-KVI, based on the consumed energy and the environmental footprint of the Germany energy mix:

Table 2 Environmental Footprint of Material Lift Operation.

User-KVI	Calculated value
Global Warming potential, GWP	0.054 kg CO_2-eq.
Water consumption, WCon	0.021 m^3
Ozone depletion, ODep	1.061×10^{-9} kg CFC 11-eq.
Photochemical ozone formation, PhOz	1.65×10^{-4} kg NMVOC-eq.
Consumed electricity per kilogram of transported mass, E	1.97×10^{-4} kWh/kg

The successful implementation of the use case illustrates 5G's potential to act as an enabler for the acquisition of high quality, reliable data that can be utilized to gather valuable and valid insights into processes or systems. These insights can then be utilized in next steps to derive optimization measures or compare different solutions for environmental footprint reduction.

Key results

- It was shown that the Meter-X device can be used in a harsh outdoor environment.
- The 5G NSA connection and automatic measurement transmission to an edge cloud server were successfully tested.
- The remote management and easy deployment based on the auto deployment platform developed in TARGET-X were shown.
- The power consumption of the material lift was evaluated, and the weight dependency could be shown; in addition, the environmental footprint of the material lift operation was calculated
- In contrary to the expectation the material lift feeds back power in the grid when lowering
- It was shown that a warning sound of the lift, just before lowering, could be identified in the power measurement. This could be used to enhance construction site awareness.

3.5 Energy Awareness in a Manufacturing Environment

Within this trial, the energy awareness in a manufacturing environment was shown. The trial focused on a robotic arm that was used to move a weight from one side of a table to the other side of a table.

This setup was chosen to allow for a controlled environment of the test while allowing to evaluate the results with different weights. The test is shown in Figure 3.4.

Figure 3.4 Kinova robot arm moving a fixture with variable weights and measured by the Meter-X device.

Key results

- It was shown that the Meter-X device, which is developed for three phase loads up to 22 kW can also be used to analyze a robotic arm, which is a single-phase load with up to 100 W. This was done without any modification.
- It was shown that the 5G SA connection could be established, and the measurements have been transmitted to a local edge cloud server.
- The robot arm movement was successfully analyzed.

3.6 Energy Awareness in an Automotive Environment

Within this trial, the 5G-edgePMU was deployed in a car to measure the power consumption of a router. The goal was to evaluate the ruggedness of the 5G-edgePMU in a mobile environment as well as to the cloud continuum use case with the 5G-edgePMU software stack. This section describes the energy side while in section 6 Automotive the cloud continuum trial is described. The deployment in the car is shown in Figure 3.5

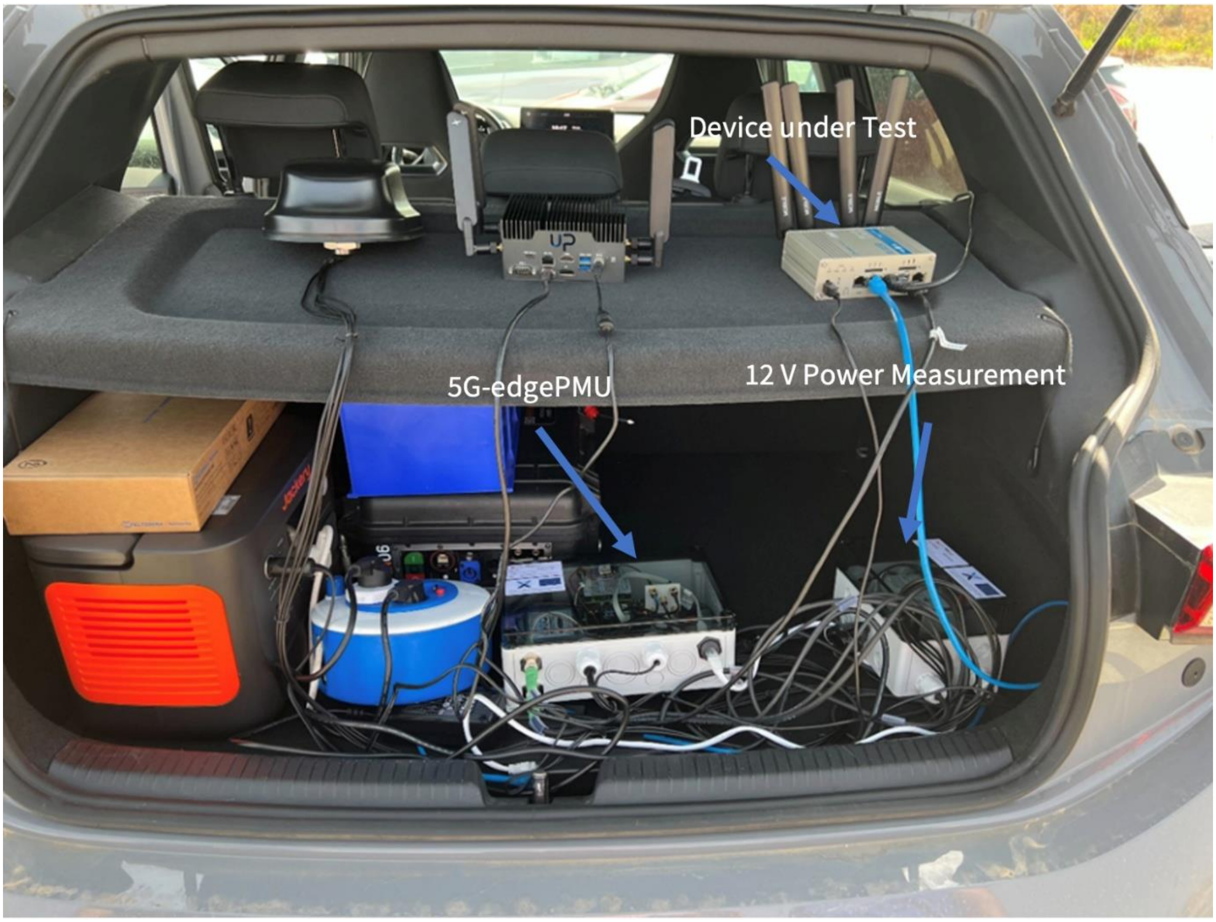

Figure 3.5 5G-edgePMU mounted in a car for power consumption measurement

Key results

- The 5G-edgePMU was successfully deployed
- The 5G-edgePMU was able to measure the power consumption on a 12 V DC supply rail
- It was shown that the application stack of the 5G-edgePMU can change the main compute resource based on the local 5G link quality.

3.7 Overview of the FSTP projects from both open calls

Name	OC1	OC2	Description	Partner 1	Partner 2
5GEdge_ForecastOptimiser	X		TOWARDS OPTIMAL FORECASTS FOR 5G Edge (5GEdge_ForecastOptimiser) aimed to implement a methodology that dynamically chooses the optimal forecasting algorithm with	Lamda Networks Private Company	

		respect to the load patterns within the energy scenario.	
DAEMON-LEC-5G	X	The Project “Distributed Active Energy Monitoring and Optimization Network (DAEMON-LEC-5G) implement a hardware-software framework in the field of monitoring and optimization of electrical energy using the 5G network capabilities.	RBZ Robot Design S.L.
EHBear	X	The Energy harvesting from bearing rotation (EHBear) project developed an energy harvesting system suitable for driving a bearing monitoring system. A stable energy supply is crucial for 5G-enabled monitoring systems. In bearings, abundant energy is available from the bearing's rotation.	HCP Sense GmbH
FAST-SEM	X	The 5G And 6G Telemetry - Smart Energy Meter (FAST-SEM) project used a compact, 3-phase energy meter enhanced with 5G connectivity, exposing advanced power consumption parameters. Designed to fit a standard DIN box and capable of reading up to 1000A, it ensures quick and easy deployment.	Silla srl
LENSE	X	The project Low-Voltage Energy Distribution Network Monitoring (LENSE) transformed substations into intelligent connected units, offering an unprecedented level of continuous monitoring capabilities.	INSIGHIO I.K.E

LINC	X		Realtime AI: Amplifying Grid Lifespan & Capacity (LINC) aimed a new clarity to grid management. It offered DSOs real-time, AI-based digital twins that foster informed decision-making. High-speed 5G/6G networks ensure fast data collection. It also supports global green energy transitions and user data control.	LincLab Network SL	
Open Energy Box	X		The Open Energy Box project aimed a gateway to efficient, sustainable manufacturing. By providing comprehensive energy and production data, it also aimed to open new opportunities for third parties.	Connect IQ Sp. z o.o.	DRIMER Sp. z o.o.
AquaSmart360		X	The AquaSmart360 project aimed to bring modern, intelligent management and easier monitoring to small and medium-sized wastewater treatment plants (WWTP)) by combining latest IoT technologies with high-speed 5G connectivity.	Tovarna idej d.o.o.	Komunala Odtok d.o.o.
EcoPredict		X	EcoPredict is an AI-driven smart building platform which aimed to optimize energy consumption, integrate renewable sources, and enhance user comfort through predictive control and real-time recommendations.	ARTIO.Tech P.C.	Klimamichaniki S.A
ecosync		X	The ECOSYNC project addressed critical challenges in battery management and sustainability within the electric vehicle (EV) sector, with a particular usage of the 5G technology and low latency services.	Wego srl (volvero)	MinervaS SRL

EdgePMU-5G IoT	X	The project worked on the control system of the electrical energy distribution system with the help of the integration of edgePMU devices and the establishment of a real-time communication mechanism and IoT system.	INDA d.o.o.	Elektro Gorenjska d.d.
ERTM	X	The ERTM project integrated both hardware interventions and software components to improve network connectivity and enhance the responsiveness of load management systems in electric vehicle charging infrastructure.	Parity Platform P.C.	University of Patras
PMU-EC	X	The PMU-EC project deployed edgePMU technology in the town of Kistelek, on the sections of the local distribution grid and at the connection points of energy community members.	Meter Solutions Kft.	Kistelek Energy Community

3.8 Lessons learned

Within the energy vertical the deployment of more than 10 devices with 5G connectivity was accomplished. This includes the deployment in five different countries, in mobile and stationary applications as well as in 5G SA and 5G NSA deployments. After some initial hurdles all devices were deployed successfully and 5G proved its ability to accommodate for the required resources. Within the energy vertical related tests mainly the edge computing capabilities are of interest. As such the deployment within RWTH Aachen was able to showcase the edge cloud functionalities for long term storage of measurements, visualization and analysis purposes.

The major challenges encountered during deployment are due to the diverse and complex nature of 5G. The first challenge was that the difference in configuration for 5G SA and 5G NSA was not clear in the beginning and thus resulted in long debugging sessions. In the end it was understood that the specific modem, used in the test, needs to be set to 5G and LTE to be able to successfully connect to 5G NSA networks. Furthermore, in different field deployments the required default APN configuration for the specific modem and mobile network provider resulted in complex to debug issues. In one case the modem could not register to the public mobile network due to a misconfigured APN setting. The need for deep debugging sessions is a challenge when deploying 5G driven equipment and in the end results in the need of a telecom engineer for the deployment of devices in the energy domain. This is an obstacle for easy deployments.

A final challenge is the debugging of 5G communication issues. Since usually the mobile network as well as the equipment providers do not see a strong market potential in niche developments like the 5G-edgePMU or the Meter-X device, it is hard to get fast and in-depth support. Instead, long email discussions or a public forum is the preferred way of communication. This again increases the barrier for non 5G experts to deploy their devices easily.

The given lessons learned showcase that 5G is an important step forward, enabling new functionalities in the energy sector. Still, to support the 5G rollout in the energy vertical, more technical support and simplification of the technology deployment would be beneficial.

4 Cloud-Native Manufacturing

4.1 Motivation

The cloud manufacturing testbed addresses three main use cases: Environmental Condition Monitoring, Track & Tracing of Workpieces and Inline Quality Assurance for Machining. Environmental Condition Monitoring uses wireless sensors integrated into machines or workpieces to log parameters such as machine power, compressor air flow, and spindle/machine vibrations; Track & Tracing monitors condition and location throughout the process via onboard sensors measuring vibration, temperature, environment and orientation; Inline Quality Assurance leverages 5G/6G and industrial Ethernet (e.g., CC-Link IE TSN) to enable real-time wireless sensing that feeds PLCs for process control and transmits data to the factory cloud for optimized usage and digital twin creation.

The testbed has been set up at the Fraunhofer IPT in Aachen, which provides 5,000 m² lab and shopfloor to test at real industrial conditions. The machine hall is equipped with diverse machine tools such as milling and turning, laser structuring, injection molding, presses, tool grinding, EDM/ECM and multi-tool robot cells. Within the shopfloor and the labs different, commercially available and pre-commercial 5G networks provide coverage. In the following sections, different trials that were carried out in accordance with the three use cases are described. The evaluations with the MAF have been conducted for some of the trials so that each use case has been evaluated properly.

4.2 5G RedCap for wireless sensor systems

The trial evaluated the 5G Reduced Capability (RedCap) feature. To investigate the advantages for battery-powered industrial wireless sensor platforms, during the trial a comparison of energy, latency and throughput against a standard eMBB 5G module was conducted. Test hardware comprised a Quectel RM255C (RedCap) and Quectel RM520N (eMBB) mounted on a Quectel 5G-M2-EVB (via USB-to-M.2), with power measured by a RUIDENG UM34 USB multimeter and performance measured with iperf (client/server) as shown in Figure 4.1.

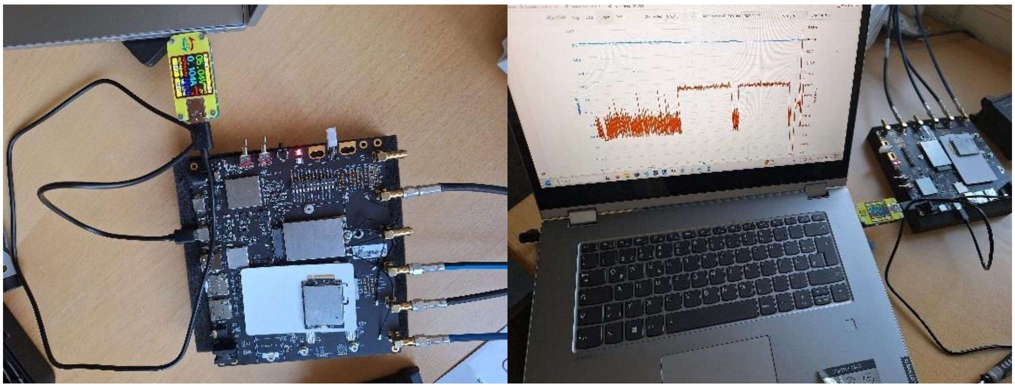

Figure 4.1 Indicate which components are RedCap vs eMBB.

Key results

The trial focussed on the energy consumption of the M.2 module. To validate the impact of RedCap not only on the energy consumption, the tests also covered multiple cycle times (5000 ms, 1000 ms, 10 ms, 1 ms) and antenna configurations (2 vs 4 antennas for eMBB) with parallel measurement of latency and bandwidth.

The key results of the Trial are:

- **Energy:** RedCap showed substantially lower power use — roughly 28–30% lower mean energy consumption than the eMBB module in throughput tests (and similar reductions in other configurations), extending battery life for IIoT sensors.
- **Latency:** Round-trip mean latencies were similar across devices and cycle times — around 12–20 ms depending on cycle.
- **Throughput:** RedCap's maximum throughput was ~18% lower than the best eMBB peak.

4.3 5G Energy Meter

This trial validated a wireless sensor platform for high-resolution machine energy monitoring by comparing it to a wired, state-of-the-art monitoring system. Test hardware included the ADE9000-based meter and a Shelly module on the WSP, plus GEMTP/GEMCPU as the wired reference; all devices measured spindle and machine power during milling/tapping tests at MMS (Chiron FZ08) and IPT (Mikron). The wireless meters transmitted measurements over 5G (MQTT) to the cloud, while the Genior Modular (GEM) reference logged over Ethernet; sampling behavior and timestamped logs were compared to assess data quality, latency and temporal resolution.

Figure 4.2 Testsite in MMS Egestorf.

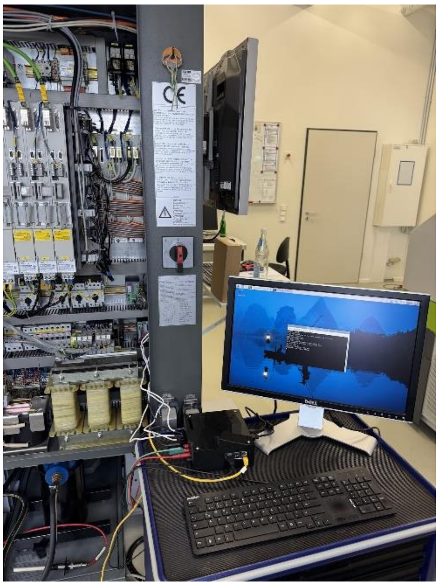

Figure 4.3 ADE9000 Testdevice.

KPI/ KVI evaluation

While the core parameter was the energy consumption of the machine, the trial evaluated also the usability of 5G and the wireless intelligent sensor platform. For that, the measurement accuracy, the temporal resolution, the latency and the throughput have been evaluated.

The selected User-KPI for the evaluation have first been described in D1.2, Sections 3.1.2.3 and 3.1.2.4 [TAR24-D12]:

User-KPI:

- Completeness of process and product data
- Timeliness of process and product data

An exemplary measurement campaign showed the capabilities of the employed hardware. Over the course of 18 minutes, 4439 measurements of electrical power were conducted with an average of 4.02 measurements per second. The measurement data was subsequently sent to an edge cloud for analysis purposes. This indicates a very high completeness and timeliness of the data, as a comprehensive dataset on the energy measurement could be created based on the employed hardware.

User-KVI:

- Global Warming Potential, GWP
- Water consumption, WCon
- Ozone depletion, ODep.
- Photochemical ozone formation, PhOz.

Based on the measurements of the electrical power consumption, the environmental User-KVI were calculated following the LCA-method and the environmental footprint of the German energy mix. With this approach, the following results listed in **Fehler! Verweisquelle konnte nicht gefunden werden.** were calculated, based on the total consumption of 0.16 kWh of electrical energy.

Table 3 Environmental Footprint of a Milling Operation

User-KVI	Calculated value
Global Warming potential, GWP	0.079 kg CO_2-eq.
Water consumption, WCon	0.01655 m^3
Ozone depletion, ODep	8.16×10^{-10} kg CFC 11-eq.
Photochemical ozone formation, PhOz	1.27×10^{-4} kg NMVOC-eq.

The successful calculation of these exemplary User-KVI shows that the developed solution enables the acquisition and utilization of high-quality electrical energy consumption data to precisely calculate the environmental footprint of manufacturing operations which provides valuable and valid sustainability-related insights into manufacturing processes. The use of 5G allows for the transmission of high-quality data with high granularity to enable precise and reliable calculations.

Key results

The key results of the trial are:

- The ADE9000-based wireless meter on the WSP delivered substantially better temporal resolution (≈200 ms updates) than the Shelly device (~800 ms), enabling capture of transient current peaks relevant for machining events.
- 5G (MQTT) enables on-demand, higher sampling rates and low-latency transport so the wireless platform can dynamically increase temporal resolution to observe short transients that would be missed at low sample rates.
- Wireless (WSP+ADE9000) is a viable, more flexible alternative to wired metering for many monitoring and energy-management tasks, trading some absolute fidelity for installation flexibility and dynamic sampling.
- Key integration points: accurate timestamps, synchronized logging across meter types, and consistent sampling strategy are essential to make meaningful comparisons and to analyse transient events.

4.4 5G monitoring of chatter vibrations

During the trials, the developed wireless sensor platform has been validated within a milling machine. The goal was the monitoring of a milling process, and the detection of anomalies such as chatter vibrations. Milling trials on a Chiron FZ08S used a 6 mm ball cutter with two experiment series (varying spindle speed at fixed feed, and varying feed at fixed spindle) covering typical chatter-prone conditions (spindle 5,100–10,100 rpm, feed 200–450 mm/min). The resulting spectrograms clearly differentiate good (few harmonics, limited peaks) and bad (many broadband peaks) processes.

Figure 4.4 Surface of the workpiece with chatter marks.

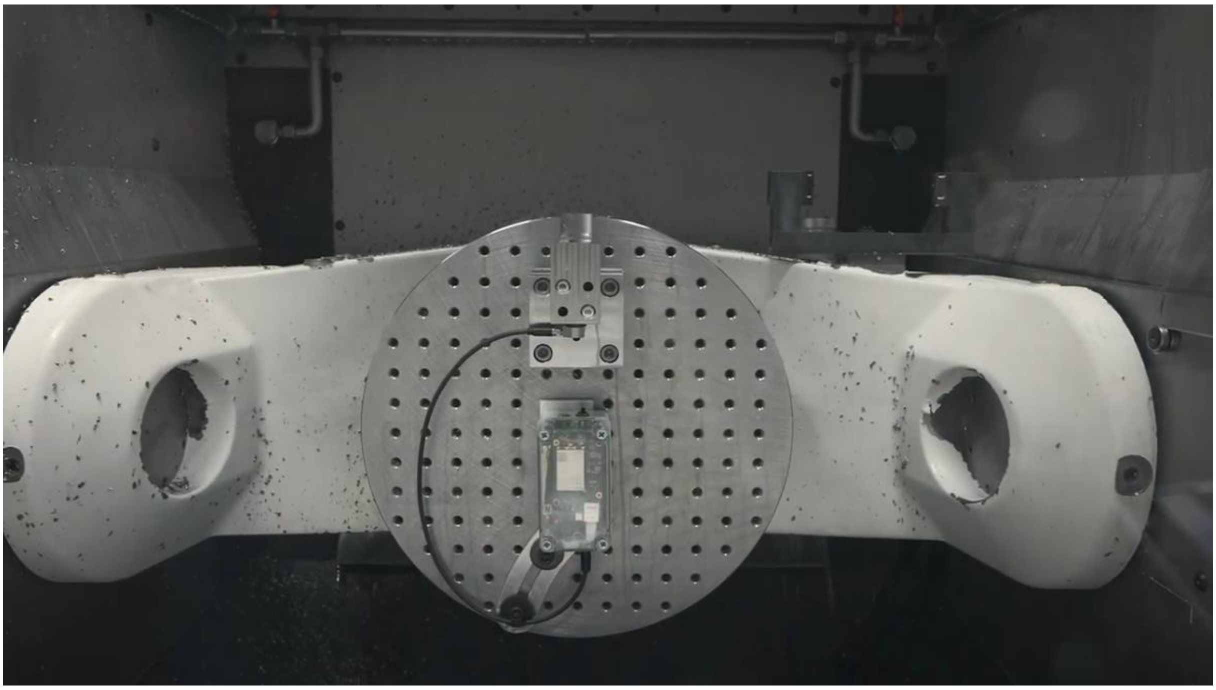

Figure 4.5 Wireless sensor platform integrated into a milling process.

