6G SNS IA

The Voice of European Industry and Research for Next Generation Networks and Services

Large-Scale Trials in SNS JU Projects

Technical Insights

White paper

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Trials Working Group

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Executive Summary

This White Paper is produced by the 6G Infrastructure Association (6G-IA) Working Group on Trials, one of the technical working groups operating under the 6G-IA umbrella. It consolidates the technical insights, measurement methodologies and lessons learned from 27 large-scale trials and pilots conducted across projects selected under the Smart Networks and Services Joint Undertaking (SNS JU), co-funded by the European Commission under Horizon Europe. Industry, research institutions, universities and operators across ten European countries contributed to trial design, testbed operation, measurement methodology and vertical application development.

The 6G-IA has a central role in ensuring that the research and validation activities carried out by its member organisations collectively advance Europe's technological sovereignty in communications infrastructure. The Working Group on Trials was established precisely to provide this coordination layer: to aggregate learnings across projects, identify convergent patterns, and translate fragmented experimental evidence into actionable insights for the broader 6G-IA research community and for European policy.

The added value of organising these activities under the 6G-IA Working Group structure is threefold. First, the Working Group provides a neutral coordination forum where member organisations from different projects share technical findings that would otherwise remain fragmented within individual consortia. Second, it enables the kind of cross-project analysis presented in this document, identifying patterns, such as the independent convergence on the same 5G technology stack across uncoordinated projects, that no individual project team could observe from within its own boundary. Third, it creates a direct channel from experimental evidence to 6G-IA strategic positions.

White Paper: Technical Insights from Large-Scale Trials under SNS projects.

1. INTRODUCTION

The transition from 5G to 6G is not merely a generational technological upgrade—it represents a foundational shift in how networks will sense, compute, and communicate across physical and digital realms. In this transformation, Europe has positioned itself at the forefront through the Smart Networks and Services Joint Undertaking (SNS JU), which aligns research, innovation, and large-scale validation activities under a coherent strategic vision.

Within this initiative, the **HORIZON-JU-SNS-2022-STREAM-D-01-01** call focuses specifically on **Large-Scale Trials and Pilots (LST&Ps) with Verticals**. Its purpose is to validate advanced 5G and pre-6G technologies in real-world conditions, co-designed and co-executed with vertical industries such as manufacturing, health, mobility, public safety, and media. These trials are essential for understanding how technical innovations behave under real-world constraints and for collecting Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) that reflect both network capabilities and user-perceived value.

This white paper provides a **technical overview of the trials conducted by the projects selected under Stream D**, offering insights into the architectures, deployments, methodologies, and results obtained across a diverse range of use cases. Rather than organising by project, this paper is structured **by use case domain**, reflecting the multi-sectoral ambition of the SNS JU and highlighting the horizontal impact of network technologies.

Each section focuses on a particular vertical use case—such as immersive media, connected mobility, smart manufacturing, or eHealth—and includes detailed descriptions of the trial scenarios, platforms used, KPIs measured, and technical outcomes. By organising the content in this way, we emphasise the **cross-cutting capabilities of the technologies**, the **adaptability of the infrastructures**, and the **lessons learned that inform the path toward 6G**

2. Use cases

2.1 PUBLIC SAFETY

2.1.1 5G for Public Protection and Disaster Relief (PPDR)

Trial Title: 5G for Public Protection and Disaster Relief (PPDR)
Project Acronym: FIDAL
Project Full Name: Field Trials Beyond 5G
Contact Person: Almudena Diaz Zayas (adz@uma.es)
Project Website: https://fidal-he.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 44
Geographical Location(s): Málaga, Spain
Supported testbed (s): Victoria Network (University of Malaga)

Trial Overview

The PPDR trials aim to demonstrate how 5G technology, specifically network slicing and Quality of Service (QoS) capabilities, can prioritise critical communications for emergency services during large-scale public events. The trial validates the reliability of mission-critical communications and real-time video transmission, even under severe mobile network congestion conditions.

Trial deployment including integration with vertical solutions

Telefónica's commercial 5G Standalone (SA) network with dedicated network slicing capabilities was used during the trial. The vertical domain systems (MCPTT applications, video streaming services, surveillance tools) are connected to the 5G SA network via specialised SIM cards. The PPDR slice is assigned at the SIM level, ensuring all traffic from emergency services devices is automatically prioritised. The QoD service is integrated through OpenGateway Mobile APIs, enabling the command-and-control center to dynamically request different 5QIs for specific SIM cards based on operational needs. Airbus provides the MCPTT and Mission Critical Video applications. At the same time, Onesource's Mobitrust solution aggregates data from multiple sources (wearables, drones, fixed cameras) and delivers it to the CCC through the prioritised network slice.