KPI/ KVI evaluation

The wireless sensor platform can use the sensor data to evaluate and optimize machining processes. To evaluate this capability, the connectivity within a metal housing, the latency, the reliability and the usability have been evaluated. Further the usability of the data provided for chatter detection has been evaluated in two experiments.

Key results

The key results of the Trial are:

- Detection outcome: Spectrogram analysis clearly separated stable (harmonic-dominated) versus unstable (broadband, non-harmonic peaks) cutting; chatter produced distinct non-harmonic peaks across the spectrum.
- Prototype limitations: The prototype suffered from mains-frequency interference (50 Hz and 150 Hz) due to insufficient EMC/shielding.
- Practical viability: With improved shielding and calibration, the WSP approach reliably supports real-time chatter monitoring and process control.
- Usability: Using 5G for wireless communication enabled easy and fast integration into the machine. New process insights can be gathered due to the compact form factor.

4.5 Bluetooth and 5G based Localization

The localization validation tested a BLE-based positioning system with 5G as connectivity solution for workpiece/asset tracking across a 60 m × 30 m shop-floor. While Bluetooth offers a low-cost localization solution, the connectivity is very limited. By combining 5G and Bluetooth, the strengths of both solutions could be evaluated. The trial used eight ESP32 beacons and a Wireless Sensor Platform (tracker). The solution used a weighted-average centroid algorithm plus a Kalman filter to smooth estimates; trilateration was rejected due to poor robustness in noisy RF conditions. The study concludes BLE centroids are a low-cost, robust option for zone-level tracking in industrial environments but are unsuitable for sub-meter precision without denser infrastructure, better antenna orientation control, and further calibration.

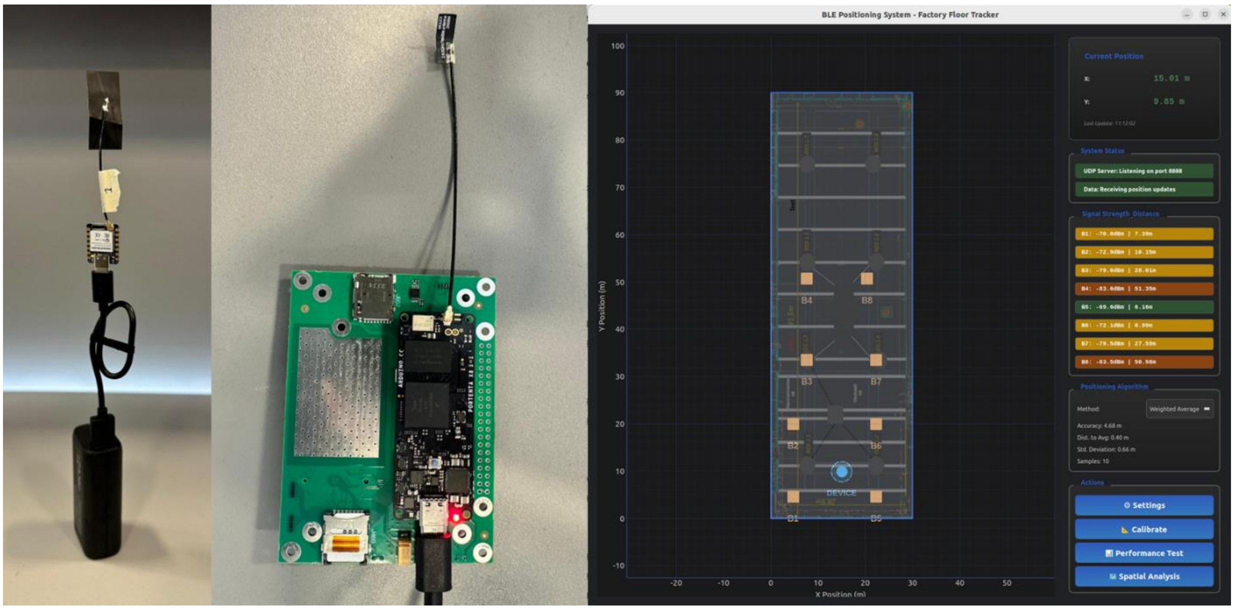

Figure 4.6 On the left side one of the Bluetooth beacons with the battery, in the middle the wireless sensor system as tracker and on the right the positioning of the dots in the implemented user interface.

KPI/ KVI evaluation

The trial focused on the positioning accuracy, the RSSI stability and the availability of the signal.

The selected User-KPI for the evaluation have first been described in D1.2, Section 3.1.3.3 [TAR24-D12]:

User-KPI:

- Completeness of process and product data
- Cycle time
- Throughput

Regarding completeness of process and product data, localization offers the potential to combine positioning with process data (vibration measurements acquired through the wireless sensor platform as well as electrical power consumption data). In this way, a comprehensive data set could be created that enables the determination where a specific workpiece was machined and how. The positioning had an accuracy of 4 m, which, in a shop floor setting, enables the assignment of measurement data (in this case vibration measurements) to individual processing steps. Therefore, it can be concluded that the completeness of process and product data can be increased significantly through the combination of the wireless sensor platform with localization.

Figure 4.7 shows a combined illustration of consumed electrical power and the vibration spectrogram, both measured for the same process (pre-milling). The figure shows five subsequent cycles with an average cycle time of 5 minutes. In this way, the cycle time and the throughput of milling operations can be calculated, matched with localization data and improved e.g. through the reduction of idle times between processing steps.

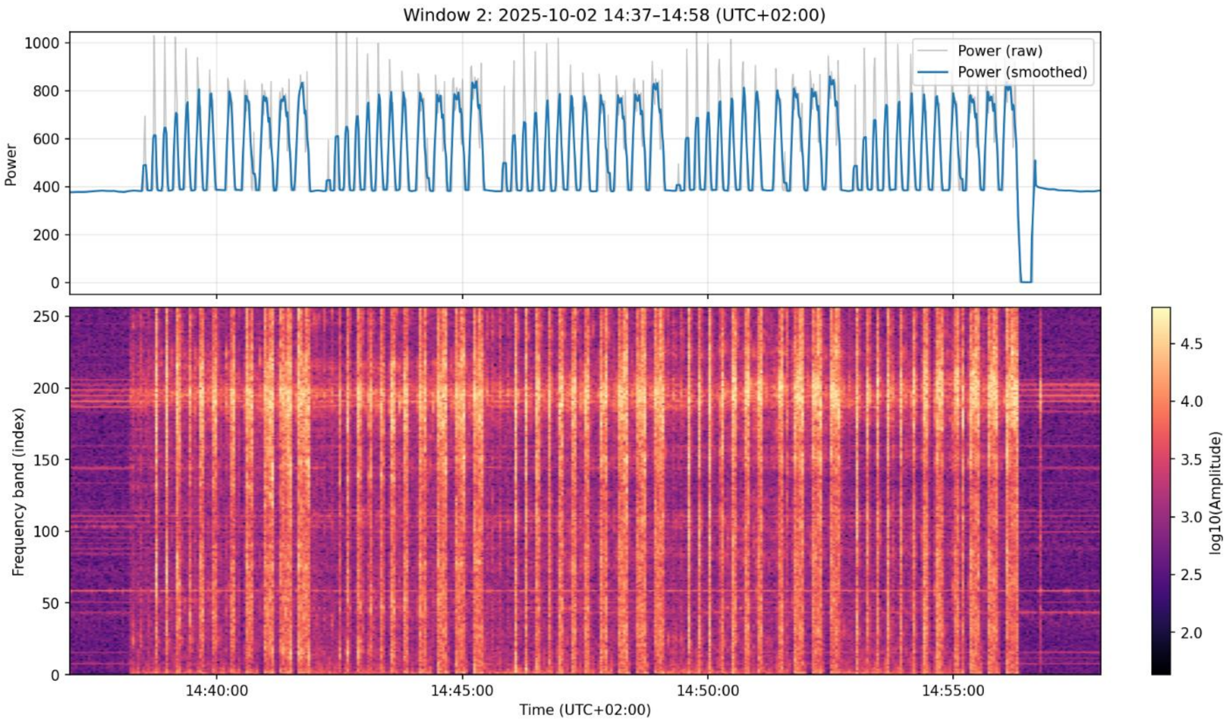

Figure 4.7 Electrical Power Consumption and Vibration Data Visualisation of a Pre-Milling Operation

Key results

The key results of the trial are:

- BLE RSSI variability (σ ≈ 6.6 dB) limits distance estimation accuracy and makes geometric methods (trilateration) unstable in industrial RF conditions.
- Errors increase near the beacon perimeter and in heavily obstructed areas (metal, machines), producing systematic centroid bias.
- Bluetooth offers a low-cost localisation solution which high RSSI fluctuations lead to imprecise and inconsistent localisation results. With an accuracy above 4 meters, the solution has a limited use. However, the functionality was successfully exploited in the trial to assign process measurements with localization.

4.6 Time-sensitive communication

Time-sensitive networking (TSN) is an established way to communicate deterministic, time-critical data, therefore has similar requirements like conventional fieldbus communication protocols used in industrial communication, while TSN is more generic. Therefore, TSN over 5G has the potential to replace wired fieldbus with wireless solutions.

The objective of this validation was to test and quantify a 5G-TSN pipeline carrying CC-Link IE TSN Class A/B traffic across a 5G radio link, verifying whether end-to-end deterministic, time-sensitive communication (latency, jitter, availability) required by industrial fieldbus control can be sustained in realistic shop-floor deployments. The validation therefore compared different TSN standards to evaluate the real-time capability.

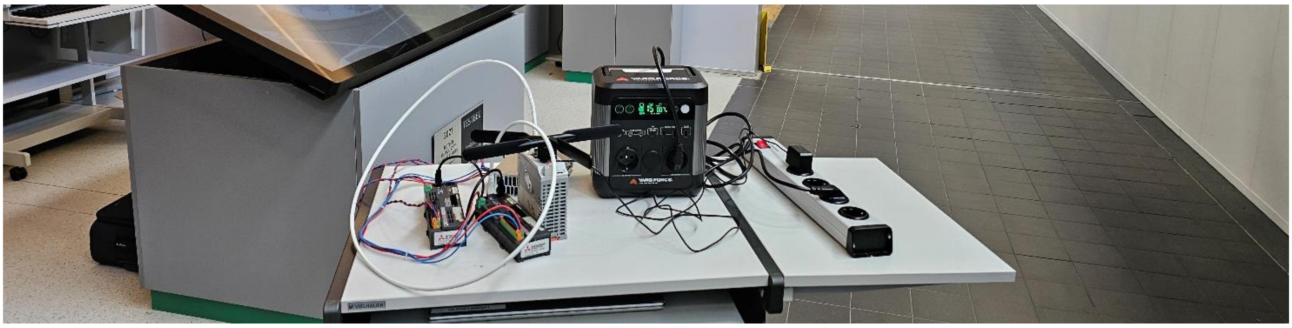

Figure 4.8 CC-Link IE TSN remote station connected via 5G to the PLC.

Key results

The key results of the trial are:

- First real-time communication of fieldbus protocols such as CC-Link IE TSN via 5G using commercially available OT-devices.
- Demonstrated suitability of 5G, TSN and industrial communication.
- Missing features that needed to be implemented manually for the trials, such as Layer 2 support and time synchronization over the air.

4.7 High reliability communication

The objective of this validation was to demonstrate and quantify whether redundancy mechanisms (IEEE 802.1CB FRER) combined with multi-path 5G deployments can provide a reliable, bounded-latency communication. The goal for the trial was to achieve ≤10 ms latency for 99.99% of packets. While 5G introduces variable delays, retransmissions and path outages that can break deterministic fieldbus sessions, the trial aimed to use Frame Replication and Elimination (FRER) to overcome single-path failures by duplicating frames over independent paths. The trials therefore aimed to validate FRER's real-world benefit and limits to quantify trade-offs and to derive deployment guidance for achieving production-grade high reliability over 5G in industrial environments. During the trials different 5G networks, using different frequency spectrums have been used.

Figure 4.9 Setup of the FRER measurements at IPT.

KPI/ KVI evaluation

The selected User-KPI and User-KVI for the evaluation have first been described in D1.2, Section 3.1.1.3 and Section 3.1.1.4 [TAR24-D12]:

User-KPI:

- Completeness of process and product data
- Timeliness of process and product data
- Process capability (c_p & c_{pk})
- Flexibility

To evaluate the completeness and timeliness of the data as well as the process capability, FRER measurements were conducted to evaluate latency, jitter and packet loss. These measurements showed that the setup can significantly increase the completeness and timeliness of the acquired data. For approximately 350,000 packets sent, the FRER setup was able to achieve a mean latency of 6.51 ms, with the 99.9 percentile at 8.54 ms and the 99.99 percentile at 8.78 ms. This indicates the ability to significantly increase the completeness and timeliness of the data as 99.99 % of packets arrive on time. For the same measurement, the capability was calculated to be c_{pk} = 1.34 demonstrating that the packet-transmission process is stable when using FRER. Regarding flexibility, the plug-and-play solution showed that set up times can be reduced significantly. The wireless solution can be installed within a 10-minute time window, while traditional setups are estimated to require approx. half a workday to integrate measurements with cabling, integration, and calibration.

User-KVI:

- Work accident rate manufacturing

The developed solution has a positive impact on shopfloor safety. The verified process capability lays the foundation for the implementation of wireless emergency stops. In addition, the reduced amount of cabling will also increase accessibility while reducing tripping hazards at the same time.

Key results

The key results of the trial are:

- 5G using FRER reduces tail latency and eliminates large outliers—enabling meeting the 10 ms for 99.99% of the packages in all tested multi-path setups.
- FRER is most beneficial when individual paths show similar performance behaviours.
- Practical trade-offs: FRER increases hardware, spectrum and configuration complexity (tunnels/Layer-2 support) but significantly improves robustness in realistic industrial environments (blockage, multipath).

4.8 Overview of the FSTP projects from both open calls

Name	OC 1	OC 2	Description	Partner 1	Partner 2
5G4ProMain	X		AAS-based and 5G enabled Proactive Maintenance: New generation of proactive maintenance systems which can resolve previously unknown anomalous situations, based on AAS and 5G infrastructure: paving the way for a new generation of cloud-based services for proactive maintenance of plasma-metal-cutting machines which can support dynamic anomaly detection scenarios in various types of these machines	Nissatech	DRUŠTVO ZA PROIZVODNJU I INŽENJERING EM DIP DOO NIŠ
BILEN-5G	X		BILEN-5G Smart Maintenance Platform for Factories using the Asset Administration Shell (AAS) framework and AI models to analyze production cycles, predict equipment failures, and detect raw material variations.	The Data Cooks	SKATechnologie GmbH
astreo	X		Energy monitoring of industrial machinery using 5G: Innovating Energy monitoring of industrial machines by using 5G and AI analysis: Innovating energy monitoring with a non-invasive 5G-enabled sensor. Real-time data collection and automated intelligent insights for industrial machines.	Astreo srl	
RadioCAT	X				

METALINK	X	Metal AM: 5G Monitoring and Control: METALINK enhances Metal Additive Manufacturing (MAM) via a 5G-enabled monitoring and control system. The project will be conducted at the University of Luxembourg (UL) and with the support of Fraunhofer IPT (F-IPT).	University of Luxembourg	
5G-EQCT	X	5G - Enhanced Quality Control Tool for Composites: Transforming the Quality Control process in manufacturing, utilising AI & 5G. The proposed solution automates quality control, delivering precise surface scanning & air inclusion detection through ultra high-definition visible and thermal cameras.	TRYGONS S.A.	iThermAI B.V.
LPS-5G	X	LPS-5G initiative merges passive and active sensing with 5G to enable precise tracking and analysis of interactions among assets, and personnel.	Univerlab S.r.l	DOMINA SRL

4.9 Lessons learned

The trials demonstrated that wireless 5G-enabled can be an essential asset for industrial manufacturing, meeting the strict requirements for various use cases. Two main use case classes have been analysed, wireless intelligent sensors and wireless real-time communication for control applications.

For sensing, the trials have shown a large variety of benefits for manufacturing when using wireless solutions, key lessons learned included: 5G RedCap is a strong choice for battery-powered IIoT sensors, due to the reduced energy consumption. Design decisions for sensor platforms should prioritise RedCap for long-lifetime devices and eMBB where peak bandwidth is critical. A sustainable production needs transparency of its resource and energy flows to be capable of optimizing the utilization. 5G enables monitoring solutions offering synchronized logging across meter types, and consistent sampling strategies, which are essential to make meaningful comparisons and to analyse transient events. While the overall accuracy of fixed integrated solutions is higher, 5G-enabled sensors offer a scalable, easy to integrate solution with reduced costs compared to state of the art solutions. 5G offers coverage even in milling machines providing high data rates supporting quality critical use cases such as real-time chatter monitoring. The easy and fast integration of 5G enabled sensors, combined with the coverage and bandwidth, creates a strong solution for industrial production, generating new process and product insights. The positive evaluation results based on the defined User-KPI and User-KVI underline these findings.

The trials successfully demonstrated real-time communication with proven viability of Layer 2-based industrial Ethernet over 5G, establishing a stable connection. This key achievement confirms that 5G is fundamentally ready for the first OT applications, marking a significant milestone. While the achieved latency and jitter results indicate the need for further optimization to meet stringent industrial requirements, they provide crucial insights. Our research indicates that when implementing TSN over 5G, parameters for time synchronization and cycle times will likely require more generous configurations. This understanding is a critical step toward successful integration. Further, with the FRER trial, a 5G communication pipeline meeting the latency requirement of 10 ms for 99.99% of the packets in all tested multi-path setups had been implemented. This shows the great benefit of FRER even when using only one network, proven by the evaluation of process stability.

Overall, the trials highlighted the value of testing in real shop-floor conditions with real OT-hardware. Crucial insights for compatibility and coverage can only be gathered during a field trial showcasing the real behaviour of the system and clearly demonstrating the tangible value proposition for end users.

5 Edge Mobile Robotics

5.1 Motivation

The manufacturing industry is undergoing a profound transformation to meet growing demands for shorter production cycles, higher customization, and increased efficiency. Automation and digitalization play a central role in this shift, particularly through flexible assembly systems that rely on mobile manipulators and automated guided vehicles (AGVs). These systems enhance agility by allowing reconfigurable robotic resources to autonomously navigate and execute dynamic tasks. However, the computational demands of AI-based perception, localization, and motion planning often exceed the onboard capabilities of such robots, requiring distributed architectures for real-time decision-making.

Edge computing addresses these limitations by offloading computationally intensive processes, such as Simultaneous Localization and Mapping (SLAM), object detection, and path & motion planning, to nearby edge servers (enabled with higher GPU). Yet, this approach is only viable when supported by a communication infrastructure that combines low latency, high reliability, and scalable data throughput. 5G uniquely provides these characteristics, enabling real-time robotic edge control with dependable uplink capacity and secure, on-premises data handling. Its flexibility and configurability allow fleets of robots to operate simultaneously, each transmitting large volumes of sensor data without compromising performance. This positions 5G as a key enabler of large-scale, safe, and flexible automation, bridging the gap between industrial robotics and next-generation network technologies.

To investigate this potential and as indicated by [TAR25-D22, TAR25-D23, TAR25-D25], the WZL Testbed for Flexible Assembly Automation at RWTH Aachen University was established as part of the 5G-Industry Campus Europe. Operated by the Sensing & Robotics department within the Chair of Intelligence in Quality Sensing, the testbed serves as a large-scale research facility for applying and validating new 5G functionalities in manufacturing, focusing on the edge-controlled robotic assembly use case. The 25×5 m^2 facility hosts a modular fleet of mobile and semi-stationary robots based on a ROS 2 architecture, complemented by high-precision metrology systems (laser trackers, motion capture) for benchmarking localization and motion accuracy.

5.2 Edge-Controlled Automation with Mobile Manipulation

The *Edge-Controlled Automation with Mobile Manipulation* use case at RWTH Aachen University's WZL testbed demonstrates how 5G enables flexible robotic (dis)assembly in modern manufacturing. The scenario focuses on disassembly tasks of EV battery modules, where a mobile manipulator (MM) performs Simultaneous Localization and Mapping (SLAM), navigation (dynamic & autonomous path planning), object detection, pose (position & reference) estimation, grasping, and placement, all coordinated by an edge server via a private 5G Non-Standalone (NSA) network. An open-source Robot Operating System (ROS) 2-based state machine manages the workflow, ensuring reliable, low-latency communication between robot and edge server for real-time control. Figure 5.1 illustrates the robotic disassembly process and the sequence of automated operations across multiple workstations.