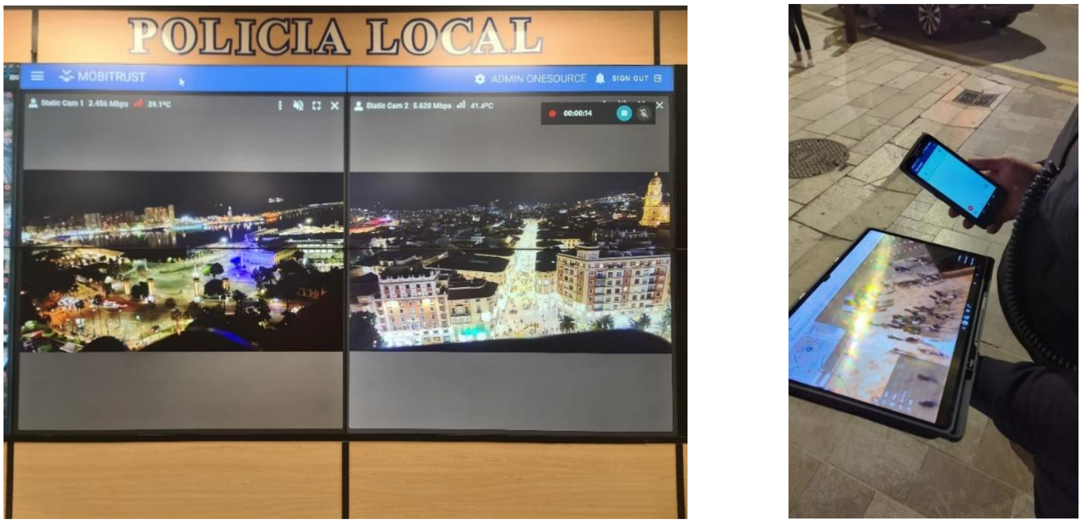


Figure 1. 5G UEs, MCPPT application, live video streaming

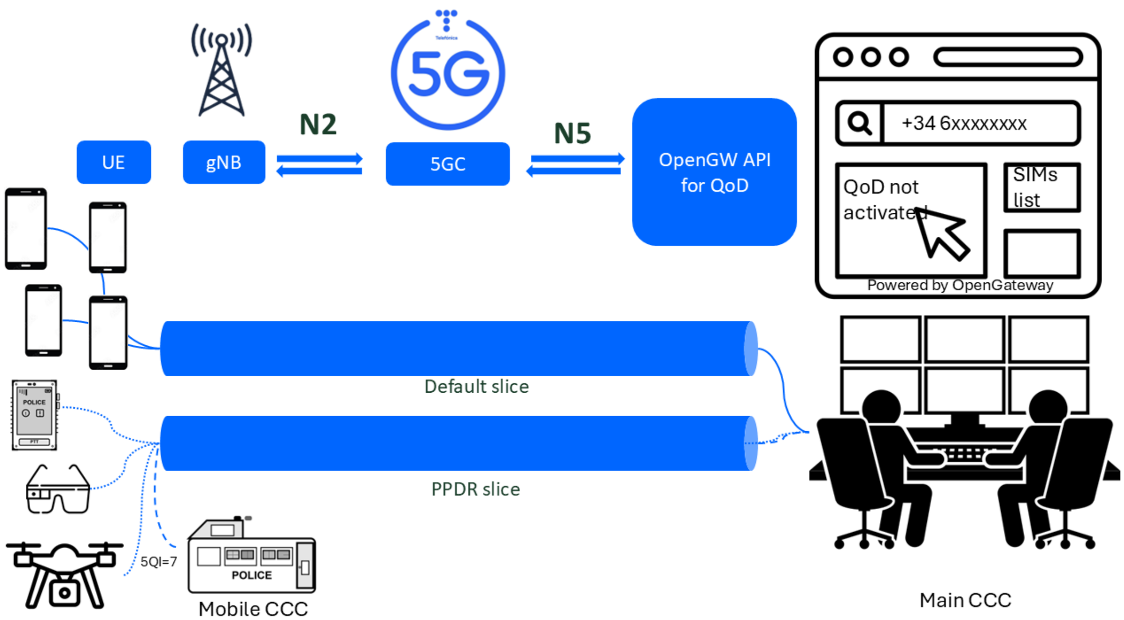


Figure 2. End-to-end trial architecture

Key 5G Technologies Used:

- 5G Standalone (SA) Network,
- Network Slicing (one default slice
- + one prioritized PPDR slice),
- Quality on Demand (QoD) / Dynamic QoS (based on 5G Quality Indicators(5QI) configuration),
- OpenGateway APIs (GSMA initiative),

KPIs and KVIs

- **Technical KPIs:**
    - MCPTT access time
    - MCPTT access time end-to-end
    - Video Quality: Resolution and video bit rate
    - QoS Levels: Performance across different 5QI configurations
    - Network Slice Isolation: Verification of priority traffic separation from default slice
    - Radio quality and signal parameters: SS-RSRP, SS-RSRQ, SS-CINR, and RSSI
    - MAC/RLC/PDCP KPIs: Metrics at the MAC, RLC, and PDCP layers are gathered

- **Vertical KVIs:**
    - Operational Efficiency: Improvement in police response coordination during events
    - Public Safety Enhancement: Better surveillance coverage and incident detection
    - Communication Reliability: Percentage of time critical communications are maintained during congestion
    - Situational Awareness: Quality and timeliness of information delivery to the command centre
    - User Satisfaction: Feedback from police officers on system usability and reliability

- **Measurement Methodology:**

Network KPIs were measured through the Nemo Handy measurement tool, including 5QI and slicing ID. The MCPTT and video services under test were instrumentalised to report application performance metrics. Application metrics have been integrated into the FIDAL Monitoring Analytics and are visualised in real time during the trials (see Figure 3). KVIs were collected through operational feedback from Málaga Local Police via questionnaires and post-event debriefings with field officers.

Lessons learned

Technical insights: Network slicing on commercial networks requires careful coordination between network operators and service providers. Dynamic QoS via OpenGateway APIs offers significant flexibility but requires well-defined policies for automatic or manual activation.

Operational insights: Police officers appreciated the reliability of communications during congested events, but emphasised the importance of simple, intuitive interfaces for field use. The command-and-control centre benefited significantly from aggregated video feeds, improving situational awareness. Training and familiarisation with technology proved essential for effective deployment.

Measurement insights: It is very difficult to measure the impact of slicing in a public network. Drive test tools such as NEMO are needed to force the connectivity in the 5G mobile devices to the 5G SA network and also force the connectivity of the UE to a specific cell. Network congestion must be avoided even when extra terminals generate traffic and are connected to the same cell.

Contribution to Standards / Open Source:

- Validation of GSMA OpenGateway initiative APIs in real-world public safety scenarios
- Input for future enhancements of network slicing for PPDR use cases
- Feedback to the OpenGateway community on QoD API usage

References

Related Publications:

- https://fidal-he.eu/sites/default/files/publication/file/2024-06/Demonstration%20of%20slicing%20for%20PPDR%20communications.pdf

Related Deliverables:

- https://fidal-he.eu/sites/default/files/pd/file/2023-07/D2.1_FIDAL.pdf
- https://fidal-he.eu/sites/default/files/use-case/factsheet-pdf/2025-05/FIDAL%20UCs%20-%20FACTSHEET_A5_0.pdf

Links to Videos / Demos:

- https://youtu.be/9vL4Ka3kWvc

2.1.2 AI/ML-based preventive and reactive emergency handling toolset and dataset for mission-critical services

Trial Title: AI-PREMSET-MCX – TrialsNet
Project Acronym: AI-PREMSET-MCX
Project Full Name: AI/ML-based preventive and reactive emergency handling toolset and dataset for mission-critical services
Contact Person: Adrian Santiago (adrian.santiago@nemergent-solutions.com), Eneko Atxutegi (eneko.atxutegi@nemergent-solutions.com)
Project Website: https://trialsnet.eu/subprojects/Sub-Project-5/
Funding Programme: “TrialsNet: TRials supported by Smart Networks beyond 5G - Horizon-JU-SNS-2022 Research and Innovation Programme under Grant Agreement No. 101095871”
Main Vertical(s) Addressed: Infrastructure, Transportation, Security & Safety (ITTS)
Replicability: 57
Geographical Location(s): Iași, Romania (Stefan cel Mare pedestrian alley urban area)
Supported testbed (s): Iași and Bucharest Orange Romania 5G SA/NSA networks – TrialsNet

Trial Overview

The AI-PREMSET-MCX trial set out to validate a 3GPP-compliant MCX solution running over experimental and commercial 5G infrastructures in Romania. The main goal was to assess how well mission-critical group communications perform under realistic emergency scenarios, using both private 5G SA and commercial 5G NSA networks. The trial also aimed to test hybrid network operations (private/public), gather detailed service and network metrics, and build datasets to support AI/ML-based optimization of MCX deployments, while enhancing MCX services with monitoring and adaptive configurations features. A final objective was to involve real first responders and assess how they perceive the usefulness and usability of the solution, and how the trials should be adapted to real operation conditions.The trial was carried out in an urban pedestrian area, combining dense buildings, high pedestrian density, and multiple intersecting streets nearby, where several emergency scenarios were staged (urban fire, severe weather event, building collapse and medical emergency outbreak), with end-users moving along predefined paths while using MCX services, so that coverage, mobility, and group coordination could all be assessed under controlled but realistic conditions. Real first responders were involved in the trial, and tests were conducted in collaboration with TUIASI students, increasing the number of active users, while commercial users were in the area, connected to the 5G NSA commercial network. All use-cases relied on MCPTT group calls (including supergroups/regrouping) over hybrid 5G networks, with scripted movements and actions for each user group.

Figure 3: AI-PREMSET-MCX TrialsNet trial execution and captures of operation and training

Trial deployment including integration with vertical solutions

The MCX system was deployed end-to-end over the Romanian TrialsNet site hosted on the ORO 5G platform. On the client side, rugged and commercial 5G devices acted as MCX UEs, connecting either to a private 5G SA network or to a commercial 5G NSA (4G/5G) network. On the server side, a dedicated AI/ML-capable cloud server located in Nemergent Solutions' premises, was integrated with the ORO lab, hosting a Kubernetes cluster where MCX microservices were deployed. Additional Kubernetes worker capacity was provided from ORO premises to support cloud–edge deployments. A data collection and analytics stack sat alongside the MCX services, ingesting metrics from the MCX applications, infrastructure and RAN/5GCore exporters. In addition to RAN networks, additional MCX UEs were connected also over Wi-Fi networks, to analyze multi-technology deployments and their feasibility and potential benefits for MCX operations.

The MCX platform configuration and trial execution plan was adapted to the operational workflows of public protection and disaster relief (PPDR) users with the collaboration of EENA, in particular first responders from Serviciul de Telecomunicații Speciale (STS). Trial scripts and procedures were prepared together with end-users so that the system behavior followed realistic emergency operations.

The trial was conducted over TrialsNet's site in Iași, combining both private and commercial infrastructures. The RAN and 5G Core were provided and managed by ORO. Additional pre-trial and hybrid environment validations were performed over Wi-Fi in Erandio (Nemergent Solutions headquarters) and Bucharest (ORO 5G Lab), and over LTE/5G-NSA/5G in ORO's Laboratory, Campus and Commercial networks in Bucharest. The same MCX cloud-native deployment was reused across these environments, with Kubernetes clusters and monitoring components acting as the common backbone.