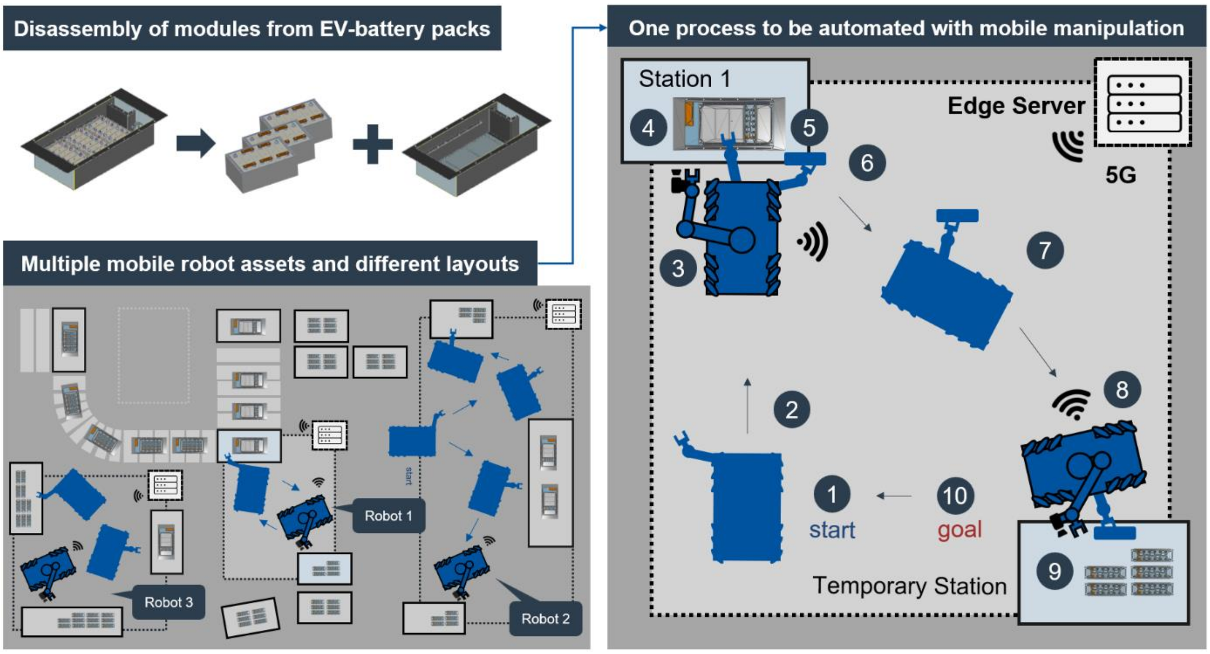

Figure 5.1 Edge-controlled mobile manipulation for disassembly of EV battery modules. The top view shows multiple robotic stations, while the right panel illustrates the automated process steps. Source: adapted from [TAR25-D25].

The use case integrates an RB-Kairos+ mobile platform with a UR10 robotic arm, equipped with 2D/3D LiDAR sensors, a depth camera (RGB-D), and IMU sensors. Computationally intensive tasks such as localization, perception, path & motion planning, and digital twin simulation (Isaac-Sim) are offloaded to the edge server. Software components are containerized using Docker and managed through CI/CD pipelines for modular deployment and rapid updates. Figure 5.2 shows the hardware and software architecture of the edge-controlled system, highlighting onboard and edge-level computation and the integrated monitoring pipeline.

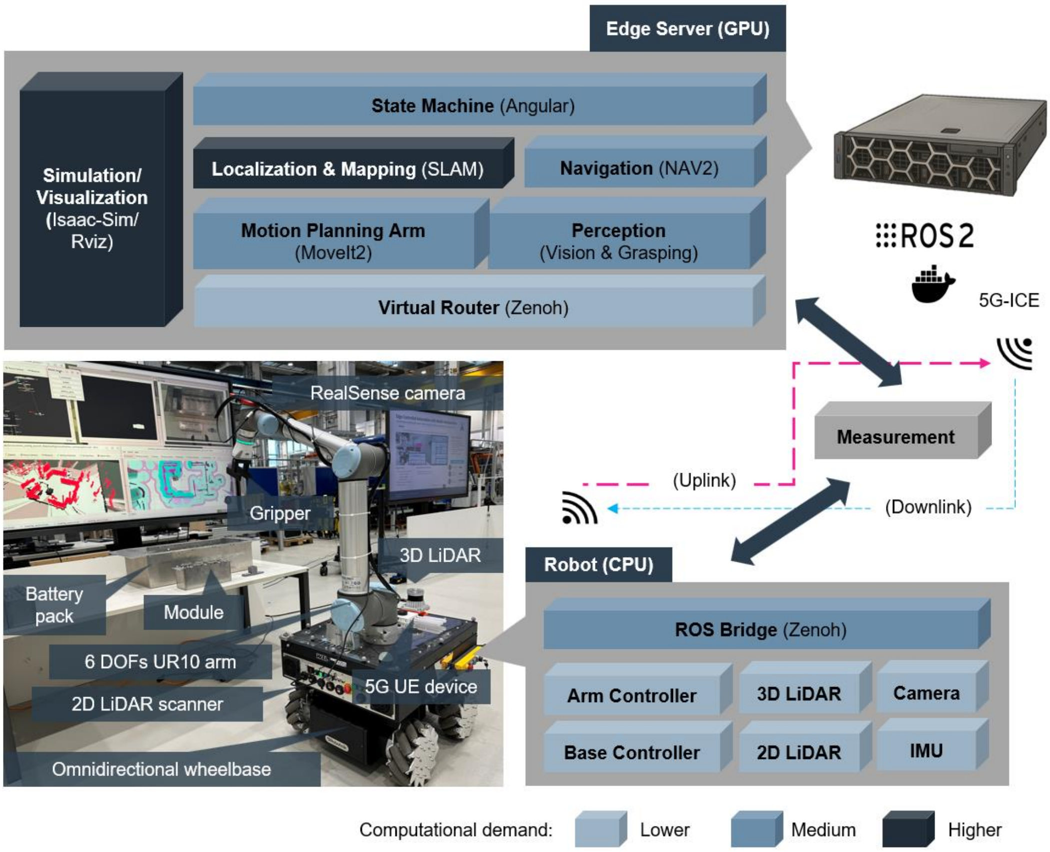

Figure 5.2 Hardware and ROS 2-based software architecture of the edge-controlled robotic system. Onboard and edge components are color-coded by computational demand, including the monitoring and communication layers. Source: adapted from [TAR25-D25].

Trials conducted jointly by RWTH-WZL and Ericsson (as indicated in the **Fehler! Verweisquelle konnte nicht gefunden werden.**) under realistic shop-floor conditions showed uplink demands of approximately 142 Mbit/s at < 20 ms latency, later optimized to 37 Mbit/s through LiDAR data reduction. A non-intrusive monitoring pipeline (ROS 2 diagnostics, iPerf3, Wireshark/tshark) provided full visibility into network performance, demonstrating both the communication demands of edge-controlled robotics and the scalability potential of 5G-enabled automation.

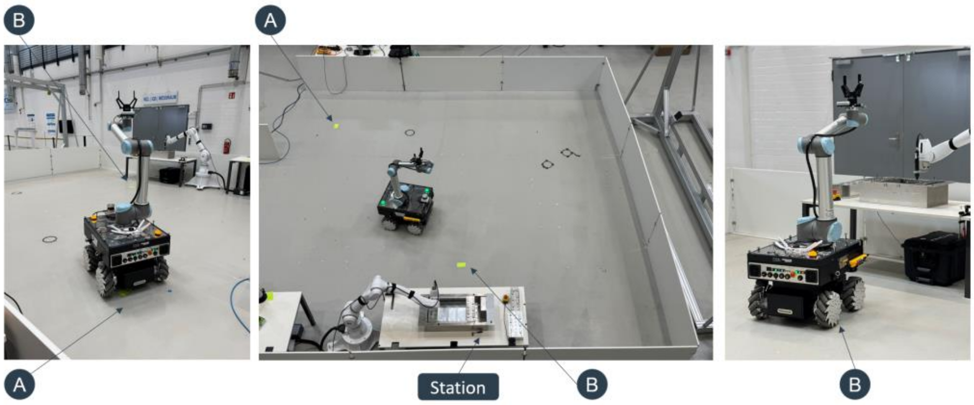

Figure 5.3 Photographs of the trials conducted at the WZL Testbed. The physical locations of Position A (start) and Position B (disassembly station) are indicated for reference. Source: from [TAR25-D25].

KPI/ KVI evaluation

The selected User-KPI and User-KVI for the evaluation of this trial have first been described in D1.2, Sections 3.2.1.3 and 3.2.1.4:

User-KPI:

- Cycle time
- Throughput
- First pass yield
- Overall Equipment Efficiency, OEE

In order to evaluate the developed solution, testing was carried out with both WiFi and 5G as communication technologies. For both network types, 50 cycles were carried out in which the mobile robot executed a transition between poses which are characterized by a fixed position and a reference. For the successful completion of a cycle, the robot had to go from Pose 1 to Pose 2 and back to Pose 1 again autonomously. For each cycle, the execution was measured. In addition, the number of failed operations were recorded for both network types. Based on these measurements, the following analysis results could be achieved:

On average, the execution time of the implementation with 5G is 2.41 seconds lower than with WiFi. The failure rate of operations with 5G was 3 % and 6 % with WiFi. Therefore, users can conduct 518 cycles per day (8-hr shift) with WiFi and 560 cycles per day with 5G. Theoretically, 577 cycles would be possible, if no failures occurred. Therefore, the implementation with 5G enables an improvement of the cycle time (2.41 s) and the potential to increase the throughput by 42 more successful cycles (approx. 8% more) per day with 5G. The means that a positive impact of 5G on the User-KPI cycle time and throughput could be demonstrated.

Based on the measurements of the failure rates, the first pass yield is 94 % for WiFi and 97% for 5G. The failure rates were also used to make an estimation of the impact on OEE. With WiFi, 518 cycles can be executed successfully within 8 hrs. With 577 cycles being possible in total, WiFi achieves a performance rating of 90% for successfully executed operations (577 cycles would be possible with 5G and zero failures, so this was taken as the benchmark wireless communication). With 5G, 560 cycles can be executed successfully within 8 hrs. With 577 cycles being possible in total, 5G achieves a performance rating of 97% for successfully executed operations. Therefore, the OEE of the realization with 5G is calculated to be 97% while it is 90% with WiFi.

User-KVI:

- Work accident rate manufacturing

A positive impact in work accident rate is expected due to less failures. With 5G, the robot will have less breakdowns decreasing the probability of harmful breakdowns during operations. However, a data-based quantification of the positive impact on the work accident rate was not carried out.

Key results

The key results of the Trial 1 are:

- KR 1: **The use case demonstrator validated a multi-step, edge-controlled robotic workflow (based on open-source ROS 2 middleware) for EV-battery module disassembly**, showing that 5G-enabled edge computing reliably supported real-time SLAM, path and motion planning, and AI-based perception offloaded to a GPU-equipped edge server. This resulted in reduced application latency, improved multi-sensor perception, and an enhanced Digital Twin environment (developed in NVIDIA Omniverse Isaac-Sim) for testing and monitoring.

- KR2: **Network validation confirmed that the private 5G network at the WZL Testbed met control requirements under realistic manufacturing conditions**, achieving stable uplink (~105 Mbit/s) and downlink (~920 Mbit/s) throughput with sub-millisecond jitter and negligible packet loss. These results indicate the potential to operate up to 2–3 edge-controlled robotic cells (~ 37 Mbit/s) within the same network, highlighting clear gains in reliability and scalability over conventional wireless setups.
- KR3: **The project achieved a 74 % reduction in uplink data rate, from 143 Mbit/s at project start to 37 Mbit/s at completion, through adaptive data-rate optimization**, including LiDAR resolution reduction, point-cloud filtering, throttling, and compression. This decreased the UL/DL ratio from 14 300 to 21.8 while maintaining perception and path-planning accuracy, demonstrating efficient bandwidth management under 5G constraints and defining quantitative benchmarks for future 6G-ready, multi-robot manufacturing systems.
- KR4: The evaluation with User-KPI and User-KVI indicates the value proposition of the developed use case. With 5G, lower cycle times and overall higher throughput (number of successful operations) can be achieved in addition to a more reliable and scalable overall executability of the use case. This clearly underlines 5G's potential to provide real value for end users in industrial application scenarios

5.3 5G Positioning for Mobile Robotics

The 5G positioning use case investigates the integration of *5G Beyond* capabilities into mobile robotics to enable scalable and infrastructure-based localization for flexible manufacturing. In conventional setups, localization relies on LiDAR- or vision-based SLAM, which, while precise, becomes difficult to maintain in large or dynamic environments due to map drift, memory requirements, and manual calibration efforts. 5G-based positioning offers a global alternative by utilizing radio infrastructure to estimate a robot's position independently of onboard sensors, enabling seamless startup localization, multi-robot coordination, and asset tracking across extended production areas. This scenario, implemented at RWTH Aachen University's WZL Testbed and reported in [TAR25-D25, TAR25-D65], complements the broader manufacturing use case by exploring how 5G positioning can reduce reliance on manual mapping and support global reference alignment for edge-controlled mobile manipulators.

The experimental evaluation assessed the accuracy and stability of a 5G-based positioning pipeline against ground-truth data provided by the OptiTrack™ motion capture system installed at the WZL Testbed and in a second set of experiments by LiDAR-SLAM. A 5G-enabled smartphone mounted on the RB-Kairos+ robot's end effector was tracked simultaneously via OptiTrack™ and the 5G system, as shown in the Figure 5.4 below.

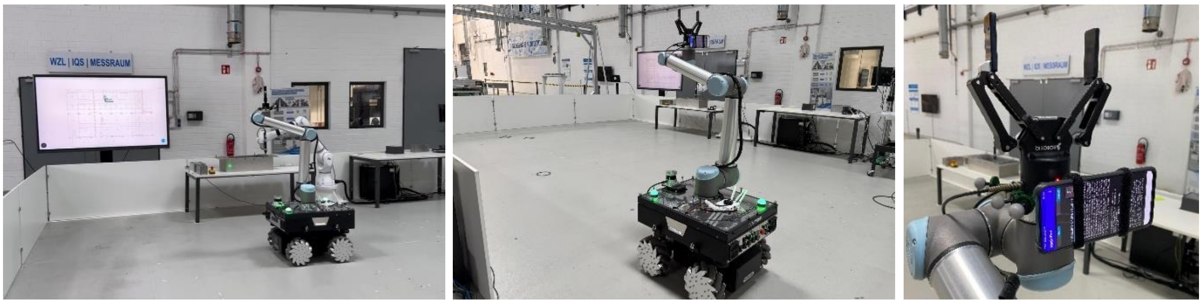

Figure 5.4 Mobile manipulator with attached markers on the end effector and the 5G smartphone device for the validation. Source: adapted from [TAR25-D2.5].

As illustrated in Figure 5.5 and Figure 5.6, the real-time visualization compared 5G-based position estimates with LiDAR-SLAM trajectories, highlighting their deviations and spatial alignment within the testbed. The results demonstrated that while LiDAR-based SLAM achieved higher precision in localized areas, 5G positioning maintained consistent estimates even beyond mapped regions, confirming its potential as a complementary solution for scalable and reliable localization in large-scale industrial environments. Detailed benchmarking and performance metrics are presented in [TAR25-D65] (WP6).

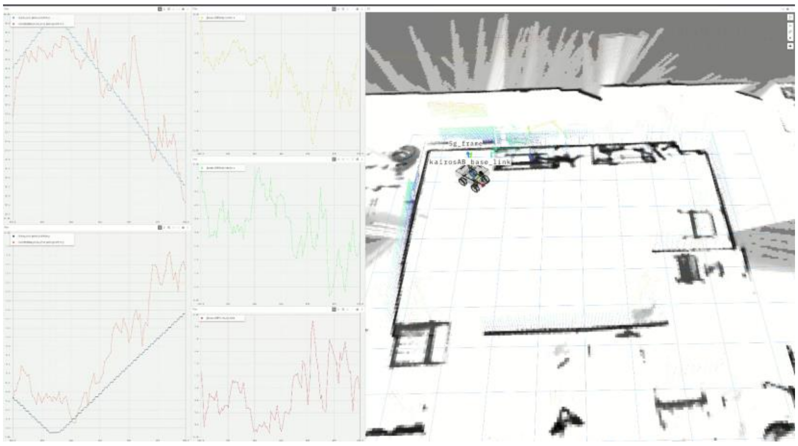

Figure 5.5 Real-time comparison between 5G-based positioning and LiDAR-SLAM at the WZL Testbed. Left: positional deviations (Δx, Δy, distance). Right: SLAM-generated map with overlaid 5G position estimates. Source: adapted from [TAR25-D25].

Figure 5.6 Photographs of the 5G-Based Positioning and LiDAR-SLAM trials conducted at the WZL Testbed. Source: from [TAR25-D2.5].

5.4 Overview of the FSTP projects from both open calls

Name	OC 1	OC 2	Description	Partner 1	Partner 2
CoRoCa	X		**Collaborative Robotics in Carbon Manufacturing (CoRoCa)** aimed to enable safe human–robot collaboration in carbon fiber prefabrication through 5G-enabled real-time communication. By combining body-worn sensors, robotic systems, and edge-based control, the project demonstrated how ultra-reliable low-latency connectivity supports safe, efficient, and flexible manufacturing in small-batch carbon production.	Pumacy GmbH (Germany)	Consider Carbon GmbH (Germany)
Li-Disarm:AI	X		**Lithium-Ion Battery Disassembly AI Solution (Li-Disarm:AI)** aimed to automate the safe disassembly of used lithium-ion batteries using a robotic arm guided by machine vision and AI. Leveraging 5G-enabled edge communication, the project demonstrated how low-latency connectivity enhances precision, safety, and efficiency in robotic recycling processes.	EN-CO Software Zrt. (Hungary)	
SBPath-5G	X		**AR WeldPath: 5G-Enhanced Robotic Welding Guidance (SBPath-5G)** aimed to transform robotic welding by integrating augmented reality, point cloud data, and 5G connectivity. Leveraging ultra-low-latency communication, the project enabled real-time visualization and adaptive path correction through AR interfaces, enhancing precision, efficiency, and safety in automated welding operations.	Metrology LAB ltd. (Bulgaria)	
MARS		X	**Mobile Autonomous Robotic Scanning (MARS)** aimed to develop a scalable 3D scanning system using quadruped robots equipped with	Caboto Srl (Italy)	Exwayz Sas (France)

		LiDAR sensors and 5G-enabled edge-cloud communication. By leveraging ultra-low-latency data exchange for real-time SLAM, navigation, and 3D reconstruction, the project demonstrated how 5G connectivity enhances precision, scalability, and efficiency in large-scale scanning applications.		
ROS2-BANDIT	X	**ROS2 Bandwidth-Aware Networking Toolkit (ROS2-BANDIT)** aimed to enhance communication efficiency for mobile robots operating over 5G networks. The project introduced a state-based policy engine that dynamically manages ROS 2 topics based on task context, robot location, and operational state. By enabling intelligent bandwidth allocation and seamless middleware integration, ROS2-BANDIT demonstrated how low-latency 5G connectivity can ensure safe, efficient, and scalable communication for edge-controlled robotic systems.	Budapest University of Technology and Economics (Hungary),	
MM-IA	X	**Mobile Manipulators for Industrial Assembly (MM-IA)** aimed to enable intelligent, adaptive assembly operations using AI-driven mobile manipulators connected through 5G and edge computing. The project developed a distributed control architecture for dynamic trajectory planning and obstacle avoidance, allowing mobile robots to assemble flexible components, such as EV battery cables, without interrupting production. By leveraging low-latency 5G communication between onboard and edge controllers, MM-IA demonstrated how connected robotics can enhance flexibility, safety, and efficiency in smart manufacturing environments.	Aldakin Automation, S.L (Spain)	Ikerlan S.Coop. (Spain)

Ros6GBUSBridge	X	**Universal ROS BUS Bridge with 5G/6G Connectivity (Ros6GBUSBridge)** aimed to enable seamless integration between industrial Ethernet bus protocols and the ROS 2 framework over 5G networks. By providing a unified communication bridge with low-latency and high reliability, the project demonstrated how standardized connectivity can enhance interoperability and scalability in next-generation robotic systems.	Logiicdeve.U (Austria)	Commissariat a l'Energie Atomique et aux Energies (France)
GRiSP.io ROS2 Topic Sniffer	X	**GRiSP.io ROS2 Topic Sniffer** aimed to enable intelligent bandwidth management for ROS 2 networks over 5G. By monitoring and prioritizing data streams in real time through edge computing, the project demonstrated how low-latency connectivity can enhance reliability, responsiveness, and efficiency in connected robotic systems.	Dipl. Phys. Peer Stritzinger GmbH (Germany)	
ROS2 on 5G Embedded Systems	X	**Integration of EtherCAT with ROS2 on 5G-Enabled Embedded Systems (ROS2 on 5G Embedded Systems)** aimed to enable seamless communication between industrial Ethernet protocols and ROS 2 through 5G connectivity. By developing a protocol translation layer and a hardware abstraction stack, the project demonstrated how low-latency 5G networks can unify real-time industrial control and robotic systems, enhancing interoperability and scalability in manufacturing environments.	SIA "ITsolutions & programming" (Latvia)	

5.5 Lessons learned

The *Edge-Controlled Automation with Mobile Manipulation* use case demonstrated how 5G-enabled edge computing can effectively support complex robotic operations, such as SLAM, perception, and motion planning, while maintaining reliable real-time communication between the robot and the edge server. The lessons learned build directly on these achievements, emphasizing methodological refinement, scalability potential, and strengthened interdisciplinary collaboration.

Early development stages focused on ensuring robust communication and stable operation under real-world conditions. This approach successfully reduced uplink data consumption per robotic cell from 143 Mbit/s to 37 Mbit/s, confirming the effectiveness of adaptive data-rate optimization techniques (as demonstrated in KR3). These optimizations established the technical foundation for exploring scalability, QoS configurations, and multi-robot coordination, topics that will guide future extensions of the testbed toward larger-scale 5G and forthcoming 6G deployments.

The *5G Positioning* experiments further confirmed the feasibility of radio-based localization as a complementary method to LiDAR- and vision-based SLAM, validating its ability to maintain spatial consistency beyond pre-mapped environments. While additional large-scale and multi-device trials are planned, these findings highlight 5G's potential for enabling infrastructure-based, scalable localization, which is a key step toward fully flexible and autonomous production environments.

Within WP1 and the *Methodological Assessment Framework (MAF)*, the evaluation process evolved dynamically as the trials progressed. Initially, cycle time was selected as the main KPI; however, continued experimentation revealed that indicators such as reliability, handover performance, and interference tolerance more accurately capture network effects on edge-controlled robotics. This iterative learning process reflects the project's adaptive and evidence-driven approach, resulting in a more representative KPI framework for future benchmarking of industrial 5G and 6G applications.

Finally, one of the most valuable outcomes of the project was the convergence of expertise between the telecommunications and robotics domains. As illustrated by KR1–KR4, this collaboration not only enabled the validation of a full edge-controlled robotic workflow but also fostered a shared understanding of industrial needs and network capabilities. The establishment of this common language represents an essential milestone for future interdisciplinary research, paving the way for scalable, safe, and data-driven manufacturing systems powered by next-generation communication technologies.