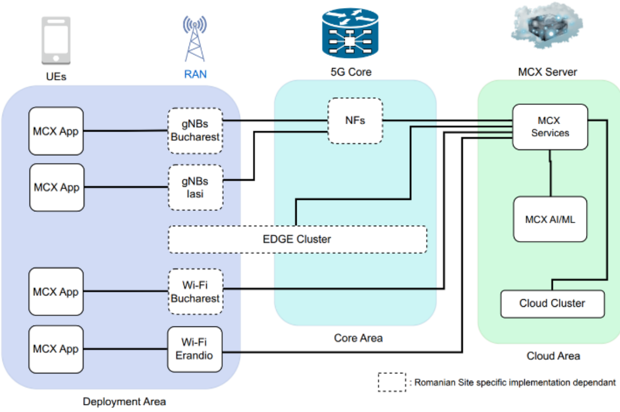


Figure 4: AI-PREMSET-MCX infrastructure diagram

Key Technologies Used:

- 5G SA and 5G NSA, LTE/4G
- 3GPP-compliant MCX (MCPTT, MCData) and IMS/SIP,
- microservice-based architecture: Kubernetes, container registries
- Monitoring stack: Prometheus, PostgreSQL, InfluxDB, Kafka, Parquet, Grafana
- AI/ML: TensorFlow/scikit-learn for model training/inference over collected datasets.

KPIs and KVIs

- **Technical KPIs:**

For the **TrialsNet KPIs**, we considered: Downlink throughput per device, Uplink throughput per device, Application round-trip latency, and Service availability. For the **MCX-specific KPIs**: End-to-end Latency, DL/UL data rate (peak and aggregate), End-to-end Communication Service Availability, MCX Access Time (3GPP TS 22.179), MCX End-to-end Access Time (3GPP TS 22.179), MCX Mouth-to-ear Delay (3GPP TS 22.179), Active MCX users, Active MCX private calls: number of concurrent private calls, and Active MCX group calls. For the **AI/ML-specific KPIs**, considering that the final models were regression-oriented: AI/ML accuracy (proportion of predictions whose error falls within a predefined tolerance threshold), and Average error magnitude (measured using standard regression metrics such as MSE or MAE, to characterize the typical size of prediction errors).

- **Vertical KVIs:**

From an **economic** perspective, TrialsNet participation had a clear impact on innovation and market reach, being invited to join new project proposals and being the solution considered relevant for solving existing and emerging problems and improving market access. On the **environmental** side, device reuse played a central role, giving a reuse ratio of 2:1, supporting both waste reduction and increased lifespan of products, having been assessed in the user survey and maintaining compliance with ISO 14001. From a **societal** perspective, the trial contributed to skills and knowledge development, as well as to perceived safety and usability. The **flexibility** of the solution is also reflected in the way resources can be allocated, mitigating over- or under-provisioning and improving performance during critical operations. **Transparency** and **data accessibility** were addressed by making all datasets available on *Zenodo*, ensuring that the collected data can be reused for research and audit purposes. Finally, **data protection** was handled in line with GDPR.

- **Measurement Methodology:**

Technical KPIs were obtained from the MCX system itself and from the surrounding infrastructure. MCX applications and servers exported detailed metrics, ingested by a central Data Collector and stored in PostgreSQL, InfluxDB, Kafka and Parquet files for later analysis. RAN and 5G Core data were also included when available via dedicated exporters. Vertical KVIs were collected through structured questionnaires filled in by all participants after the trial, covering usability, perceived safety, operational value, and overall satisfaction.

Lessons learned

The trial successfully demonstrated that a 3GPP-compliant MCX system can operate over a hybrid 5G environment combining private 5G SA and commercial 5G NSA networks. In areas with sufficient coverage, the system met its target KPIs for latency, reliability, and group communication performance, especially after optimizing user group placement and scaling Kubernetes-based service components.

The most critical factor observed during the trial was radio coverage. Even with a robust core and scalable microservice architecture, weak or uneven coverage had a clear impact on mission-critical performance. This underlines the importance of careful RAN planning and, where possible, pre-emptive measures to secure sufficient radio conditions in key operational areas. The pre-trial and trial also showed the value of close collaboration with organizations involved in the development of emergency communications, such as EENA, and with first responders: early involvement of STS, Orange Romania and TUIASI, helped refine scenarios, scripts and procedures, and their feedback directly improved the execution. On the technical side, the microservice and Kubernetes-based design proved well suited to reacting to changing conditions, for example by scaling MCX servers and shifting workloads to different nodes when needed. Finally, the experience highlighted the need to plan device and SIM availability early on to reach the desired scale.

Contribution to Standards / Open Source:

The trial produced curated datasets combining MCX service metrics, infrastructure data and, when available, RAN/5GC information, which address a gap in current research on MCX over 5G. These datasets, together with the architectural insights from the Romanian site, are being used within AI-PREMSET-MCX/TrialsNet to inform future work on MCX systems and AI/ML-based optimization of mission-critical communications. At this stage, there are no formal public contributions to standardization bodies or scientific journals, but the datasets are open-source and published in Zenodo repositories, including both pre-trial and trial stages.

References

Related Publications:

- *Santiago Santo-Tomas, A. (2025). AI-PREMSET-MCX-Simulations-and-Trial-Results (v1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15299734*

2.1.3 Ubiquitous B5G/6G communication and slice deployment across operators for PPDR AR/VR-assisted control centres

Trial Title: Ubiquitous B5G/6G communication and slice deployment across operators for PPDR AR/VR-assisted control centres
Project Acronym: AMAZING-6G
Project Full Name: Amazing Large-Scale Trials and Pilots for Verticals in 6G
Contact Person: Andreas Georgakopoulos (andgeorg@wings-ict-solutions.eu)
Project Website: https://amazing6g.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2024-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 53
Geographical Location(s): Greece (Patras and Athens)
Supported testbed (s): Patras 5G testbed, WINGS private testbed, OQTec NTN aspects

Trial Overview

The objective of the trial is two-fold with innovations at the network and the application integration layer. At the network layer, we need to ensure ubiquitous connectivity for the PPDR emergency teams, over multiple private B5G/6G networks and public ones. The end-to-end quality of service requirements for the PPDR slice will be defined, and the required reliable mechanisms will be investigated. This Use Case will also demonstrate fast private B5G/6G network set-up, addressing areas where B5G/6G coverage is poor or nonexistent. At the application layer, PPDR campaigns rely on various applications as shown in Figure that follows. In order to demonstrate an autonomous operation at the edge of the network, this use case will showcase situation monitoring, including the ground assets, through Unmanned Vehicles (UMV), closed loop control and collaboration among robots, it will execute prediction models for the situation propagation, while AR/VR will enhance PPDR awareness.

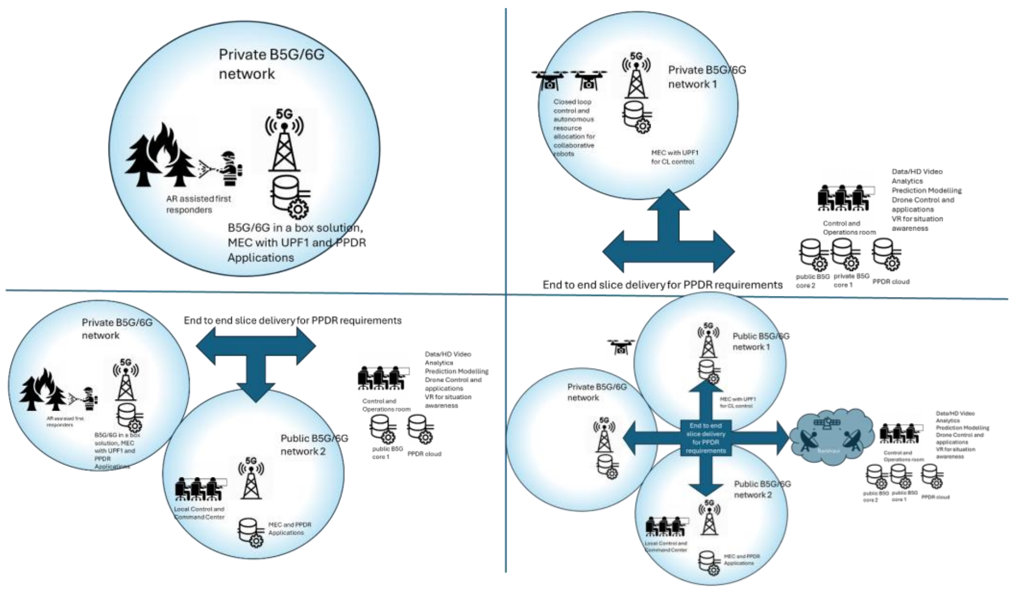


Figure 5 Ubiquitous B5G/6G communication and slice deployment across operators for PPDR AR/VR assisted control centres

Trial deployment including integration with vertical solutions

The WINGS testbed provides E2E 5G/B5G functionality, along with extensive cloud and edge computing capabilities, leveraging the 3GPP (Release-16 and beyond) Public Network Integrated Non Public Network (PNI-NPN) with shared CP (at a first phase) and isolated, Stand-alone Non-Public Network (SNPN), with all NFs (UP and CP) inside WINGS premises, isolated from the public network in the final phase. The site offers a range of 5G/B5G services and will be gradually evolved to 6G. It supports various vertical domains, with WINGS providing the necessary HW, software, and configurations to enable the testbed to handle diverse use cases. WINGS testbed serves as a testing ground for services, equipment, and new features before they are commercially released. WINGS has progressively extended the existing software, HW, and network functionality to support Cloud, Mobile Edge Computing (MEC), Extreme Edge and IoT functionalities. WINGS has demonstrated advanced use cases on digital twins, Collaborative Robots with native-AI B5G/6G capabilities of the system. Also, the required frameworks to build, test, and validate innovative 6G applications are part of the overall infrastructure.