6 Automotive

6.1 Motivation

In the automotive testbed, the primary focus is on deploying tools and mechanisms that support cooperative perception, enable the development of automotive digital twins, and enhance tele-operated driving safety through Quality of Service (QoS) prediction. In addition, a dynamic service orchestrator was integrated in three other use cases to feature the concept of cloud continuum. The main objective is to evaluate the performance of these automotive use cases over 5G networks within the IDIADA Connected Vehicle Hub (CVH) or IDIADA testbed (Figure 6.1). The testbed comprises a 5G NSA network complemented by legacy 2G–4G connectivity, an edge computing infrastructure, hyperscaler public cloud integration, and a fleet of connected vehicles.

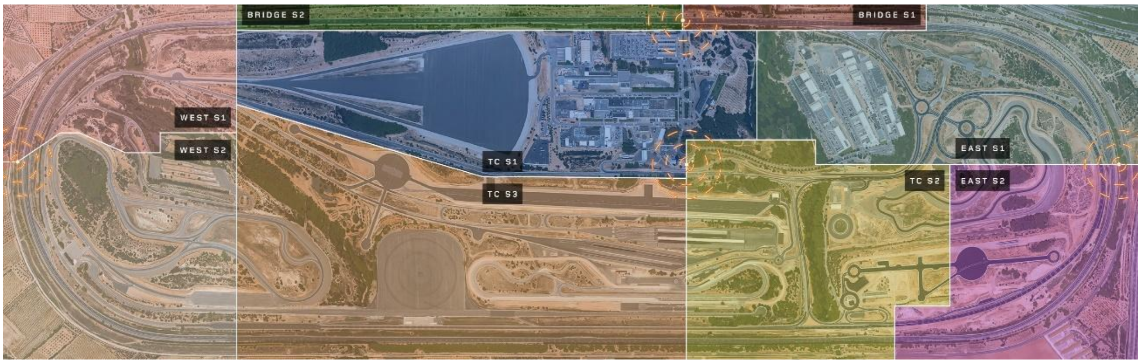

Figure 6.1 IDIADA Connected Vehicle Hub and coverage map.

6.2 Cooperative perception

In the cooperative perception use case, vehicles enhance their environmental awareness and perception by exchanging sensor data both with the infrastructure and with other vehicles. To evaluate the developed cooperative perception framework, two representative test scenarios were defined for this use case: the zero-visibility intersection (Figure 6.2 a) and the road-damaged vehicle (Figure 6.2 b), as described in Deliverable D4.1 [TAR23-D41].

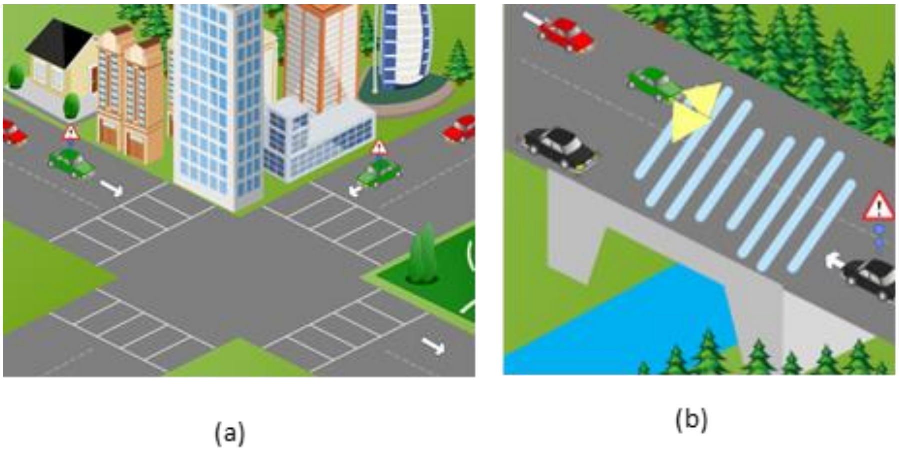

Figure 6.2 Cooperative perception scenarios (a) zero visibility intersection and (b) road damaged vehicle [TAR23-D41].

In both scenarios, when a Connected Vehicle (CV) enters a new area, it communicates with the Cooperative Intelligent Transport System (C-ITS) to exchange information about the road layout, static infrastructure, and nearby connected vehicles, thereby constructing a comprehensive understanding of its surroundings. The information exchange is carried out using Cooperative Awareness Messages (CAM), Decentralized Environmental Notification Messages (DENM), and Collective Perception Messages (CPM).

KPI/ KVI evaluation

The selected User-KPI and User-KVI for the evaluation of this use case have first been described in D1.2, Sections 3.4.1.3 and 3.4.1.4 [TAR24-D12]:

User-KPI:

- Process capability (c_p & c_{pk})

The performance of this use case was evaluated with latency measurements for three types of messages: CAM, CPM, and DENM. Measurements were conducted with different settings for the two scenarios and the evaluation of process capability was done for Scenario 1 with both cars sending CAM messages. The C-ITS infrastructure was deployed on the edge and the tests were conducted once with a legacy 4G and once with a 5G network. The results for mean end-to-end latency, standard deviation, and cpk (for an upper tolerance limit of 200 ms) are shown in Table 4. To further illustrate reliability, the process capability was converted into parts-per-million (ppm) values.

Table 4 Evaluation Results of Process Capability.

	4G	**5G**
mean End-to-end latency	140.33 ms	110 ms
Standard deviation	27.81 ms	24.82 ms
c_{pk}	0.715	1.209
ppm	16,100	144

The results underline the fact that the realization of the solution with 5G is more stable, reproducible, and reliable than with 4G. Testing of Scenario 2 with different configuration settings (C-ITS deployed either on the edge or cloud, 4G vs. 5G) confirms this finding, so that it can be concluded that the use of 5G makes the Cooperative Perception more capable and improves the reproducibility of its results.

User-KVI:

The evaluation of the use case with the User-KVI “Absolute number of prevented traffic accidents” will be explained together with the explanation of the Digital Twin use case in Section 6.3.

Key results

The key results of the Trial 1 are:

- KR1: The median service one way latency is reduced by a factor between 33% and 56% when using the edge instead of the cloud. It should be noted that this conclusion cannot be generalized as it will depend on the location of the cloud server, which is in this case hosted in Malaga, Spain.
- KR2: The DENM message latency is in general much lower than the one of CAM (A reduction in the average between 15% and 45% depending on the technology and the location of the C-ITS system). This difference is because DENM is transmitted in downlink while CAM is transmitted in uplink.
- KR3: The average latency when using 5G is between 10% and 25% less than when using 4G, depending on the message type.
- KR4: The average reliability of the three messages when using 4G/5G technologies and when the C-ITS is hosted either in the network edge or the cloud is always higher than 99%.
- KR5: The evaluation of process capability shows a significant improvement for 5G usage, enabling safe and reliable wireless communication.

6.3 Digital twin

The automotive digital twin use case aims to develop a digital replica that enables the evaluation of cooperative perception techniques through simulation, reducing evaluation cost and safety risks. In this use case, a virtual representation of the vehicles, road environment, and the messages exchanged between the CVs and the C-ITS was created using data collected from Scenario 1 of the cooperative perception use case.

The developed digital twin also allows the integration of virtual vehicles, for example to simulate stopped vehicles on a highway, thereby supporting the testing of cooperative perception solutions in a simulation environment before performing costly and time-consuming real-world evaluations see Figure 6.3.

Figure 6.3 Snapshot of the digital twin showing vehicle-in-the loop.

KPI/ KVI evaluation

The performance of this use case was evaluated using the replicability, which measures the average deviation in message periodicity between the original and the replayed messages that create the digital twin. The average replay deviation was calculated to be 2.00 ms. Since the average end-to-end latency (see Cooperative Perception use case) was calculated to be 110 ms, the average replay deviation of 2.00 ms is adequately representing the reality.

The User-KVI described in D1.2, Section 3.4.2.4 is the "absolute number of prevented traffic accidents". The Digital Twin use case can, in combination with the Cooperative Perception use case, significantly contribute to the reduction of traffic accidents occurring at road junctions. In the EU, a total of 20,593 fatalities caused by traffic accidents occurred in 2022. 18 % of these fatalities occurred at road junctions which is a total of 3,706 fatalities [EC25]. As shown with the calculation of c_{pk} = 1.209, the developed solution offers a very reliable method to send safety critical messages wirelessly between different vehicles. Therefore, it can be stated, that the developed solution can significantly decrease the 3,706 fatalities per year if deployed at large scale. Based on the ppm value of 144, which means that 144 failures can occur per million cases, it can be said that all but one of the 3,706 fatal cases can be avoided through cooperative perception and the use of the digital twin due to the system's very short and reliable response times.

Key results

The key results of the Trial 2 are:

- KR1: The average replay deviation was calculated to be 2.00 ms.
- KR2: By accurately representing vehicular environment and the V2X messages, the developed digital twin can enable the development of efficient cooperative perception mechanisms with reduced cost while allowing a reduction in vehicle accident.

6.4 Predictive QoS for Tele-operated driving

Without transparency of network conditions, a Tele-Operated Vehicle (ToV) may become stranded if connectivity issues occur in a given area, potentially requiring manual intervention or even towing. To prevent such situations, the ToV utilizes information provided through the TARGET-X network exposure interface. By leveraging the Quality of Service (QoS) prediction function developed in TARGET-X, the remote driver receives early warnings about potential connectivity degradation, enabling timely braking or rerouting decisions. This proactive approach helps avoid abrupt stops, thereby minimizing both operational disruptions and the risk of road obstruction as shown in Figure 6.4.

Figure 6.4 Demonstration snapshot of predictive QoS functionality in tele-operated vehicle scenario.

KPI/ KVI evaluation

The selected User-KPI for the evaluation have first been described in D1.2, Section 3.4.3.3 [TAR24-D-12]:

User-KPI:

- Process capability (c_p & c_{pk})
- Cycle time
- Worker efficiency

For the evaluation of process capability, the following analysis was conducted: Two ToV (ToV A and ToV B) travel on the same route. The route has 5G coverage and tele-operation of the vehicles is carried out through the 5G network. At some point along the route, a degradation of the QoS occurs, so that the tele-operation is potentially disrupted. Utilizing the QoS prediction function, the remote driver can make a rerouting decision to prevent the car from stalling. To evaluate the capability of the QoS prediction function, a comparison between a ToV with the QoS prediction function and another one without the QoS prediction function was carried out for two different routes in a highly dense European city. For the evaluation of the process capability, the following results listed Table 5 were calculated based on the travel times.

Table 5 Calculation of Travel Times and Process Capability.

	With prediction function		**without prediction function**	
	Route One	**Route Two**	**Route One**	**Route Two**
Mean travel time	30.93 minutes	27.45 minutes	71.04 minutes	57.28 minutes

c_{pk}	1.082	2.838	0.228	0.153

The results show a significant improvement when the QoS prediction function is employed, proving that the QoS prediction function can guarantee a stable and reproducible process while also significantly reducing the travel times which in this case is synonymous with the cycle times.

Based on the recorded travel times, further calculations of the worker efficiency have been carried out. If a tele-operated vehicle needs on average 30.93 minutes with QoS prediction and 71.04 minutes without QoS prediction for route one, a remote driver can (in theory) conduct 15.52 operations during an 8-hr shift with QoS prediction in comparison to only 6.76 operations during an 8-hr shift without the QoS prediction. This represents an increase in worker efficiency of approximately 230 % for route one. For route two, the remote driver can conduct 17.48 operations during an 8-hr shift with QoS prediction while only 8.38 operations can be conducted without the QoS prediction. This represents an increase of 209 % for the implementation of the solution with the QoS prediction function. These improvements could potentially have a significant impact on the profitability if the solution is implemented on a large scale, as the same number of remote drivers can carry out more than twice the number of operations in comparison to the implementation without the QoS function.

Key results

The key results of the Trial 3 are:

- KR1: Significant decrease in average latency when using 5G compared to when using 4G by 47%.
- KR2: The average values in the two scenarios with exposure APIs (Scenario 1: notification via connected vehicle, and Scenario 3: notification via Ericsson Dashboard) are both in the range 20-50 ms (38.1 ms for scenario 1 and 36.3 ms for scenario 3) specified in D4.1 [TAR23-D41] as a target. Even the 95th percentile is within this range (49.3 for scenario 1 and 50 ms for scenario 3). This is not the case in scenario 3 where no exposure APIs are implemented (average 65.4 ms and 95th percentile 148.5 ms).
- KR3: The command latency is significantly more stable when using predictive QoS, in both implementations, compared to Scenario 2, where no predictive mechanism was used during cell deactivation. Specifically, the standard deviation of latency dropped by 92% in both scenarios, demonstrating far less performance fluctuation when proactive notifications are in place.
- KR4: The reliability in both links was always higher than 99% and this is because, when the cell was turned off, the remote driver had to stop the vehicle either before reaching the zone without coverage or directly when reaching that zone.
- KR5: The average values in the two scenarios with exposure APIs are in all scenarios in the range 10 – 50 Mbps (19.2 Mbps for scenario 1, 16.4 Mbps for scenario 2, and 19 Mbps for scenario 3) specified in Deliverable D4.1 as a target. However, the minimum values in scenarios 1 and 3 are 15.3 Mbps and 16.4 Mbps, whereas it can reach 0 in the case of scenario 2.
- KR6: More stable video throughput performance when using predictive QoS, in both its implementations, compared to Scenario 2. Specifically, the standard deviation of the

throughput dropped by 67% in Scenario 1 and 76% in Scenario 3, demonstrating far less performance fluctuation when proactive notifications are in place.

6.5 Dynamic Service orchestrator

In this trial, we evaluated the dynamic service orchestrator (Figure 6.5) in three use cases: VISTA (Visibility, Insights, Signal Telemetry, and Analytics), remote power consumption monitoring tool, remote environment monitoring tool for automated vehicles. The first use case shows how the dynamic service orchestrator will allow the measurement tool to switch between two modes: data transmission mode when network conditions allow it, and backup mode where measurements are locally stored when the network conditions do not allow the data to be reliably transmitted. The second use case, developed in collaboration with WP3, showed how the dynamic service orchestrator will allow the dynamic offloading of some of the services of the VILLAS framework used in the power consumption monitoring tool. The third use case, developed in collaboration with one of the FSTP projects impact-xG, shows how the dynamic orchestrator enables different compression rates used in the watchdog of tele-operated driving.

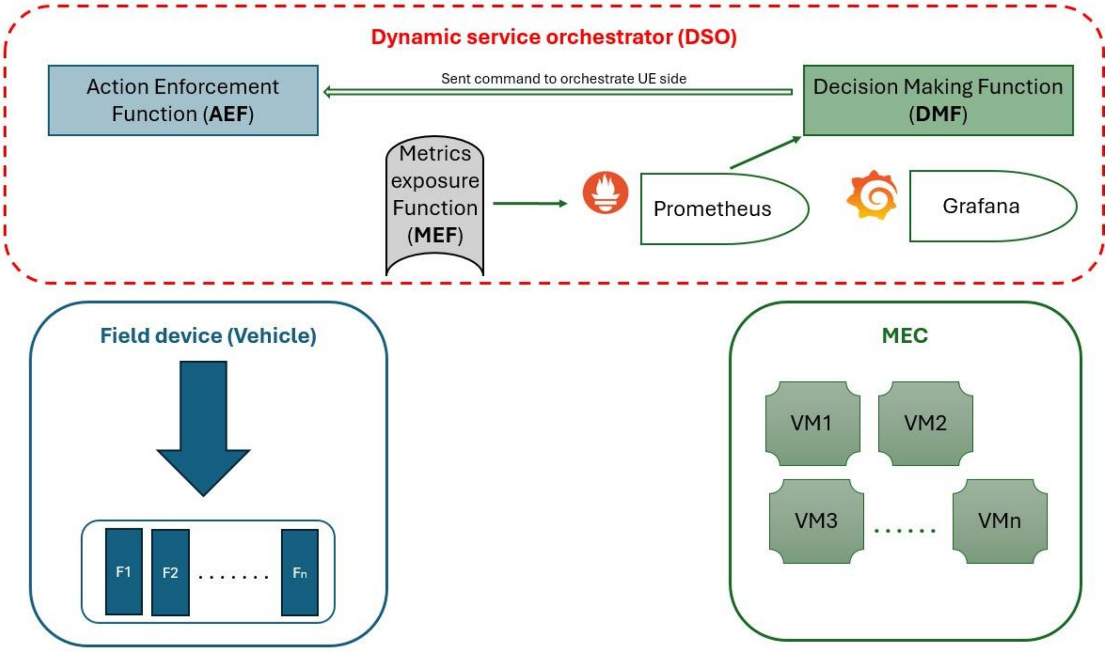

Figure 6.5 Dynamic service orchestratora rchitecture [TAR25-D43].

KPI/ KVI evaluation

This trial is evaluated by showing the gain obtained when using the dynamic orchestrator, which is triggered through a Signal to Noise (SNR) threshold. For instance, Figure 6.6 shows the difference in CPU consumption when the orchestrator triggers the service container to run on the MEC (0.4%) when network conditions allow it, and when it triggers the service container to run on the field device (21%) when network conditions are bad.

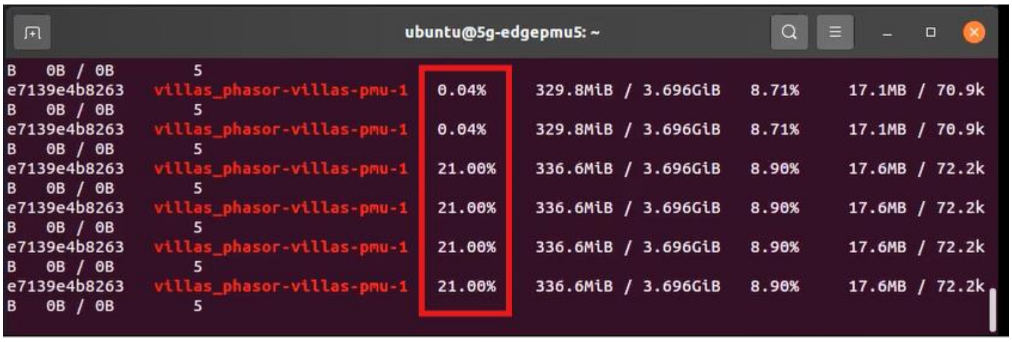

Figure 6.6 Comparing field device computational resource consumption when the orchestrated container is running on the edge versus running on the field device [TAR25-D44].

Key results

The key results of the Trial 4 are:

- KR1: The dynamic service orchestrator was able in the three cases to guarantee a seamless service while network conditions were significantly changing.
- KR2: In the use case related to power consumption, the integration of the dynamic orchestrator showed a significant decrease in power consumption while guaranteeing the continuity of the service.

6.6 Overview of the FSTP projects from both open calls

Name	OC 1	OC 2	Description	Partner 1	Partner 2
Demeter	X		Scalable technology service that revolutionizes urban mobility by integrating Volvero's vehicle-sharing platform with MinervaS's advanced 5G-driven driving optimization technology.	MinervaS	Volvero
SPARTA	X		Developed secure, open, user-friendly APIs that simplifies the work of automotive application developer by exposing mobile sensor data and infrastructure status of different technologies including 5G.	Digiotouch	
CO-PARKNET	X		5G IoT-based smart parking network that uses Cooperative Perception and V2X communication to enhance parking detection accuracy, optimize traffic flow, reduce carbon emissions, and improve accessibility for all drivers.	Flash Park	

V-STREAM	X		Dynamic video streaming watchdog that enhances remote vehicle safety by predicting and preventing communication breaks, improving video latency stability, reducing freezes, and ensuring reliable detection of video loss or quality issues.	|pipe|	
HybridCAVs	X		Leverages 5G communication to enable vehicle platoons that balance safety and energy efficiency through data sharing, coordinated speed control, and precise distance maintenance between vehicles.	Ada Guzey Engineering Software Mechatronics Ltd.	
RTR	X		Enhancing critical care during patient transport via real-time 5G communication, ensuring road safety through digital twinning, and improving health outcomes.	logimade	
DynoSafe	X		Enhancement of network performance measurements for safer automated driving systems. Integration of network performance measurements directly into the Dynamic Operational Design Domain of Advanced Driver Assistance Systems (ADAS).	IVEX	
SafePerception		X	Real time generation of digital twins based on vehicles perceptions of the road users. Data is processed in the edge using 5G and C-V2X Collective Perception.	idneo	Universidad Carlos III de Madrid
VINS-RTK Mapper		X	Based Visual-Inertial Navigation Algorithm with RTK, together with mapping technology, the surrounding environmental twin of the environment will be constructed in real-time based on collected data using 5G.	Link Robotik Teknolojileri Makine San. ve Tic. A.S	
IMPACT-xG		X	Design and implement a watchdog, namely a full-fledged video/voice quality estimation and prediction system for the bi-directional 5G link between an autonomous vehicle and the human supervisor.	StreamOwl Private Company	Athens University of Economics and Business

LiTO	X	5G-enabled networked vehicle platform designed to enhance intersection safety by integrating sensors, predictive models, and communication systems, ensuring seamless real-time data exchange and low-latency performance in real-world conditions.	D.R RoadsA.I Ltd.	
VISTA	X	Addresses the regulatory and technical challenges of remotely supervising autonomous public transport vehicles. It integrates the |pipe| watchdog into MOTOR AI's platform to ensure reliable low-latency video streaming, enable remote trajectory approval, and adapt to varying 4G/5G conditions while developing certification ready documentation and regulatory alignment.	|pipe|	MOTOR Ai
Digital Twin CAV	X	Creating a real-time, 5G-enabled digital twin of the road environment by integrating data from diverse sensors using advanced AI.	Ada Guzey Engineering Software Mechatronics Ltd.	

6.7 Lessons learned

The design, integration, and validation activities in WP4 revealed several important lessons regarding the deployment of advanced V2X (Vehicle-to-Everything) applications and their enabling 5G infrastructures. These lessons provide critical insights for future large-scale deployments [TAR25-D44]:

Need for Road and Network Digital Twins

The trials demonstrated that assessing V2X applications at scale is challenging using only physical testbeds. Accurate evaluation of mass-deployment scenarios (e.g., thousands of connected vehicles) requires the creation of road digital twins and network digital twins (NDTs). These twins can emulate dense vehicular traffic, diverse network conditions, and dynamic radio environments, enabling the study of system-level behavior, scalability, and resilience without the high cost and complexity of full physical deployment.