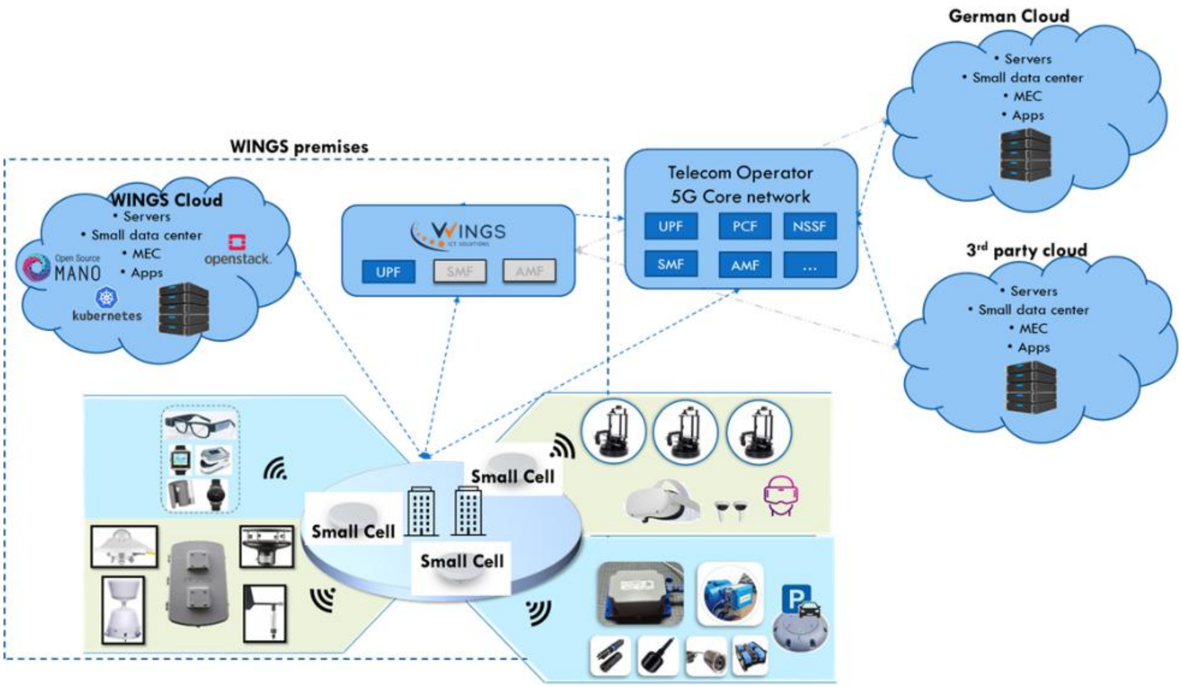


Figure 6 WINGS testbed architecture for experiments

The Patras 5G Facility provides a private 5G network, acting as a playground for deploying 5G test cases and testing applications. Operating under the Network Slice as a Service (NSaaS) model, the facility offers customized network slices tailored to the needs of different verticals, such as PPDR and MEDIA domains. Each vertical utilizes these slices to conduct trials for a range of use cases, assessing and documenting KPIs under diverse network conditions. The Patras5G testbed includes three main site deployments, offering services within the department building and the University of Patras campus. These deployments consist of two indoor and one hybrid (indoor/outdoor) sites, ensuring comprehensive coverage and accessibility to external users. Most of the installed components are offered as Open Source but there are also dedicated components and services to support 5G and IoT scenarios. Numerous partners have deployed their technologies in the Patras 5G /Greece facility, thus creating a unique 5G playground for KPI validation and support on future verticals.

Key 5G Technologies Used:

- **Private 5G/6G network with PPDR services/applications**

In order to demonstrate autonomous operation at the edge of the network, this PPDR Use Case will showcase the following indicative services:

- Push-to-Talk (PTT) and Mission-Critical (MCx) PTT (MC-PPT): instant voice communication with group calls, priority handling, and low latency; essential for PPDR field coordination (including but not limited to point to point, multicast, etc.);
- Video Streaming: live video streaming from body cameras, drones or vehicles to Control Centers; critical for situational awareness, with optional stream selection;
- Group messaging and data exchange: secure, group-based messaging with voice, text, image, and video capabilities for team collaboration;
- Geolocation and asset tracking;
- AR/VR optimized service;
- Emergency Alert Broadcast System (public warning system);
- Orchestration: on demand 5G/6G network set up to provide guaranteed resources depending on requirements and reconfiguration needs for network slices.

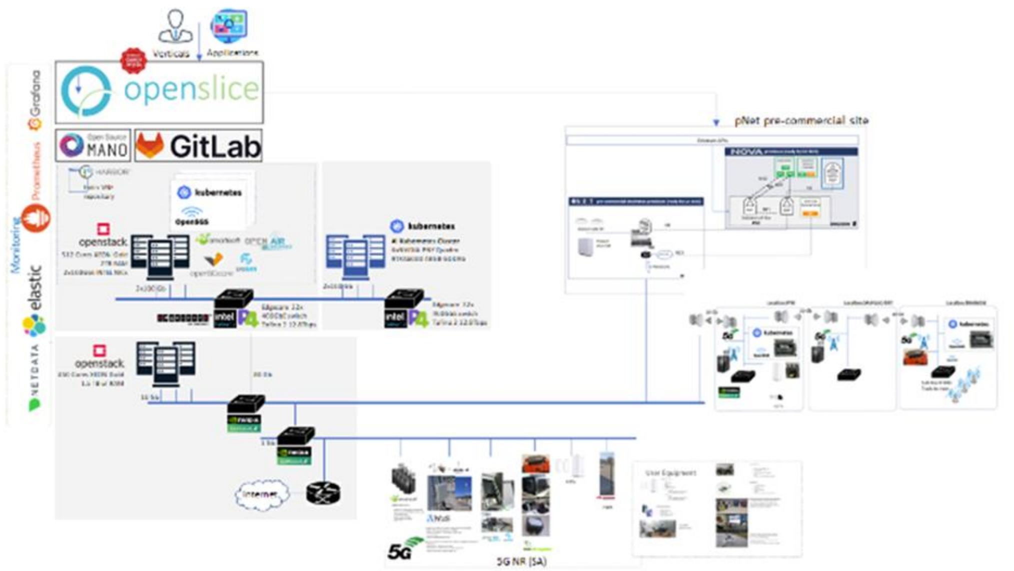


Figure 7 The Patras 5G facility is an "isolated" Non-public Network for 5G and IoT applications.

- **Private network connected with central Control Center**

PPDR slice set-up between the (remote) emergency site and the Central Control Centre. Mechanism for surveying backhaul availability is developed and deployed.

- **End-to-end slice delivery for PPDR requirements**

- **Slice deployment over multiple private and public B5G/6G networks**

PPDR network slice deployment with high priority and increased quality. Main challenges will be the orchestration of the network resources on demand, and the interconnection of B5G/6G core networks, as well as the effect of a fully disaggregated B5G/6G architecture on the overall delay and on XR-assisted PPDR campaigns.