Tight Integration of Predictive QoS and V2X Applications

The results of the predictive QoS (pQoS) for Tele-Operated Driving (ToD) use case clearly show that reliable ToD performance depends on bidirectional data exchange between the network and V2X applications. Network-side information about congestion, radio conditions, and resource allocation must be made accessible to applications, while applications must provide service-level requirements (e.g., latency budgets, bandwidth needs) back to the network. This confirms the need for standardized interfaces enabling real-time pQoS feedback loops, such as the Linux Foundation's CAMARA project, which is an open-source community addressing telco industry API interoperability [CAMARA].

Challenges with Coarse network analytics exposure

Current network analytics functions typically expose aggregated KPIs at coarse time intervals. For instance, in IDIADA, the network status is updated every 15 minutes in the network Dashboard. This relatively long period can be reduced in some network implementations, but it is always in the order of minutes. For current services, there is no urgent need to make it lower. However, future safety-critical V2X applications demand second-level, fine-grained analytics (e.g., instantaneous RSRP, SINR, scheduling delays) to make timely decisions. To enable such application, it is critical that future networks support network functions capable of exposing analytics with lower granularity, accessible through standardized APIs.

Challenges with Spectrum regulation

Current 5G Time Division Duplex (TDD) spectrum regulation focuses on harmonized TDD frame structure in all public network operators to ensure proper synchronization. The recommended TDD frame structures in Europe for the 3.5 GHz are DDDSU (i.e., three downlink slots and one uplink slot in a frame) or DDDDDDDSUU (i.e., seven downlink slots and 2 uplink slots in a frame) [5GAA], which means that the ratio of downlink to uplink resources is 3 to 1 or 7 to 2, with clear bias toward downlink. This is justifiable by the fact that most current applications (e.g., video streaming, application downloads) require more downlink bandwidth than uplink bandwidth. However, this is not the case in many automotive applications (e.g., cooperative perception using CPM, ToD as shown in this document), where much more bandwidth is required in uplink than downlink.

7 Construction

7.1 Motivation

The objective in the work package "Construction" during the final project phase was to implement the concepts for the cyber-physical construction site on the construction testbed. To this end, a living lab with a collaborative demonstrator platform was established. In this environment, the 5G applications for the construction use cases were evaluated to determine their potential contribution to the automation of deconstruction processes and the development of a more circular economy in the construction sector.

7.2 Automated robotic unbolting

This trial focused on demonstrating an automated robotic unbolting process for structural steel components. It was conducted at the Reference Construction Site in Aachen (the construction testbed) as part of the activities within TARGET-X's construction vertical.

The setup consisted of a mobile robotic platform equipped with a KUKA Iontec KR70 R2100 manipulator, a stereo depth camera for environmental perception, a force–torque sensor for haptic feedback, and an impact driver integrated into the robot's end effector for unbolting operations. The system was connected to the on-site 5G network through an onboard router, enabling data exchange between the robot, the edge-computing infrastructure, and a web-based supervisory interface accessible via tablet. Through this interface, the remote operator could monitor the robot's actions in real time, receive live sensor feedback, and if required, intervene remotely. The overall configuration of the robotic system and its operator dashboard is illustrated in Figure 7.1.

Figure 7.1 (left) Automated robotic unbolting setup and operator interface at the Reference Construction Site in Aachen, showing the 5G-connected robotic platform, integrated sensors and tools, and (right) the web-based dashboard used for process supervision as presented in deliverable D5.3.

Perception relied on AI-based visual models to identify hexagonal bolt heads and recognize beam geometries within the as-built structure. When visual detection of bolts became uncertain e.g., due to reflections, shadows, or partial occlusions, the robot switched to an adaptive probing routine that detects structural beams and uses haptic sensing to determine the bolt's location through contact with the inner beam surfaces. This combined perception strategy, integrating visual and tactile feedback, enabled a robust understanding of the as-built-environment deviations and ensured accurate alignment of the robot's end effector. Once a bolt was detected, the robot autonomously positioned the impact driver, unfastened the bolt, and deposited it in a storage container, thereby completing a full removal cycle without human physical intervention, as illustrated in Figure 7.2. More details about the robotic unbolting process can be found in deliverables D5.2 and D5.3 [TAR24-D53, TAR25-D53].

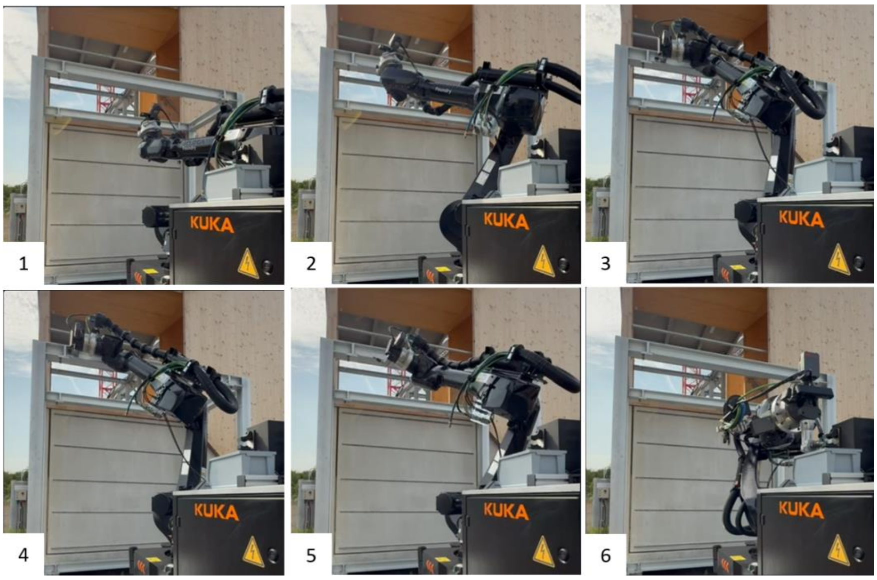

Figure 7.2 Sequence of the automated unbolting process showing the robot's main stages: home position, visual inspection, beam approach, tactile sensing and unbolting, bolt retraction, and storage as in Deliverable D5.3.

To expand the operational scope beyond unbolting, an additional end-effector equipped with magnetic grippers was developed and tested. This tool enables the robot to handle and extract loosened steel components following unbolting, using a similar detection algorithm and control architecture.

KPI/ KVI evaluation

The selected User-KPI and User-KVI for the evaluation have first been described in D1.2, Sections 3.5.1.3 and 3.5.1.4:

User-KPI:

- Completeness of process data
- Reliability of process data
- Process capability (c_p & c_{pk})
- Throughput
- Worker efficiency

Regarding the completeness and reliability of process data, it can be said that only the use of 5G enables the collection and utilization of data generated during execution on remote construction sites. For the considered use case, precise time logs indicating the start and the completion of a robotics operation could be acquired and utilized during operation of the robot in the format hh:mm:ss with no packet losses occurring during the evaluation phase. As the data is not manipulated and can directly be sent to, for instance, an edge cloud for analysis purposes, both User-KPI completeness and reliability of process data create immediate added value.

For the calculation of the process capability, 50 exemplary unbolting operations were conducted in which two separate bolts were unscrewed from the metal beam automatically by the robot. The timestamps when the operation was started and when it was completed successfully were both logged and sent to an edge cloud. For the first bolt, a mean processing time of 137.21 seconds was recorded with a standard deviation of 5.92 seconds. For the second bolt, the mean processing time was 104.63 seconds, and the standard deviation was 5.45 seconds. Based on assumptions regarding tolerances in execution times on construction sites, it was determined that the upper and lower tolerance shall be 15 % of the mean for both processes. For the first bolt, $c_p = 1.159$ and $c_{pk} = 1.159$ and for the second bolt, $c_p = 0.960$ and $c_{pk} = 0.960$ were calculated. The results indicate that the process is at least partially stable, even if the value of 1.33 commonly used in industrial production is not achieved. It should be noted that network communication is not the only source of fluctuations in such a process. Considering that this is a prototypical process, the values achieved are considered well suited for further development. Achieving values around or above 1.00 for c_p and c_{pk} is interpreted as an indicator of feasibility, suggesting that 5G can support a stable robotic process. on the construction site. During the process execution, no execution errors like unscrewing of the wrong bolts or sorting the unscrewed bolt into the wrong container were observed so that the error rate was zero.

In order to compare the performance with manual execution, a comparative measurement was carried out in which a trained person loosened the screws manually. This person took a total of 1:51 min to loosen the eight screws on the steel beam. In a direct comparison, the automated execution with the robot is currently still slower than the manual execution by an experienced person.

However, several factors must be taken into account when evaluating the results. For safety reasons, the robot's execution speed is currently still throttled and the trajectory has not yet been optimized for speed. In the future, the robot's performance will therefore approach that of humans. In contrast to humans, the robot can also perform the task assigned to it without interruption. A human worker would not be able to perform the operations for 8 hours a day, 5 days a week, and would also see a decline in performance after a few runs, whereas the robot will not experience any degradation in its performance. Therefore, we come to the conclusion that the automated execution of this use case is able to achieve significant improvements regarding the User-KPI cycle time, throughput, error rate and worker efficiency. The User-KVI "work accident rate manufacturing" for this use case is described in Section 7.4.

Key results

- **KR1: Demonstrated automated and stable robotic unbolting**
  The robotic system successfully executed fully automated unbolting of standardized self-threading steel connections, achieving consistent performance across multiple iterations as indicated by the evaluated process capability. The process demonstrated stable operation on not-pre-programmed action with real-time sensor feedback, confirming the feasibility and scalability of autonomous deconstruction using robotic equipment. While there is optimization potential in terms of process execution time, this result already proves that such robotic systems can be used to relief physical strain from human workers by taking over repetitive and strenuous tasks.
- **KR2: Ensured reliability and material integrity**

The unbolting process was performed repeatably without the need for manual interaction near heavy structural components. All bolts and beam members remained intact after removal and storage, verifying that automated disassembly can support circular construction principles through the recovery and potential reuse of building materials.

- **KR3: Implemented AI-assisted perception and adaptive sensing**
  Generic, off-the-shelf AI-based visual models accurately identified structural geometries within as-built scenes. When visual confidence decreased, the system employed adaptive haptic probing to localize the bolt position. This combination provided robust perception under variable lighting, reflections, and occlusions.
- **KR4: Enabled 5G-based supervisory control and remote monitoring**
  The trial validated the use of the 5G network for communication between the robotic platform, edge computing, and the operator interface. The web-based dashboard allowed visualization of sensor data and robot status, enabling safe remote supervision and efficient process management from anywhere within network range.
- **KR5: Extended system capability with modular end-effectors**
  The multi-end-effector concept demonstrates the flexibility of the system to operate across different layers of materials within the deconstruction process, from removal of fasteners to secure element retrieval.

7.3 XR for deconstruction planning

As a preliminary step towards automated demolition, the project tested the use of XR for deconstruction planning. To this end, an approach based on Linked Building Data with two different types of XR user devices was investigated. Linked Building Data applies principles of Linked Data and Semantic Web for applications across the life cycle of buildings. The aim is to make this heterogeneous data manageable and actionable. Conceptually, the developed application is based on converting the building and component geometries from the BIM model into a knowledge graph. If this knowledge graph is made available to the user as a Linked Building Data model at a central location, they can make specific requests for the visualisation of assembly groups, connectors or invisible components, but also display pre-planned machine trajectories to check for collisions. From this, they can deduce how to carry out a deconstruction process in order to reclaim as many building elements as possible and at the same time ensure that the machine remains undamaged.

In the field studies at the Reference Construction Site, two different end devices were examined: a Samsung tablet as handheld device and Metaquest glasses as head mounted device.

Figure 7.3 Application of the handheld and the head-mounted XR devices on the construction testbed for deconstruction planning.

Key results of the field tests with the handheld XR device

- **KR1: Technical Readiness and Connectivity**
  The XR application on the handheld device is natively 5G-capable, enabling direct data exchange between the tablet and the edge server where the knowledge graph is stored.
- **KR2: User-Friendliness and Interactivity**
  Users were able to effectively visualise and interact with the digital model, enhancing the application's practical utility in real-world scenarios.
- **KR3: Compatibility with Safety Gear**
  The device's design proved compatible with standard safety gear, such as helmets and gloves, and remained fully operational outdoors due to its weatherproof tablet cover.
- **KR4: Reliance on Visual Markers**
  The registration of virtual elements with the real world currently depends on visual markers or anchors, which can limit flexibility and spontaneity in dynamic environments.
- **KR5: Limited Field of View**
  The device's limited field of view resulted in lower immersion, potentially impacting the user experience.
- **KR6: Limited Environmental Awareness**
  The system exhibited limited environmental awareness, and the need for numerous visual anchors throughout the demonstrator area posed logistical challenges. Initial findings and results have been presented in [WU24-UNIFI] and further expanded in [WU25-5GENA] as well as deliverable D5.2 [TAR24-D52].

Key results of the field tests with the head-mounted XR device

- **KR1: Enhanced User Experience and Immersion**
  Users could seamlessly visualise and interact with the digital model, creating a cohesive augmented experience. The device's 360° field of view delivered a high level of immersion.
- **KR2: Simplified Setup with Single Virtual Anchor**
  Unlike the handheld device, the head-mounted device required only a single virtual anchor, simplifying setup and reducing logistical constraints.
- **KR3: Improved Situational Awareness**
  The device's enhanced situational awareness improved situational understanding and interaction.
- **KR4: Lack of Native 5G Capability**
  The device is not natively 5G-capable. It requires connection to a local Wi-Fi network via a 5G-capable router, which may impact real-time data querying, processing, and general connectivity in certain environments.
- **KR5: Compatibility Issues with Safety Gear**
  The device could not be used with construction site safety helmets, limiting its applicability in industrial or hazardous settings.
- **KR6: No Weatherproofing**
  The lack of weatherproofing restricts outdoor use, posing challenges for field applications in variable conditions.

A detailed explanation and analysis of this approach can be found [TAR25-D53].

KPI/ KVI evaluation

For the evaluation of this use case, the User-KPI and User-KVI have first been described in D1.2, Section 3.5.3.3 and 3.5.3.4 [TAR24-D12].

User-KPI:

- Completeness of process data
- Reliability of process data
- Error Rate
- Worker Efficiency

For the evaluation of completeness and reliability of process data, measurements were conducted to acquire time logs of the start and end time of the XR-supported operation with the head-mounted device. For this purpose, 30 process executions were carried out and the difference between the start of the operation and its end was recorded. Time logging started when the user started to plan the path including the planning, simulation, visualisation and moving of the robot. Time logging ended when the robot arm had moved to the desired position. Over the course of approx. 30 minutes, 30 measurement points were acquired, each precisely describing the start or end data of an operation. The process executions had a mean execution time of 33.14 s and a standard deviation of 3.63 s. The time logs were sent directly from the robot's machine control to the edge cloud and no package loss occurred during the measurements, indicating a stable and reliable network connection. Therefore, it can be stated that completeness and reliability of process data are at their maximum possible values for this use case. Regarding the error rate, no errors were observed during the process execution with the head-mounted XR device, indicating that the solution is very fail-safe. The worker efficiency is also evaluated to be very high. Over the time frame of 30 minutes, 30 successful operations were executed with no errors or breakdowns occurring. Therefore, it can be summarized that the operation with the head-mounted XR device achieves the targeted value proposition of creating a comprehensive data set of time logs that increases process insights while also increasing the process efficiency.

User-KVI:

- Digital literacy

The XR use case showed significant potential to increase digital literacy of construction workers enabled by 5G. Here, not the UE (XR handheld or head-mounted device), but the 5G network was the decisive factor. As indicated by the FSTP projects in Section 7.5, 5G is the major enabling technology that enables the convenient and efficient use of digital technologies on constructions sites. Therefore, it can be stated that all construction-related use cases significantly contribute to an increase of digital literacy on construction site.

7.4 Safety assistant for deconstruction planning

Since the automated deconstruction process using robots means that machine operators no longer have to work in close and potentially dangerous proximity to the machine, it becomes necessary to transfer the machine operator's situational awareness to the robot. In our approach, the stationary deconstruction robot is accompanied by a small, mobile robot. The mobile robot monitors the work area using a 3D LiDAR sensor to detect human presence near or within the danger zone. If it detects a person in this danger zone, it can stop the deconstruction robot. The use case was first deployed with a centralised data processing approach as presented in [KIR24-LOOSE] and then adapted to local data processing in a further iteration.

KPI/ KVI evaluation

For the evaluation of this use case, the User-KPI and User-KVI have first been described in D1.2, Section 3.5.4.3 and 3.5.4.4.

User-KPI:

- Process capability (c_p & c_{pk})
- Cycle time
- Throughput
- Error rate
- Worker efficiency

The analysis with User-KPI cycle time, throughput, error rate and worker efficiency are analysed for the automation use case in Section 7.2 as the safety use case only represents the safety aspect that is necessary for the automation use case to be implemented.

Regarding the process capability, experiments were conducted on the construction site to test, whether the mobile robot supervising the work area of the stationary deconstruction robot. For this purpose, the work area was entered by a person on purpose so that the mobile robot should have detected the violation of the border of the work area. If a detection occurs, the mobile robot shall send a message to the stationary robot, so that the ongoing operation is stopped. To acquire enough data, the violation of the work area border was repeated 170 times. Based on the geometry of the stationary robot, the distance between the inner border of the work area of the robot and the danger zone is 0.6 m. With a walking speed of 5 km/h, the time until the robot must be stopped when the violation of the work area is detected is approximately 430 ms. To integrate more buffer, the latency requirement for the detection message to arrive at the stationary robot from the mobile one was set to 75 ms. The analysis of the measured timestamps shows a mean end-to-end latency of 29.98 ms and a standard deviation of 11.21 ms. This leads to the calculation of c_{pk} = 1.368 which means, if translated to ppm, that out of one million executions, approximately 20 executions are outside of the tolerance limits of 75 ms. A histogram that illustrates the measured values for end-to-end latency is shown in Figure 7.4 including the upper tolerance limit of 75 ms.

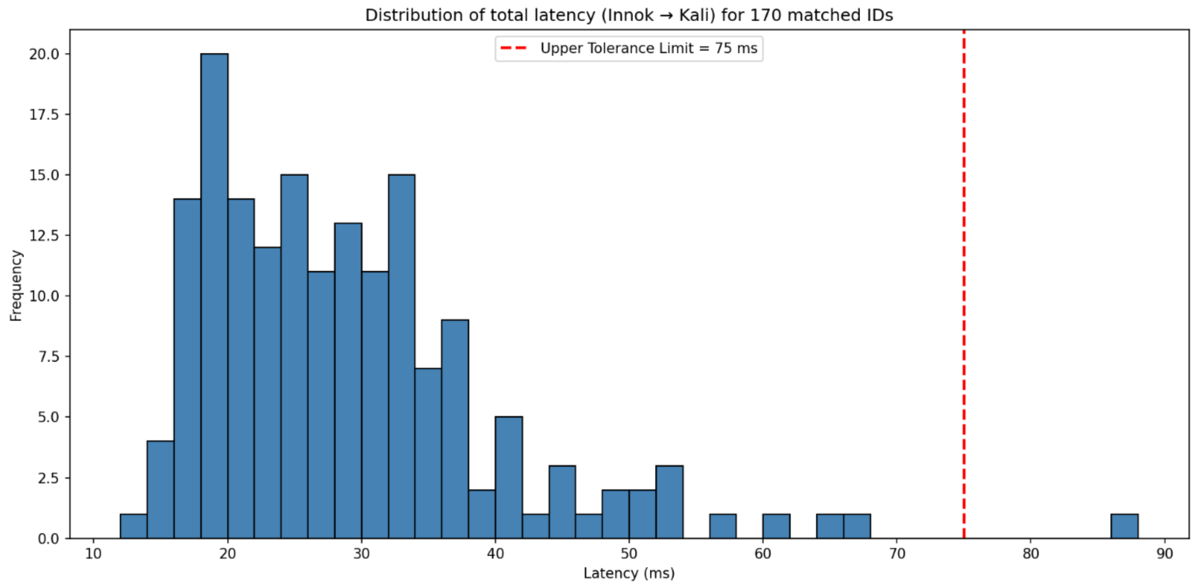

Figure 7.4: Latency Values of Work Area Violation Detection

User-KVI:

- Work accident rate construction

The developed solution will enable significant developments of safety features for construction sites. The monitoring of safety zones by a mobile robot can be applied to a variety of different application scenarios in which work areas of danger zones must be monitored. 5G's capability to enable low latencies enables the development of different solutions that employ, among other things, computer vision to detect and report the violation of work areas as well as danger or safety zones. Therefore, it can be summarized that a fail-safe safety feature has been developed with this use case. In 2024, there were 91,813 reportable accidents at work in the German construction industry and construction-related services. Last year, 78 people lost their lives in accidents at work on construction sites. Accidents involving construction machinery account for 15 percent of fatal accidents at work [BGBAU-25]. The solution developed with the Safety use case can address this figure and represents an approach to better monitor the working areas of construction machinery and could contribute to reducing these figures through improved work-area monitoring. From an economic perspective, especially the costs that are directly associated with insured events are relevant. Here, the following statistics are considered: In 2024, accident insurance providers' expenditure on benefits rose by 3.3 percent compared with the previous year in Germany. The largest share of this was accounted for by benefits for insured events, which amounted to around €12.3 billion. The costs for medical treatment and rehabilitation rose by 3.7 percent to €5.9 billion, while the costs for financial compensation for insured persons rose by 2.2 percent to €6.4 billion. Professional associations and accident insurance funds invested €1.5 billion in preventive services such as supervision, counselling, and training, 7.3 percent more than in 2023 [DGUV-25]. These statistics illustrate the economic added value that can be achieved through fail-safe monitoring of work areas on construction sites. Of course, not all costs incurred can be reduced, but the solutions developed can be used to reduce the €6.4 billion that must be spent on financial compensation for insured persons.