KPIs and KVIs

- **Technical KPIs:**
    - Reliability
    - Peak data rate
    - End-to-end service/slice provisioning
    - End-to-end service latency

- **Vertical KVIs:**
    - Societal:
        - Increased societal impact (SDGs 3, 16) especially since ubiquitous, evidence-based, PPDR decision making is supported.
        - Improved well-being and safety through efficient emergency management for affected citizens through improved situational awareness of first responder and enhanced response times.
        - Reduced loss of lives of both victims and emergency responders through better coordination of emergency services by enhancing situational awareness and by enabling highly reliable and robust communications in spite of the disaster itself.
    - Economic:
        - Reduced loss of man-made structures (e.g., buildings) through better coordination of emergency services.
        - Better use of scarce specialised human resources (experts) and digital resources (prediction models, etc.) through effective remote cooperation using advanced networks and AR/VR/XR technologies
    - Environmental:
        - Reduced loss of nature through supporting coordination of emergency services.

Lessons learned

Technical and Operational insights:

- Ubiquitous Connectivity: As in the International Mobile Communication (IMT)-2030 Framewor, ubiquitous connectivity aims to bridge the digital divide by enhancing connectivity through interworking and convergence between networks and systems, ensuring broader access to communication services;
- Fast private network provisioning and end-to-end network slicing with stringent requirements for PPDR Use Cases, including various backhaul enabling communication technologies;
- End-to-end slice orchestration with-mission critical network services and PPDR applications (e.g., push-to-talk, video streaming, Virtual Reality (VR) or Augmented Reality (AR) enabling services, collaborative robots, and emergency alert broadcast).

Challenges:

- To investigate the orchestration of PPDR slices over various private and/or public networks for interconnecting people, equipment and PPDR applications;
- To ensure fast set-up of a high-speed, bi-directional connectivity between the emergency field and the CCC, including the necessary backhaul deployments;
- To provide set-up of a B5G/6G-enabled, multi-user, location-based, AR/VR experience e.g., for the CCC operators to fully immerse themselves in the emergency;
- To investigate the effect that a fully disaggregated B5G/6G architecture and the relative placement of B5G/6G functions, interfaces, MEC, and backhaul/fronthaul solutions may have on the overall delay;
- To include AI-enabled closed loop control of drones/robots and data acquisition, in PPDR situation analysis/prediction.

References

Related Deliverables:

- https://amazing6g.eu/wp-content/uploads/AMAZING-6G_D2.1_v1.0.pdf

2.1.4 Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe

Trial Title: 5G-Neptune. Open Call project by Hewlett Packard Enterprise.
Project Acronym: Imagine-B5G
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Contact Person: Faheem Awan (Faheem.awan@telenor.com), Nicola di Pietro (nicola.dipietro@hpe.com)
Project Website: https://imagineb5g.eu/
Funding Programme: HORIZON-JU-SNS-2022, STREAM-D-01-01: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals, Grant Agreement No: 101096452
Main Vertical(s) Addressed: PPDR, Media, Education, Smart Agriculture & Forestry, eHealth, Industry 4.0
Replicability: Not applicable
Geographical Location(s): Jaren, Norway
Supported testbed (s): Telenor’s B5G experimental platform/facility and Network-on-Wheels in collaboration with PPDR partner Norwegian Defence Material Agency (NDMA) and Norwegian Police IT department (PIT)

Trial Overview

The 5G-NEPTUNE (5G-and-beyond Network Extensions towards Public neTwork integrated non-pUblic NEtworks) trial demonstrated the integration of a central public 5G infrastructure with a mobile, private Network-on-Wheels (NoW) to support mission-critical communications in the Public Protection and Disaster Relief (PPDR) domain. Conducted at Telenor's site in Fornebu (central), Norway and at Police premises at Jaren, Norway (local), the trial extended the experimental platform with Public Network Integrated – Non-Public Network (PNI-NPN) capabilities and validated the deployment of Mission-Critical Services (MCX) in realistic operational scenarios. The NoW was deployed in the field and connected to the central public network, enabling seamless service continuity and prioritised communication for first responders. Two rounds of MCX experiments were carried out by PPDR stakeholders (Police IT department): the first over the standalone NoW and the second using the integrated PNI-NoW setup, with up to 100 smartphones in use. A key feature of the trial was the integration of the MCX application over the N5 interface, allowing network services to be dynamically exposed and configured to deliver the required Quality of Service (QoS) for mission-critical operations. This ensured that PPDR users received reliable, low-latency, and prioritised connectivity, even in challenging field conditions. The trial successfully validated the PNI-NoW architecture's potential to enhance PPDR communications through flexible, edge-enabled 5G deployments.

Figure 8: Testing about 55 UE's with MCX solution at Police premises in Jaren, Norway

Trial deployment including integration with vertical solutions

The architecture for connecting central PNI and local NoW consists of a Telenor's central site and the edge, NoW, interconnected by wireless backhauling. Both central and edge had 5GC NFs and RAN, with one 5G base station. The architecture mimics the operational framework of an MNO, with a central part of its infrastructure typically supporting public 5G services and a dedicated subset of resources deployed at the edge of the network to support private services. Smartphones were used for testing the MCX services applied. *Figure **9*** shows the end-to-end architecture.