Key results

Central Processing on Edge Server

- **KR1: Coordinated Robot Operations**
  The setup enabled direct communication between the stationary deconstruction robot and the mobile robot, facilitating coordinated operations.
- **KR2: Minimal Hardware Requirements**
  Only a 5G router was required as additional hardware on the mobile platform, reducing complexity and cost.
- **KR3: Central Data Availability**
  Raw observation data was made centrally available, allowing it to be used for multiple applications and analyses.
- **KR4: High Network Demand**
  The system generated a high uplink demand (~63 Mbit/s), even at minimal LiDAR resolution, potentially straining network resources.
- **KR5: Limited Scalability**
  The high network demand limits scalability, especially in environments with multiple robots or shared network infrastructure.

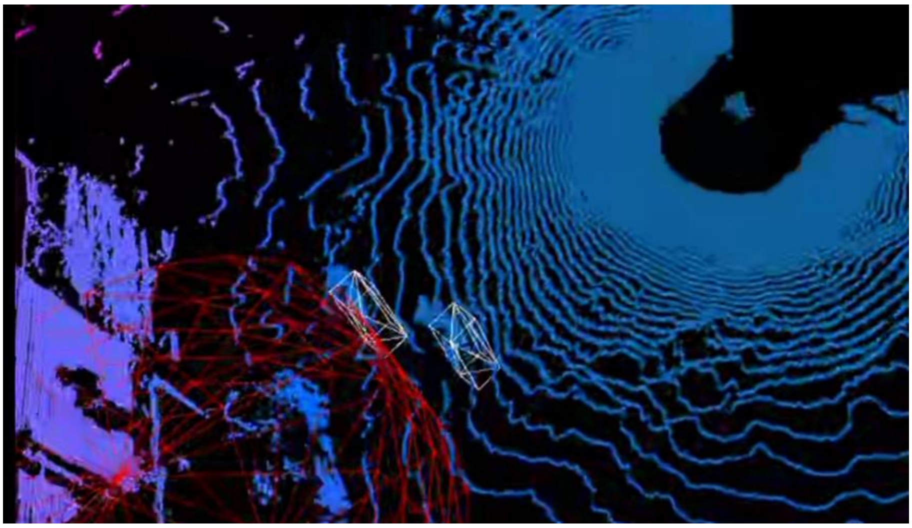

Figure 7.5 View of the deconstruction robot's workspace through the LiDAR scanner mounted on the mobile robot platform as presented in [TAR25-D53]

Local Onboard Data Processing

- **KR6: Reduced Network Load**
  Shifting to local onboard processing significantly reduced network load to <1 Mbit/s, alleviating strain on communication infrastructure.
- **KR7: Improved Scalability**
  The reduced network demand makes the system more viable for environments with multiple robots or limited bandwidth.
- **KR8: Increased Hardware Requirements**
  Local processing required additional hardware (e.g., a GPU), increasing cost and complexity.
- **KR9: Data Contextualisation Overhead**

Contextualising data from distributed sources became necessary to ensure processed information remained meaningful and actionable.

- **KR10: Practical Deployment Challenges**
  Deploying additional computer hardware in harsh construction environments posed challenges, including robustness and reliable power supply.

7.5 Overview of the FSTP projects from both open calls

Name	OC 1	OC 2	Description	Partner 1	Partner 2
Data Exchange	X		Provision of building element information and orders information for end customers on the construction site based on linked data and 5G.	LIGNOTREND Produktions GmbH	
Demon	X		Leveraging 5G for process monitoring and quality assurance for constructions according to cradle-to-cradle principles	kadawittfeldarchitektur GmbH	wh-p GmbH Beratende Ingenieure
LesMiro	X		Leveraging 5G for the tracking of prefabricated concrete elements and remote robot control in steel fabrication	RST Stahlbau GmbH & Co Kommanditgesellschaft	Florack Bauunternehmung GmbH
Remocontrol	X		5G-based remote control of solar power generators and storage for self-sufficient construction sites	Lelieur B.V.	
Tokenme 5G private network	X		5G-based asset tracking and safety monitoring on construction sites	TokenMe B.V.	
5CADE		X	5G-based remote monitoring and control of irrigation system for green facades	Technische Universität Dresden	Medicke GmbH
5G environmental monitoring		X	5G-based solution for monitoring of construction machine operation times and ERC reporting	Embneusys PC	

5g steel monitoring	X	5G for quality assurance in steel construction	Wurst Stahlbau GmbH	Laserscan OM
5Gfact	X	5G for automation of onsite handling of prefabricated timber building modules	GROPYUS AG	Ludwig System GmbH & Co.KG
Afam	X	5G for onsite data collection and backhaul for predemolition audits	Concular GmbH	
Bimonitor	X	5G fo transfer of construction progress monitoring data	Sabiedrība ar ierobežotu atbildību "WatchBuilt" LLC	ASSOCIAÇAO BUILT COLAB - COLABORATIVE LABORATORY FOR THE FUTURE BUILT ENVIRONMENT
Elrossy	X	5G for remote operation of a robot for steel manufacturing (bolted connections)	RST Stahlbau GmbH & Co Kommanditgesellschaft	
Emic5g	X	Development of a gateway to aggregate and forward data collected with low power radio technology to 5G	IMST GmbH	
Intellimat	X	Integration of low power localization system for asset tracking with a 5G backhaul for cloud connectivity	Arcology System Ltd	ResourceKraft Ltd
pirgos	X	5G for a retrofit assistance system for construction machinery	MOBACT MONOPROPOSI E.P.E	WINGS ICT Solutions SA
Wotan5g	X	5G for remote maintenance and monitoring of tower cranes	BBL Baumaschine mbH	SKA SPS-Technik GmbH

7.6 Lessons learned

Impact of Built Environment on 5G Networks

The dynamic nature of construction sites and ongoing progress directly affect 5G network performance. Network flexibility and adaptability are essential to maintain reliable connectivity. Approaches to address this challenge have been presented in [KIR24-ANONT].

Resource-Aware Design for Automated Machinery

Automated construction machinery requires sensors for environmental and situational perception but such use cases can quickly become uplink-heavy. Designing resource-aware use cases is critical to avoid overwhelming network capacity and ensure efficient operation.

Alignment Between Network and Use Case Design

Early collaboration between vertical end users and the telecom industry is vital to avoid misunderstandings and align expectations e.g., transparency about the technical and financial implication of use case design choices and network design choices respectively. Proactive communication can help turn user-side frustration into openness toward technology adoption.

Cost and ROI Challenges of 5G Hardware

5G-capable hardware remains more expensive than Wi-Fi alternatives, and the return on investment (ROI) is often unclear. Feedback from construction FSTP projects suggests that most would not invest in 5G without external funding. This highlights the need for clearer business cases or cost-effective solutions.

Trade-offs Between Central and Local Data Processing

Central processing (e.g., edge server) offers direct communication and minimal hardware requirements but creates high uplink demands (e.g., 63 Mbit/s for LiDAR), limiting scalability.

Local processing (e.g., onboard GPU) reduces network load (to <1 Mbit/s) and improves scalability but introduces hardware complexity (e.g., power supply, integration, and contextualization of distributed data).

8 Technology evolution beyond 5G

8.1 Technology evolution in the different testbeds

The work package on "Technology evolution beyond 5G" investigated various technology elements that are part of 5G but have the potential to evolve further in the timeframe of 6G. The technology bricks, as they are referred to in the project, were selected based on a combination of criteria, with the most important criteria being their relevance for the verticals in TARGET-X and the technical potential to evolve into 6G building blocks.

The relevance and potential were verified and validated by measuring key performance indicators where applicable. Where possible, technology bricks were introduced in the use cases of the TARGET-X verticals for evaluation as illustrated in Figure 8.1.

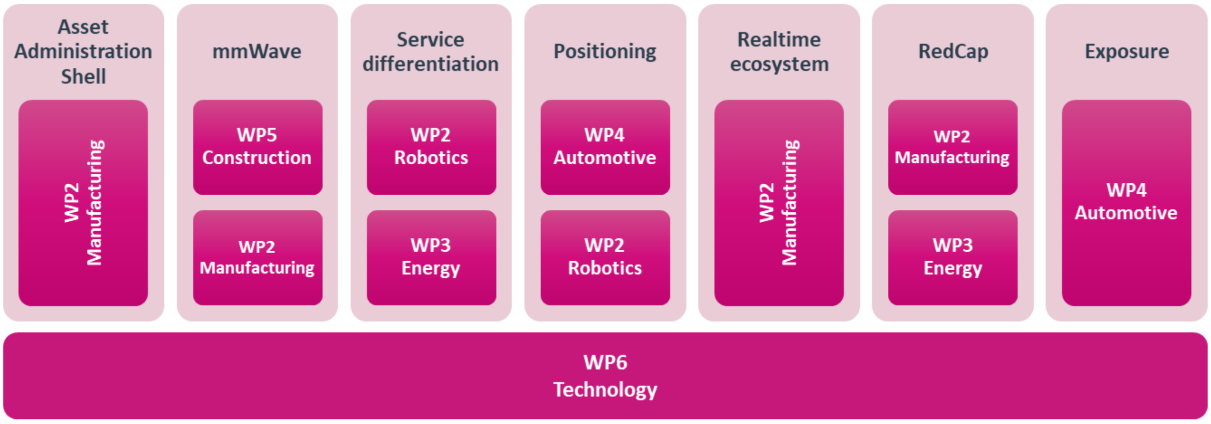

Figure 8.1 Matrix of technology bricks introduction and evaluation in verticals

The deployment and evaluation progress with its results and challenges were captured in the WP6 deliverables, with [TAR23-D61] describing the starting state of the different testbeds and the vision for the evolution the testbeds. In [TAR23-D62] an intermediate report was provided with first evaluations after deployments of first stages of technology bricks. In [TAR23-D63], the design of the different AAS models was documented and [TAR24-D64] reported on the implementation details of the defined AAS models. In [TAR25-D65]. a final report on the technology bricks is provided, including the report on our large-scale trial setup and execution. The large-scale trial was introduced into the project at a later stage, as it became clear that a validation of network KPIs with a large number of devices in realistic conditions would deliver further insights into the relevance and applicability of 5G and beyond technology on industrial shopfloors.

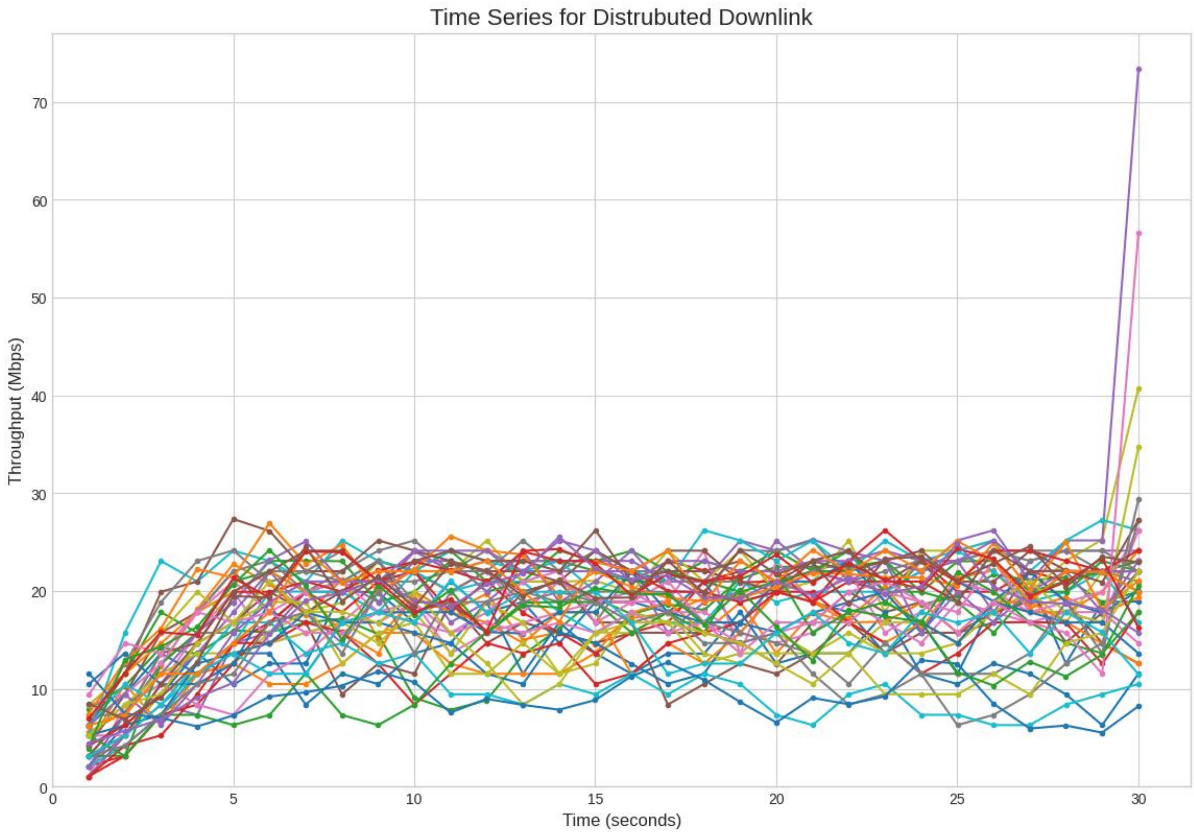

Figure 8.2 Time series of downlink performance of 55 parallel sub6 devices

As an example of the metrics that were collected, the above Figure 8.2 shows a time-series plot with 55 sub6 devices, all registered in 1 cell. The cell capacity for downlink has been determined to be around 860 Mbps. The plot visualizes the individual throughput measurements of the 55 devices, illustrating an even and fair distribution of the available bandwidth between all devices. The observed variations between the devices, are due to the differences in signal strength. Further result s are available in [TAR25-D65].

The learnings and potentials of these technology bricks will be discussed in the following sections.

A core ambition of TARGET-X was to make evolving 5G technologies accessible to vertical industries for experimentation, both for the partners in the main consortiums, as well as for the beneficiaries of the FSTP Open Calls. The project realized this ambition to provide access to different evolutions of 5G network architectures, ranging from 5G Non-Standalone architectures in private and public network segments, over 5G Standalone architectures and URLLC (Ultra Reliable Low Latency Communication) prototype network testbeds.

8.2 Service differentiation and network convergence

This section presents traffic differentiation and network convergence for enterprise private 5G, demonstrating how differentiated connectivity in private 5G networks can preserve time-critical application performance [TAR25-D65]. Enterprise 5G deployments deliver dedicated, high-performance wireless infrastructure for diverse enterprise services with varied requirements in terms of throughput, latency, and reliability. Traffic differentiation ensures critical flows are prioritized over less time-sensitive traffic, enabling reliable operation of time-critical applications in congested environments.

The empirical evaluation of differentiated connectivity with 5G was carried out at Fraunhofer IPT using an Ericsson Private 5G (EP5G) standalone (SA) system with a cloud management portal. EP5G implements five traffic priority segments and QoS via Data Network Names (DNNs) [3GP-TS23401][3GP-TS23402]. To demonstrate the traffic differentiation framework of EP5G, two DNN classes were used: “Best Effort” and “Real-time Automation,” which are mapped to non-standard 5QI values 129–133. Higher 5QI denotes higher priority. 5QIs 129–131 target streaming (typically UDP) using RLC Unacknowledged Mode and absolute priority. Such scheme enables higher QCI to transmit only after lower QCI class has drained the buffer. 5QIs 132–133 handle bulk (typically TCP) with relative priority to prevent starvation. In the demonstrator, the Cradlepoint R1900 router [ERI-R1900] streams a live video feed from a USB camera at the same time as competing background traffic. Cradlepoint’s multi-PDN/DNN support and API-driven traffic steering enables assigning traffic to distinct PDU sessions, each with its own IP and QoS treatment.

The evaluation consists of showcasing that when the video stream and background traffic share the Best Effort slice, uplink saturation causes queuing, increased delay, and visible degradation of the received video. Steering the video to the high-priority PDU session preserves original quality despite heavy load, illustrating that traffic differentiation in private 5G can protect time-critical streams from congestion and maintain service levels. However, the coexistence of multiple QoS frameworks (DNN-, SIM-, IP/Port-based) increases configuration complexity, requiring clearer mapping between applications and QoS classes. This fragmentation makes it challenging to select appropriate QoS settings consistently, increases the risk of misconfiguration, and complicates troubleshooting, ultimately impacting the ability to guarantee uniform service quality across diverse network scenarios. Furthermore, a solid understanding of application requirements is essential to select the correct and optimal QoS class in 3GPP networks. Accurately mapping these requirements to the appropriate QoS class ensures efficient resource allocation, improved user experience, and optimal network performance.

8.3 mmWave spectrum

To enable large scale deployment of some of the industrial use cases in TARGET-X, certain network features and system optimizations are required [AKS25]. One of the goals of introducing mmWave spectrum in the industry is to provide wider bandwidths (for instance, 800 MHz) and support large scale deployments with data intensive industrial use-cases. Larger sub-carrier spacing in the mmW also facilitates low latency use-cases [BAO+25]. In 5G New Radio (NR) a broader and more diverse spectrum was introduced compared to previous cellular technologies [3GP-TS38101] [3GP-TS38101] [3GP-TS38401].

The radio propagation characteristics of mmWave signals are more challenging. Signals have shorter range and are more susceptible to obstacles. In TARGET-X we investigated the performance of 5G mmWave in an industrial environment [TAR25-D65]. At Fraunhofer IPT, a 5G non-standalone (NSA) mmWave system has been deployed. The 5G mmW non-public network utilizes the 800 MHz available between the 26.7 and 27.5 GHz frequency range and includes two cells covering the whole shopfloor of 2700 m^2. The shopfloor features over 50 machines of various sizes and serves as a representative example of an industrial indoor deployment.

In TARGET-X, we have evaluated the performance of the 5G mmWave system under various radio propagation conditions, at different distances, non/line-of-sight (NLOS/LOS) scenarios, network deployments and configurations, static and mobile settings in the indoor factory environment [BAO+25]. Our results indicate high throughput performance of 5G mmWave, especially in static and LOS scenarios with ca. 4 Gbps and ca. 2.2 Gbps in DL and UL, respectively. The channel capacity in UL and DL is directly influenced by the TDD frame structure and the available support of the number of component carriers. The UL performance of the 5G mmWave system is limited due to the available test devices with support of up to 4 component carriers of 100 MHz, i.e., utilizable bandwidth of 400 MHz compared to the full 800 MHz available in DL. Our results show that 5G mmWave system can achieve 4 ms and 6 ms bounded latency at the 99.9th percentile, for UL and DL respectively. Similar results have been obtained in non-line-of-sight scenarios, with a difference in DL with 10 ms bounded latency at 99.9th percentile. These results highlight the beamforming and multipath capabilities of the 5G mmWave in an industrial setting. Nevertheless, it is worth noting that the reliability in the NLOS scenarios comes at the expense of reduced system capacity. To overcome the spectral efficiency loss in the NLOS scenarios, a denser deployment (extra mmWave cells) can provide enough coverage throughout the shopfloor. However, in such deployments coexistence issues may arise. Therefore, we further investigated the performance of the 5G mmWave system with the two mmWave cells enabled at Fraunhofer IPT. In this regard, the deployment allows full spectrum re-use with minor performance loss in inter-cell interference scenarios. The system maintained reliable performance for both latency and throughput with almost no data retransmissions required even in NLOS scenarios and two devices from different cells nearby. This highlights the beamforming capabilities of 5G mmW systems and the robustness despite non line of sight radio conditions.

As a summary, our results indicate that 5G mmWave can provide reliable low latency and high throughput to static and low mobility scenarios in industrial settings. Furthermore, we have observed that reliable low latency can be achieved in scenarios without direct line-of-sight between the transmitter and the receiver for both UL and DL. A further analysis is required to determine the directivity properties of antenna arrays for terminal devices, especially in an industrial environment with large multi-path propagation characteristics.

8.4 Asset administration shell (AAS) and network orchestration

In the project, a 5G NW AAS, UE AAS and respective active components' development were realized [TAR23-D63], [TAR24-D64]. They are filled with network exposure APIs from the network e.g. the EP5G APIs. Additionally, many other 3GPP APIs were also used to keep AAS submodel elements' values updated by the AAS active components.

TARGET-X integration of the AAS and related components was realized by deployment of AAS Server and AAS Registry on site. AASes were onboarded to the AAS server in AASX format.

The NW and UE AAS have been demonstrated by the AAS traffic steering demonstrator [TAR25-D65]. It shows the capability of AAS to support traffic steering influenced by the application domain. Visualization of the running AASes were realized using BaSyx AAS WebUI.

The outcomes of the project on 5G AAS scope shows the potential of AAS in the industrial domain, together with the 5G network and 5G enabled devices, to be utilized to support 5G network optimization and management. It brings flexibility in terms of network management by providing a common abstraction layer between the IT/OT domain and the 5G network to learn about their intended use cases.

8.5 Positioning with 5G NR

The activities in TARGET-X around positioning had two goals. On one side, it is important to validate and evaluate the performance of positioning techniques, based on 5G technology to gain better understanding of how the technology shall evolve in future generations of mobile communications technologies. On the other hand, it is equally important to work with the different verticals to understand their specific use-case requirements.

In TARGET-X, 2 different positioning tracks were worked with, being 5G NR indoor positioning and 3GPP GNSS-RTK positioning.

5G NR indoor positioning

With the specification of 5G in 3GPP, several improvements to LTE were standardized in the positioning area. The capability to determine the position of objects in a space is needed for a variety of use cases and therefore, creating a good understanding of the capabilities of 5G NR indoor positioning was determined an important task in TARGET-X.

One of the partners, WZL, has several indoor positioning solutions in operation as accurate positioning solutions are needed for their research area of mobile robotics (also see Section 5.3). In this location, the 5G NR indoor positioning solution was installed, and several measurements were executed, using one of the available positioning solutions as ground truth, allowing us to determine the accuracy of the 5G solution. Overall, the accuracy is around or below 1 m in 90 % of the measurements, with outliers to 3 m. It was observed that the environment in which the position is performed has a clear influence on the accuracy. Large reflective metal surfaces, such as material containers or metallic gate doors, that have shown to improve propagation for communication purposes due to reflections, were found to negatively affect the accuracy of positioning results. The reason is that the solution uses the time difference of arrival of signals from a UE to different antennas, and the reflections causes fluctuations in these signal runtimes and thus affect the trilateration results.

3GPP GNSS-RTK positioning

A second technology in the positioning domain that was evaluated, is the 3GPP GNSS RTK positioning. The solution relies on augmenting the results of positions received via GNSS on the UE, by applying the correction data that it receives from a base station at a fixed location. The evaluations were performed with a commonly available 5G modem and GNSS receiver, combined with prototype Gateway Mobile Location Centre (GMLC).

Initial experiments were conducted at the IDIADA test track, with further experiments executed at the 5G-Industry Campus Europe. In a set of drive tests around the 5G-Industry Campus Europe, the precision of GNSS RTK positioning was analysed in several scenarios. With the initial static test, the relative position, based on longitude and latitude was evaluated. The normal distribution of the latitude and longitude coordinates indicated a sigma of ±25.50 mm and ±10.38 mm, respectively.

The static test was followed by a number of drive tests on various trajectories, with routes permanently offering an unobstructed view of the sky and good 5G reception to routes that passed under bridges or went through tunnels.

As an outcome of these test scenarios, it could be determined that in areas with clear view of the sky an RTK fix would realize positions with a mean deviation below 80 mm. On parts of the trajectories, where RTK went into float or no fix state, due to loss of RTK reception or loss of GNSS signal, the precision dropped to mean deviations of 2.1 m and 10 m, respectively.

Our experiments in TARGET-X have demonstrated that RTK enhances the precision of GNSS positioning significantly by using well-accepted 3GPP defined interfaces and brings benefits, especially to use cases from the automotive or construction verticals. The realization of these use cases would benefit from a more diverse RTK client landscape, as currently there is only a limited variety of clients available.

As an outlook towards future generations of mobile communications, a combination of 5G positioning and ISAC (Integrated Sensing and Communication) will open for a broader realization of locating objects, with or without active transmissions.

8.6 Realtime ecosystem

In order to support the real-time ecosystem, 5G integration with Frame Replication and Elimination for Reliability (FRER) scheme has been conducted. FRER uses redundant paths to increase communication robustness. Detailed performance measurement results obtained in TARGET-X project on 5G integration with FRER indicate that redundant paths provided by the FRER protocol increases the communication reliability and as a side effect, lowers the packet delay variations and end-to-end latency [KAL+25]. This effect of reduction in latency and packet delay variation is more pronouncedly at high percentile values for both uplink and downlink directions. FRER integration with 5G having redundant paths with UEs in the same 5G network as well as on different (multiple) 5G networks has been studied.

As per the FRER protocol, the first replicated copy of a packet on any redundant path is selected and the rest of the replicated copies of the packet received are discarded. In a 5G-FRER setup with a path on the 5G midband system and a path on the 5G mmW system, the 5G mmW path is generally faster and replicated copy of packet from the 5G mmW is selected. However, 5G mmW is more sensitive to blockage and in case the direct line-of-sight communication is disturbed/unavailable, the communication delay can become large [BAO+25] and the 5G-midband path acts as a fall back to keep the overall packet delay variations and latency tractable. Our experimental validation of FRER for an industrial use-case on tool wear monitoring highlights that in challenging industrial propagation environments, 5G integration with FRER can meet the bounded 10 ms latency requirements with 99.99th percentile (also see Section 4.7) [KAL+25].

The use of FRER comes with a cost of extra spectra resources. Thus, using many redundant paths is not desirable. Also, dynamic use of redundant paths to optimize the use of radio resources depending upon the criticality of the application traffic in a real time ecosystem should be investigated.

In order to support the real time communication, radio access network (RAN) configuration parameters such as block error rate (BLER) target for uplink and downlink transmissions and time division duplexing (TDD) pattern can be configured. Our experimental results indicate that lowering the BLER target to 1% or lower tends to select lower values of modulation coding scheme (MCS), which reduces the number of Hybrid Automatic Repeat Request (HARQ) retransmissions, thereby effectively reducing the overall end-to-end latency. One downside of arbitrarily selecting a very low BLER target is that it reduces the peak data rates.

A TDD pattern with more uplink slots obviously increases uplink performance. The converse naturally applies to downlink transmissions. However, due to coexistence issues with other neighboring networks, TDD patterns should not be chosen arbitrarily and in some countries, the selection of a TDD pattern is regulated.

8.7 Reduced capability in 5G – RedCap

Evaluation of RedCap devices was introduced in a later project phase. RedCap functionality is a feature with the major impacts on RAN and a minor portion in the Core for checking the admission of RedCap devices. On NW side, RedCap-ready software became available during execution of TARGET-X and the first modules that supported RedCap were announced earlier than initial anticipated, and in the consortium an early engineering sample of such a module could be acquired. A decision was made in the consortium to do an early evaluation of this device to gain insights into the performance of the feature.

A major advantage of RedCap compared to regular eMBB devices is the lower energy consumption. In a set of experiments, the performance of both module types was tested with a set of latency and throughput tests, while measuring the power consumption. Discontinuous Reception (DRX) and Extended Discontinuous Reception (eDRX) were disabled to achieve similar conditions to perform the energy consumption measurements. A significant drop in power consumption could be noted, and results are documented in [TAR25-D25], also see Section 4.2. As the energy saving features were disabled, the reduction of power consumption is to be attributed to the simpler design of the modules with less RF branches and bandwidth limited to 20 MHz, as per 3GPP specifications.

Looking towards future activities, RedCap modules provide a very compelling platform for the development and integration of industrial use cases going forward. This is also supported by already lower initial pricing of these modules, with a potential for further reducing due to increasing demands. Further evaluation of RedCap is recommended to assess the balance between performance and energy efficiency.

8.8 Overview of the FSTP projects from both open calls

Name	OC1	OC2	Description	Partner 1	Partner 2
5G-BenchMotiv	X		5G Benchmark measurements for vertical, based on a “golden unit”. Golden unit is a device with known performance and can be used to benchmark other devices.	FERON TECHNOLOGIES; Greece	-

INTERACT-B5G	X	Interactivity Evaluation in Beyond-5G Networks by means of automated and systematic network performance measurements	Karlstad University (KAU); Sweden	-
X-CRAIG	X	Develop and make available to the community the tools for easy and fast 5G heatmapping of indoor locations.	ESPACIO SOA SL; Spain	-
INSIGHT5G	X	develop a mobile application featuring a 5G heatmap for visualizing signal quality indoors. The app will utilize smartphone sensors for indoor localization, allowing users to select their preferred data sources or employ sensor fusion	Flanders Make vzw; Belgium	-
Measure-X	X	a tool for carrying out 5G measurements with multiple devices and traffic profiles. Besides collecting the data and extracting the main network metrics, the Age of Information and energy consumption are also measured.	University of Pisa; Italy	-

9 Cyber Security Aspects

In Task 1.5, a cybersecurity concept for industrial 5G use cases was developed to ensure cybersecurity considerations were integrated throughout the verticals' technical development. As cybersecurity-related concerns usually are a central barrier for adoption of the technology, the objective was to support the technical development of the use cases by developing the cybersecurity concept. In this way, concerns based on cybersecurity issues were proactively addressed by the TARGET-X project, to help mitigate concerns that could otherwise hinder broad 5G adoption in industry.

The developed cybersecurity concept adapts and simplifies NIST SP 800-30 [NIST12] into an entity-centric, qualitative risk assessment focused on permission management for 5G networks. NIST SP 800-30 was chosen since it provides a structure process to carry out risk assessments of information systems The framework consists of three steps. First, the assessment is prepared by defining the communication architecture and the entities involved in communication. Second, the actual risk assessment is conducted by the identification of potential threat events, identification of potential vulnerabilities and a subsequent determination of the threat likelihood, the threat impact, and the overall entity risk. In the third step, the risk mitigation is implemented based on the results of the second step through the assignment of individual entity permissions.

The developed concept has been applied to two different TARGET-X use cases: The XR-assisted deconstruction in construction (also described in Section 7.3) and the edge-controlled mobile manipulation for EV battery disassembly (also described in Section 5.2). The collected threats included compromised edge servers, DoS/DDoS, jamming, man-in-the-middle, eavesdropping, malware, malicious containers, and dependency confusion; vulnerabilities include weak firewalls, unpatched software, insufficient MQTT/ROS encryption (missing TLS layers or unencrypted intra-ROS 2 topics), lack of network segmentation, and weak CI/CD controls. The assessment results of the XR use case on the construction site show mostly medium and some low risks, leading to moderate permissions for the edge server and the deconstruction robot with limited admin rights, and broader but controlled rights for the XR tablet. For the mobile robotics (manufacturing) use case, both entities, the edge server as well as the mobile manipulator, received moderate permissions.

Overall, the developed concept provides a practical starting point to reduce cybersecurity barriers to 5G adoption and can be refined through validation in industrial settings. However, some limitations remain: reliance on expert judgment; focus on permission management and within-use-case scope; the need for complementary measures like stronger encryption; incident response planning.

In addition to the cybersecurity concept, two FSTP projects were mentored by the TARGET-X project team. Both projects are listed in the table below.

Name	OC1	OC2	Description	Partner 1	Partner 2
5G-SAIIoT		X	5G Secure Authentication for Industrial IoT: authentication through a 3-layers approach: device-level, network-level and	i46 s.r.o.	Institut mikroelektronických aplikací s.r.o.

		cloud-level authentication, emphasizing device-to-device authentication. Leveraging proven methods, it empowers users & secures IIoT systems.		
SCAX	X	SDR based X-G cyber security for Industry5.0+: SDR based 5G+ cyber security assessment for Industry 5.0+ focused on physical layer vulnerabilities.	CISC Semiconductor GmbH	Vysoké učení technické v Brně

10 Financial support for third parties in TARGET-X

10.1 TARGET-X Open Calls

This section summarises the structure, timeline, and outcomes of both TARGET-X Open Calls, including key procedural stages and evaluation criteria.

PHASE	CRITERIA	1st Open Call		2nd Open Call	
		RESULTS	DATE	RESULTS	DATE
APPLICATION	Application posted online through the FundingBox Platforms via the https://target-x.fundingbox.com/ and https://target-x-2oc.fundingbox.com/	259 applications started	8th of May – 2nd of August, 2023	352 applications started	6th of December, 2023 – 6th of March, 2024
SUBMITTED	Applications submitted online through the FundingBox Platform via the https://target-x.fundingbox.com/apply and https://target-x-2oc.fundingbox.com/apply	132 applications were submitted from 29 countries	2nd of August, 2023	159 applications were submitted from 28 countries	6th of March, 2024
ADMISSIBILITY AND ELIGIBILITY CHECK	Proposal submitted by the eligible entity The application was complete, readable, and in English. Must be submitted in an eligible country. The proposal addresses one of the announced Topics within the TARGET-X Open Call (Annex 1 to the 'Guide for Applicants'). No conflict of interest.	FINAL RESULTS: 130 proposals were eligible	3rd of August, 2023	FINAL RESULTS: 159 proposals were eligible	7th of March, 2024
IN/OUT SCOPE SCREENING	The 'Selection Committee' reviewed the proposal in terms of the general objectives of all proposals assessing the following aspects: **Scope.** The objectives of the proposal must fit within the scope of the project; **European Dimension**. The project should have a European dimension.	FINAL RESULTS: 87 proposals passed this phase	4th of August - the 28th of August, 2023	FINAL RESULTS: 118 proposals passed this phase	11th of March - the 20th of March, 2024
EXTERNAL EVALUATION + CONSENSUS GROUP MEETING	Criteria [Scoring]: 1. Excellence [0 to 5] 2. Impact [0 to 5] 3. Implementation [0 to 5]. For each section, the minimum threshold is 3 out of 5 points. The default overall threshold, applying to the sum	N° applications evaluated: 87	12th of September - 26th of September 2023	N° applications evaluated: 118	N° applications evaluated: 118
		N° applications above threshold: 62	29th of September, 2023	26th of March - 9th of April, 2024	26th of March - 9th of April, 2024

	of the three individual scores, was set for a minimum of 10.				
CONSENSUS MEETINGS	The 'List of the Finalists' and 'Reserved List' were decided by the 'Selection Committee'.	FINAL RESULTS: 27 proposals were pre-selected; 10 proposals were on the 'Reserved List'	16th and 17th of September 2023	FINAL RESULTS: 40 proposals were pre-selected; 7 proposals were on the 'Reserved List'	23rd of April, 2024
FORMAL CHECK	Formal verification of all pre-selected applicants.	Nº of pre-selected projects: 27 Nº of selected projects: 26	20th of October, 2023 – 17th of January 2024	Nº of pre-selected projects: 40 Nº of selected projects: 40	24th of April, 2024– 15th of August, 2024
ETHICS CHECK	All pre-selected proposals were checked against the highest ethical standards and principles applicable in the EU. Revision of the possible ethical issues was carried out. An 'Ethics Summary Report' was produced for each of the beneficiaries.	Nº of produced Ethics Summary Reports': 26	October – November 2023	Nº of produced Ethics Summary Reports: 40	May – June 2024

10.2 TARGET-X FSTP partners

TARGET-X had 98 entities as beneficiaries in both support programmes. As shown in Figure 10.1, startups and innovative SMEs dominate the landscape, while midcaps are nearly absent, and universities and research & technology organisations play a moderate role.

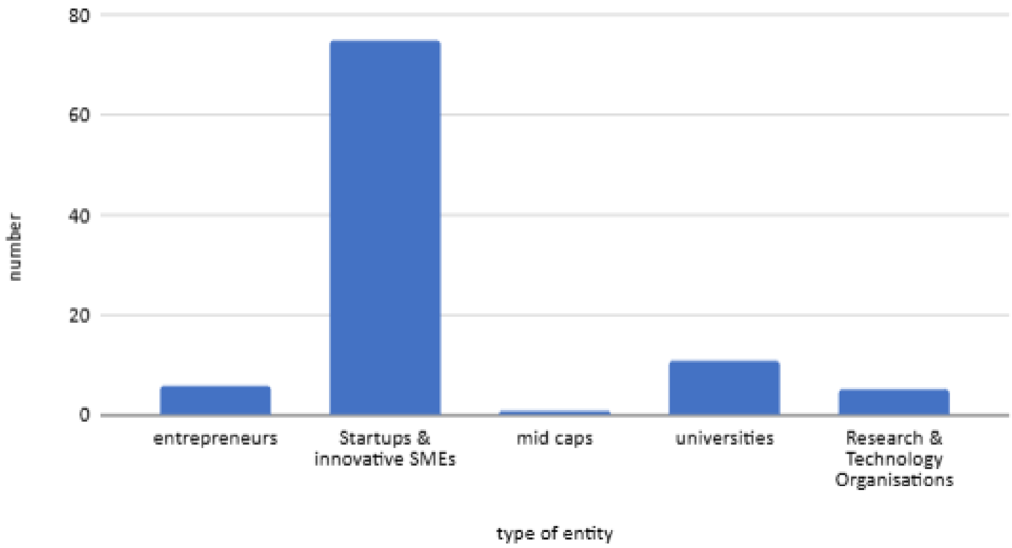

Figure 10.1 Entities of the Open Calls are predominantly SMEs

10.3 Results & lessons learned

This section summarises the main lessons learnt during the implementation of the **TARGET-X Support Programmes** and associated dissemination and engagement activities. The insights presented below are based on the consortium's internal reflections, feedback from mentors and participants, and the evaluation of both Open Calls.

- **Project Duration**
 The overall duration of the project should ideally exceed **34 months** to allow sufficient time to complete and evaluate the first Support Programme before initiating the second. In TARGET-X, the overlapping of both programmes limited the opportunity to fully integrate the lessons learnt from the first Open Call and placed additional workload on mentors and consortium partners. Extending the total duration would enhance continuity, learning transfer, and programme efficiency.
- **Duration of the Support Programme**
 Each Support Programme should have a duration of **9 to 12 months** to ensure adequate time for the supported experiments to be properly implemented, monitored, and evaluated.
- **Eligibility**
 To broaden participation and strengthen innovation capacity, the **TARGET-X Consortium** expanded the eligibility criteria to include a more diverse mix of entities. Following approval from the Project Officer, this adjustment successfully enhanced inclusivity and increased the diversity of beneficiaries, contributing to a richer and more dynamic innovation ecosystem.
- **European cross border collaboration**
 The Support Programmes demonstrated the importance of cross-border collaboration and the integration of SMEs, industry players, and research organisations across Europe involving over 30 countries in proposal submissions and over 20 in implementation.
- **Comprehensive Feedback and Further Recommendations**
 Detailed feedback has been gathered from third parties, as well as specific recommendations for future programme design.
- **Mentoring**
 Overall, the projects have appreciated the mentoring from the consortium, found it helpful for the project's success and found they provided sufficient guidance. Several participants highlighted the mentoring as one of the project's most valuable aspects.
- **5G**
 For most of the projects, it was their first or one of their early encounters with 5G. They found that the technology provided clear benefits but also considered other technologies for implementing their use cases.

11 Innovation Radar Findings

As part of the TARGET-X project, the consortium and the beneficiaries of the Open Calls participated in the European Commission's Innovation Radar initiative. The European Commission's Innovation Radar initiative serves as a tool to detect and promote high-potential innovations emerging from EU-funded projects. It enhances visibility, supports innovators in commercialization, informs policy development, and ensures that public R&D investment translates into tangible socio-economic impact.

A survey was conducted among the 40 projects of the 2nd Open Call, focusing on identifying innovations, assessing their maturity, and understanding their potential market and societal impact.

11.1 Innovation Findings

General Insights

- 30 out of 40 beneficiaries identified specific innovations in their projects.
- The results reveal a robust development pipeline, with most innovations already developed or currently under active development.
- Product type innovation dominates, emphasizing new or significantly improved offerings.

Maturity and Commercialization

- Most innovations are market-ready or nearing commercialization, aligned with customer needs and market demand.
- Prototyping and technical validation are the most advanced stages, with 27 projects having completed or ongoing prototypes and 21 feasibility studies.
- Commercialization strategies focus primarily on internal exploitation and business integration, rather than spin-offs or licensing.
- Funding needs are moderate: the majority require € 100K–€ 500K, while some seek up to € 2M for scaling.

Ownership and Market Orientation

- 16 projects have a single innovation owner, while 12 share ownership within consortia.
- Most innovators target emerging markets (26 projects), reflecting a strong preference for areas with growing demand and lower competition.
- The market outlook is highly positive: 22 projects target growing markets, and 17 expect commercialization within 1–3 years.
- Only 3 innovations have registered trademarks, revealing a gap in intellectual property protection.

Customer and Competition

- New customer acquisition is a key driver: 19 innovations are aimed at expanding into new market segments.
- Competition levels vary, but many innovators are positioned in less saturated or developing markets, enabling them to establish early leadership.

11.2 Impact on Society

The innovations developed under TARGET-X contribute directly to the European Union's sustainability and digital transformation goals.

Relevance to Societal Challenges

- Climate action and environmental sustainability dominate, with 16 innovations contributing to resource efficiency and emissions reduction.
- Other key focus areas include secure energy (7 projects), smart transport (7), health and well-being (5), and societal resilience (6).

Alignment with UN Sustainable Development Goals (SDGs)

- The strongest alignment is observed for the following goals:
  - SDG 9 – Industry, Innovation and Infrastructure (26 mentions)
  - SDG 11 – Sustainable Cities and Communities (10 mentions)
  - SDG 12 – Responsible Consumption and Production (9 mentions)
  - Contributions to SDG 3 (Health) and SDG 8 (Economic Growth) also demonstrate the portfolio's holistic impact.

Climate Change Focus

- 14 innovations address climate mitigation, targeting emissions reduction and sustainable production.
- 6 innovations focus on adaptation to climate impacts, while 10 are not directly related but may have indirect environmental benefits.

11.3 Strategic Insights and Recommendations

The TARGET-X innovation portfolio shows strong technical maturity, high commercialization potential, and clear alignment with EU sustainability priorities. However, to maximize impact, several strategic actions are recommended:

1. **Strengthen Intellectual Property Protection**
   Trademark and patent registration remain limited across most projects. Securing IP rights will be essential to attract investors, safeguard innovation, and enhance competitiveness.
2. **Enhance Market Intelligence**
   Market studies are underrepresented (5 projects identified this as a gap). Structured market analysis will improve business models and help identify untapped opportunities.
3. **Expand Collaboration and Scaling Efforts**
   With partnerships already being a key strength, innovators should continue leveraging networks with large corporations and SMEs to accelerate deployment and scale innovations across Europe.
4. **Secure Sustainable Financing**
   Focused efforts on raising private capital (€ 100K–€ 2M range) and leveraging public funding (e.g., EIC Transition, Horizon Europe, or national innovation grants) will support the transition from prototype to market.

5. **Maintain Focus on Societal Value**
   Continue aligning innovations with climate action, digital transformation, and sustainable industrial growth, reinforcing the EU's broader policy goals.

12 Dissemination and impact

The dissemination activities of TARGET-X were organized in WP8, which did track and control scientific impact, public relation, end user outreach, and events. Key activities are summarized below.

12.1 Key activities

- Creation of a dedicated project website and LinkedIn presence as the main dissemination channels
- Corporate design with project logo, MS Word and PowerPoint templates
- Dissemination planning and tracking of dissemination KPIs
- Design and printing of project marketing material: brochure, rollup, sticker
- Webinar series
- TARGET-X events: Open Day 2024, Open Campus Week 2024 & 2025, Automatica Stage, 6G-SNS Management Team visit, Final Event
- TARGET-X Trial Brochure with results of the consortium trials and FSTP projects
- Editorship of 6G-SNS Whitepaper on 6G in Manufacturing/Industry 4.0
- Video series showcasing the project results

12.2 Statistics

The website served as a communication hub for the project and was very frequently visited. Publications, videos and deliverables were uploaded and linked on the project website: PUBLICATIONS - TARGET-X. The website received an average of 5.000 visits a month, which contributes significantly to the dissemination of the project.

Table 6 TARGET-X website visits

WEBSITE (01.04.2023 – 16.10.2025)	
VIEWS	177.836
VISITORS	47.480

LinkedIn

With around 730 followers, the LinkedIn page [TAR-LI] is relatively successful in direct comparison to similar project pages and reached more than 30.000 impressions each year. Figure 12.1 shows the development of the follower numbers over the project runtime.

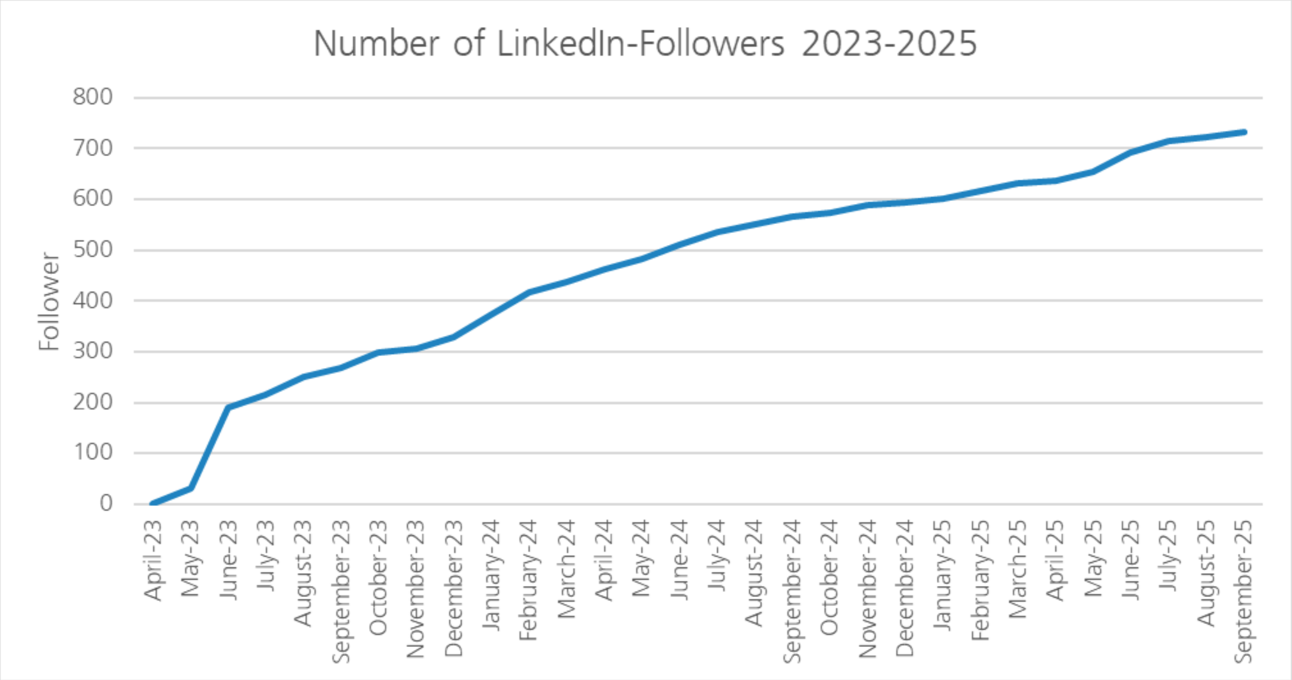

Figure 12.1 Development of LinkedIn followers over the project runtime.

Webinar series

In 2025, a webinar series was conducted providing information and training on the results of TARGET-X, covering all WP, except WP8 and WP9, in eight webinars. The webinars were accompanied by a dedicated campaign combining LinkedIn posts and emails by the 6G-IA mailing list, ultimately leading to 219 participants in total with an average of 27 participants per webinar. All webinars were recorded and publicly made available on the TARGET-X website.

Table 7 Overview of TARGET-X webinar series

DATE	Webinar Title	Number of participants
10.04.2025	Robotics Deep Dive: Edge-Controlled Automation with Mobile Manipulation	28
08.05.2025	How to evaluate the Impact of 5G Use Cases in Industry: Insights into a Methodological Assessment Framework	30
28.05.2025	Energy Deep Dive: Energy Monitoring and Energy Consumption Awareness	32
19.06.2025	Network Edge orchestrator | Dynamic service orchestration	18

04.07.2025	Automotive Deep Dive: TARGET-X Predictive Quality of Service for Tele-operated Vehicles	26
22.07.2025	Construction Deep Dive: 5G for Automation and of Deconstruction Processes	19
09.09.2025	TARGET-X Outcome and Results	51
18.09.2025	Next-Gen Manufacturing: Virtual PLCs in the cloud using real-time wireless protocols	15
	TOTAL	**219 (Ø 27)**

12.3 Publications

TARGET-X Trials Brochure

The consortium has planned, collected and designed a brochure containing a description of the TARGET-X testbeds, and furthermore all results of the trial works carried out by the consortium, additionally many FSTP beneficiaries contributed to the brochure with description of their projects and results. The brochure has 212 colored pages, has a DOI, and has been printed as physical book to be handed out at 6G events, trade shows and to important stakeholders of the community. The brochure is also available on Zenodo and the project website [TAR25-TRB].

Figure 12.2 Title page and table of contents of the TARGET-X Trials Brochure [TAR25-TRB].

Further publications

Publications from the TARGET-X consortium are continuously listed and referenced to the original paper. For this purpose, TARGET-X has a dedicated section on the project website https://target-x.eu/ and a dedicated Zenodo community https://zenodo.org/communities/targetx/. The latter serves as a platform to preserve the project output after the termination of the project and shutdown of the website. Zenodo also contains further project outputs such as deliverables, videos, brochures, measurement data, etc. The publications are listed in Annex 1.

12.4 TARGET-X Community and Partners

TARGET-X Discord Community

The TARGET-X community on Discord was launched by FundingBox following a transition from the original community hosted on Spaces (https://spaces.fundingbox.com/c/iot-edge-community) to improve real-time engagement around dissemination, events, and networking during the project.

Discord was selected for its persistent topic channels, native voice and video, role-based permissions, and accessible user experience for organizations not previously engaged in the FundingBox ecosystem. FundingBox created a dedicated Discord server and invited legacy Spaces members to re-join while onboarding new stakeholders directly on Discord. The server was positioned as the official hub for TARGET-X community activity to access news and events, share outcomes and materials, and connect with peers across the project's priority domains in 5G/6G and industrial use cases.

Membership grew substantially compared with the Spaces baseline, reaching 796 members. The composition also reflected the project's ecosystem, including 300 startups and SMEs, 23 mid-caps, 46 large companies, 36 investors, 98 universities members, 73 digital innovation hubs, and 162 research and technology organizations. The community was actively maintained with announcements, events, news, discussion threads, practical tips, and relevant funding opportunities.

Supportive partners

As part of the stakeholder engagement task, a comprehensive stakeholder mapping was carried out to identify relevant entities within the domains of energy, construction, automotive, and manufacturing. The objective was to establish a network of **Supportive Partners** aligned with the TARGET-X vision to accelerate the digital transformation of key industrial sectors through 5G/6G technologies. Following the mapping phase, targeted outreach activities were conducted to invite selected entities to collaborate with the TARGET-X project in a win-win cooperation framework. Each Supportive Partner committed to contributing to the dissemination and promotion of the project's activities and results through their communication channels and networks.

Engagement Offer

Supportive Partners were invited to:

- Communicate about TARGET-X activities through their channels.
- Provide visibility for TARGET-X (e.g., logo placement and project references).
- Promote the TARGET-X community and activities in their respective ecosystems.
- Contribute insights and participation during the **TARGET-X Open Day** on **September 17th in Aachen, Germany**.

In return, TARGET-X offered visibility across its digital platforms (website, LinkedIn, FundingBox community, newsletter) and access to networking opportunities within the project ecosystem.

Results Achieved

- **17 organisations** confirmed their participation and became active Supportive Partners.
- Partners actively contributed to dissemination by **resharing TARGET-X posts** and promoting project results through their networks. They also participated in **TARGET-X webinar on the outcomes of the project.**
- This collaboration broadened the project's outreach across the targeted industrial sectors.

13 Conclusion

In summary, TARGET-X has been successful in accelerating digitalization in Energy, Manufacturing, Construction and Automotive through:

- Demonstrating and validating industrial 5G/6G technologies and architectures in large-scale pilots in four different verticals using 41+ applications from both the consortium and the FSTP projects
- Investigating 5G/6G and peripherical technologies across the whole value chain (devices, connectivity, service delivery) to identify, assess and propose new 5G/6G features targeting connected industries.
- KPI and Key (Societal) Value Indicator (KVI) generation from real use cases validated on large scale trial sites
- Enhancing the 5G/6G ecosystem in the manufacturing & robotics, automotive, energy, and construction verticals
- Dissemination and communication of the outcomes of the TARGET-X project and contribution to standards, the scientific and industrial domains, and the subsequent SNS phases.

Beyond these overall results, three key achievements particularly highlight the project's impact:

Massive validation across five trial sites, in which diverse and numerous validation works were carried out. With its consortium members representing different vertical industries, twelve use cases were implemented and validated. The unique feature of TARGET-X is, that the use cases are distributed across the verticals manufacturing, construction, energy, and automotive, representing four of the most important European vertical industries. Additionally, through the FSTP projects carried out mostly by small and medium-sized enterprises, a large number of companies were given access to 5G technology in the various trial sites, so that innovative solutions using 5G could be tested in an application-oriented manner. Before TARGET-X, access to 5G technology that was limited to a few large enterprises, meaning that small and medium-sized enterprises in particular were often excluded from its use and application-oriented testing. The funding of the FSTP projects enabled many SMEs to engage with the technology, conducting application-oriented research and generating valuable insights. The close cooperation between the members of the TARGET-X consortium and the funded companies significantly expanded the existing 5G ecosystem, enabling partnerships to be developed for future collaborations. For the organizations of the TARGET-X consortium, this has not only resulted in valuable contacts and relationships for initiating further research activities, but also new perspectives regarding the potential benefits of 5G in the various verticals.

Methodological Assessment Framework (MAF), which utilizes User-KPI and User-KVI to capture the value proposition achieved through the implementation of use cases in the individual verticals of TARGET X. Across all use cases, 5G improved process capability, stability, and reproducibility, which are key prerequisites for industrial adoption. The increased capability was verified by real process data within the project, demonstrating 5G's potential to provide tangible value propositions in the different verticals. The MAF has also been transferred into a web-based assessment tool.

Technical impulses: TARGET-X is offering a wide variety of testbeds across four key sectors: energy, manufacturing, construction, and automotive. The project leverages both Non-Standalone (NSA) and Standalone (SA) networks, incorporating a blend of established and novel features deemed crucial for implementing and evaluating use cases. It facilitates use case implementations on both public and private networks, mirroring the diverse implementation options available to these sectors. Through these initiatives, TARGET-X demonstrates its commitment to enhancing technological capabilities across multiple industries, facilitating innovation, and enabling the efficient deployment of advanced network solutions. The project is forging pathways for future advancements and fostering collaboration between network technologies and industrial processes to drive progress in the evolution towards beyond 5G and 6G.

14 References

[TAR23-D11]	TARGET-X, Deliverable 1.1 "Forward looking use cases, their requirements and KPIs/KVIs", December 2023
[TAR24-D12]	TARGET-X, Deliverable 1.2 "Forward looking use cases, their requirements and KPIs/KVIs", December 2024
[TAR23-D21]	TARGET-X, Deliverable 2.1 "Report on system design options and 5G/6G setup for tracking, monitoring, and inline quality assurance in manufacturing", December 2023
[TAR23-D22]	TARGET-X, Deliverable 2.2 "Report on system design options and 5G/6G setup for edge robotics", December 2023
[TAR24-D23]	TARGET-X, Deliverable 2.3 "Report on implementation of the wireless edge control robotics use-case", October 2024
[TAR24-D24]	TARGET-X, Deliverable 2.4 ": Report on implementation of options for the tracking and inline quality assurance system", October 2024
[TAR25-D25]	TARGET-X, Deliverable 2.5: "Report on working demonstrators and validation implemented for 5G/6G technologies in manufacturing", August 2025
[TAR23-D31]	TARGET-X, Deliverable 3.1 "Pilot implementation plan", May 2023
[TAR23-D32]	TARGET-X, Deliverable 3.2 "Energy data and automation architecture report (Draft)", December 2023
[TAR23-D41]	TARGET-X, Deliverable 4.1 "Integrated pilot setup", September 2023
[TAR23-D42]	TARGET-X, Deliverable 4.2 "Automotive toolset and service implementation", December 2024
[TAR25-D43]	TARGET-X, Deliverable 4.3 "Enhancement of automotive use cases with 5G and beyond", March 2025
[TAR25-D44]	TARGET-X, Deliverable 4.4 "Integration and validation outcomes", September 2025
[CAMARA]	CAMARA project, https://camaraproject.org/ [last visited17.09.2025]
[5GAA]	5GAA Automotive Association, "5G TDD synchronisation, guidelines and recommendations for the coexistence of TDD networks in the 3.5 GHz range."
[TAR23-D51]	TARGET-X, Deliverable 5.1 "Roadmap for the 5G/6G empowered deconstruction robotic platform", June 2023
[TAR23-D61]	TARGET-X, Deliverable 6.1 "Description of the testbed capabilities and envisioned evolution within the project", April 2023

[TAR23-D62]	TARGET-X, Deliverable 6.2 "Report on the deployment and testing of evolved features", March 2024
[TAR23-D63]	TARGET-X, Deliverable 6.3 "Design and implementation of required submodels, exposures and interfaces", December 2023
[TAR24-D64]	TARGET-X, Deliverable 6.4 "Development of AAS instances and realizing the network / asset orchestration", December 2024
[TAR25-D65]	TARGET-X, Deliverable 6.5 "FINAL REPORT ON APPLIED BEYOND 5G TECHNOLOGIES", October 2025
[6GIA22]	6G Infrastructure Association, "What societal values will 6G address? Societal Key Values and Key Value Indicators analysed through 6G use cases, May 2022
[TAR23-D84]	TARGET-X, Deliverable 8.4 "COMMUNITY SETUP", June 2023
[TAR23-D71]	TARGET-X, Deliverable 7.1 "1st CALL ANNOUNCEMENT AND GUIDE FOR APPLICANTS DELIVERABLE", May 2023
[TAR23-D91]	TARGET-X, Deliverable D9.1 "Project Website", January 2023
[TAR23-D92]	TARGET-X, Deliverable D9.2 "First intermediate project report", December 2023
[TAR23-D95]	TARGET-X, Deliverable D9.5 "Data management plan", June 2023
[TAR25-TrB]	TARGET-X, TARGET-X Trials Brochure, September 2025, https://doi.org/10.5281/zenodo.17175347
[TAR25-D36]	TARGET-X, Deliverable D3.6 "ENERGY PILOT ANALYSIS", September 2025
[TAR24-D52]	TARGET-X, Deliverable D5.2 "Prototype system for controlled deconstruction process"
[TAR25-D53]	TARGET-X, Deliverable D5.3 "Report on living labs and task assessment"
[TAR-LI]	TARGET-X LinkedIn Channel, https://www.linkedin.com/showcase/target-x/ [last visited: 30.10.2025]
[5GAC25]	5G Alliance for Connected Industries and Automation (5G-ACIA), "Business Value and Return-on-Invest Calculation for Industrial 5G Use Cases", Whitepaper, August 2025 (available online: https://5g-acia.org/whitepapers/business-value-and-return-on-invest-calculation-for-industrial-5g-use-cases/)
[BGBAU-25]	Berufsgenossenschaft der Bauwirtschaft – "Weniger Arbeitsunfälle, mehr Berufskrankheiten" (available online: https://www.bgbau.de/meldung/bg-bau-weniger-arbeitsunfaelle-mehr-berufskrankheiten)

[DGUV-25]	Deutsche Gesetzliche Unfallversicherung – „Unfallrisiko bei der Arbeit 2024 erneut zurückgegangen" (available online: https://www.dguv.de/de/mediencenter/pm/bilanz-2024.jsp)
[EC25]	European Commission (2024). Road safety thematic report – Main factors causing fatal crashes. European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport. (available online: a7428369-8eaf-4032-806e-ea08b46028c0_en)
[NIST12]	National Institute of Standards and Technology, "NIST SP 800-30 Rev. 1 Guide for conducting risk assessments," Gaithersburg, MD, 2012
[KAL+25]	Kehl PE, Ansari J, Lovrin M, Mohanram P, Liu C-C, Yeh J-L, Schmitt RH. 5G-TSN Integrated Prototype for Reliable Industrial Communication Using Frame Replication and Elimination for Reliability. Electronics. 2025; 14(4):758. https://doi.org/10.3390/electronics14040758
[BAO+25]	Biosca Caro J, Ansari J, Olsson B-E, Beckmann N, König N, Schmitt RH, Popp F, Scheike-Momberg D. Empirical Performance Evaluation of 5G Millimeter Wave System for Industrial-Use Cases in Real Production Environment. Electronics. 2025; 14(3):607. https://doi.org/10.3390/electronics14030607
[AKS25]	J. Ansari, P. Kehl and R. Schmitt, "Reliability enhancements for mmW communication using IEEE 802.1CB," In Proc. of 29th *ITG-Fachtagung Mobilkommunikation,* Osnabrück, 2025.
[3GP-TS23401]	"TS 23.401: General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access." Available: https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=849.
[3GP-TS23402]	"TS 23.402: Architecture enhancements for non-3GPP accesses." Available: https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=850.
[3GP-TS38101]	"TS 38.101: NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone" Available: https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=3284
[3GP-TS38104]	"TS 38.104: NR; Base Station (BS) radio transmission and reception" Available: https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=3202
[ERI-R1900]	"Ericsson Cradlepoint R1900," Ericsson. Available: https://cradlepoint.com/product/endpoints/r1900-series/. [Accessed: Sep. 11, 2025]

[KIR24-LOOSE]	“Loosely coupled observation processing and data exchange system for complex teams of on-site construction robots”, Kirner, Oraskari, Zöcklein, Kamp, Claßen, Brell-Cokcan, 2024
[KIR24-ANONT]	Kirner er al., "An ontology for signal strength estimation of nomadic 5G networks on construction sites", 2024, DOI 10.35490/EC3.2024.202.
[WU24-UNIFI]	Unified framework for mixed-reality assisted situational adaptive robotic path planning enabled by 5G networks for deconstruction tasks, C.H. Wu, M. Zöcklein, S. Brell-Cokcan, 2024, DOI: 10.22260/ISARC2024/0022
[WU25-5GENA]	5G-Enabled Augmented Reality for Dynamic Interaction with Linked Building Data and Voxelised Spaces, Chu Han Wu and Sigrid Brell-Cokcan, 2025, DOI: 10.18154/RWTH-2025-06783

Annex 1 Publications

Publications

No.	Title	Persistent identifier / available at:
1	A New Formulation of Dynamic-Phasor-Based State Estimation With Inclusion of an Equality Constraint	10.1109/TIM.2024.3398107
2	Adaptive Control Strategies for Networked Systems: A Reinforcement Learning-Based Approach	10.3390/electronics14071312
3	Empirical Performance Evaluation of 5G Millimeter Wave System for Industrial-Use Cases in Real Production Environment	10.3390/electronics14030607
4	STRAUSS: Scalable intent-driven industrial network service quality assurance with asset administration shells	10.52953/RYYS9175
5	The Application of 5G Networks on Construction Sites and in Underground Mines: Successful Outcomes from Field Trials - Extended Version	10.1016/j.comcom.2025.108175
6	Towards Human-machine Collaboration in Autonomous Material Handling on Construction Sites	10.30658/hmc.9.11
7	VILLASnode: An Open-Source Real-time Multi-protocol Gateway	10.21105/joss.08401
8	5G-Enabled Augmented Reality for Dynamic Interaction with Linked Building Data and Voxelised Spaces	10.18154/RWTH-2025-06783
9	A Low Cost Phase Estimation Device for PMU Phase Validation	10.1109/PEDG61800.2024.10667414
10	An Ontology for Signal Strength Estimation of Nomadic 5G Networks on Construction Sites	10.35490/EC3.2024.202
11	Automated Deployment of Single-Board Computer Based Grid Measurement and Co-Simulation Equipment	10.1109/OSMSES62085.2024.10668996

12	Design and Implementation of 5G Asset Administration Shells: Bridging Networks and Industry 4.0	10.1109/ETFA65518.2025.11205619
13	Embodied AI Agent Framework for (Re)Programming Robotic Tasks in Flexible Assembly using LLMs and VLMs	PROCIR-D-25-01008
14	Enabling Circular Construction: Evaluating ICDD for Effective Deconstruction Processes	10.15480/882.13525
15	Enhancing Energy Monitoring in Construction and Robotics with Plug-and-Play Solution Meter-X	10.35490/EC3.2025.386
16	Future Directions on Enhanced Positioning Services with Predictions for Smart Factories	10.23919/CNSM62983.2024.10814496
17	Loosely coupled observation processing and data exchange system for complex teams of on-site construction robots	https://robarch2024.org/
18	On the TSN and 5G network integration approaches, 5G features proof, advantages and challenges	10.1109/EuCNC/6GSummit60053.2024.10597062
19	Reducing travel times of Tele-Operated vehicles through Connected Road Maps	-
20	Remote Monitoring and Control of Distributed Energy Resources via 5G	10.1109/GPECOM65896.2025.11061986
21	The Application of 5G Networks on Construction Sites and in Underground Mines: Successful Outcomes from Field Trials	10.23919/WONS60642.2024.10449502
22	Towards Automatic Semantic Capability-Matching for On-site Construction Machinery	https://3dgeoinfoeg-ice.webs.uvigo.es/proceedings
23	Unified framework for mixed-reality assisted situational adaptive robotic path planning enabled by 5G networks for deconstruction tasks	10.22260/ISARC2024/0022
24	Video Quality Monitoring for Remote Autonomous Vehicle Control	10.48550/arXiv.2506.03166
25	Low Cost Analog Input Stage for PMU Applications in the Low Voltage Grid	Not yet available

26	Development and Application of a Vertical-Agnostic Methodological Assessment Framework for Evaluation of 5G-Based Use Cases	Not yet available
27	5G-ACIA Whitepaper: "Business Value and Return-on-Invest Calculation for Industrial 5G Use Cases"	https://5g-acia.org/whitepapers/business-value-and-return-on-invest-calculation-for-industrial-5g-use-cases/
28	TARGET-X Trials Brochure	10.5281/zenodo.17175347
29	5G-TSN Integrated Prototype for Reliable Industrial Communication Using Frame Replication and Elimination for Reliability	10.3390/electronics14040758