The NoW's UPF is configured to give mobile users direct access to a local DN hosting the services and applications that run over the NoW's computing equipment (in particular, an MCX application that enables MCPTT and MC video). Note that the co-location in the NoW of a gNB and a UPF enables traffic localisation and edge computing when the destination is the local DN, which decreases communication latencies, reduces potential backhaul bottlenecks, and increases data privacy by shortening the path of transmitted packets. The central UPF, instead, connects the 5G system with a central DN, typically the Internet.

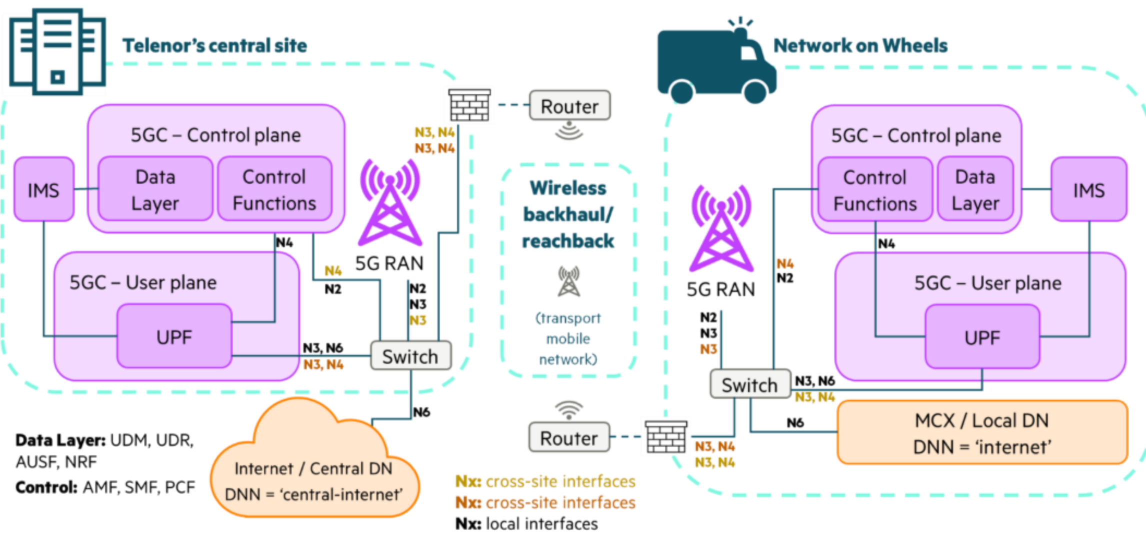


Figure 9: High-level architecture of the 5G-Neptune trial

Key 5G Technologies Used:

- 5GSA,
- PNI-NPN
- Private 5G edge
- Capability exposure (N5)
- Slicing capability

KPIs and KVIs

- **Technical KPIs, for vertical trials:**
    - Up to 55 users participated in MCPTT unicast sessions, exceeding the target of 10.

- Bit rate per user was 0.27 Mbps, slightly above the 0.15–0.2 Mbps target, with no performance issues.
- PTT access time was typically under 3 seconds (peak 6s), above the <1s target; performance remained acceptable.
- Downlink throughput on the central core was very high, nearing the 900 Mbps target.

- **Measurement Methodology:**

The 5G-NEPTUNE trial included four progressively complex, vertical-agnostic experimental network scenarios designed to fully exploit the capabilities of the deployed 5G system. To assess network access control via Data Network (DN) separation, two user profiles were defined and linked to provisioned SIM cards within the 5G core: a privileged profile for MCX users in PPDR use cases, and a general profile for standard users of the public infrastructure. While privileged users could access both central and local DNs, general users were restricted to the central DN regardless of their point of access. Across all scenarios, a total of 18 functional validation tests were conducted to verify the correct operation of the 5G infrastructure, all of which were successfully completed.

Lessons learned

- 5G-NEPTUNE validated a replicable PNI-NoW architecture—an autonomous, portable 5G and edge computing solution integrated with MNO infrastructure—supporting operations in areas without public coverage.
- The two-site setup enabled deployment of NPN slices within public networks, raising the solution's TRL from 6 to 7 and demonstrating commercial potential.
- MCX services were successfully deployed over the N5 interface, supporting up to 100 users with dynamic QoS control for mission-critical communications.
- HPE's 5GC APIs enabled real-time network reconfiguration, demonstrated via the provisiosync tool, supporting zero-touch network management.
- The solution improved coverage and edge access in PPDR contexts, with validation from real-life end users (NDMA, PIT).

References

Related Publications/Deliverables:

- Nicola di Pietro (HPE), et al, 2025, Deliverable D2, Final Report and Results 5G-NEPTUNE and PNI-NPN Experiments
- Torrelba, A., Lara, A. I. (eds), 2024, Deliverable D1.1, Use cases, Ecosystem Analysis and KVIs/KPIs for OC1 and OC2 (https://imagineb5g.eu/results/#deliverables)
- Boutiba, K (ed). 2025, D2.4, Imagine-B5G Final Integrated Platform (https://imagineb5g.eu/results/#deliverables)

Links to Videos / Demos:

- https://imagineb5g.eu/imagine-b5g-webinar-highlights-innovations-from-open-call-1/
- https://imagineb5g.eu/5g-neptune-in-imagine-b5g-open-call-1/
- https://www.linkedin.com/posts/imagine-b5g_norwegian-facility-open-call-1-of-imagine-b5g-activity-7310260926677450752-kpYU?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAGM-WkBfsT3IyTY84bBVECp2kVnGHKwq_I

2.1.5 Leveraging 5G and USVs for Enhanced Maritime Port Surveillance and Safety

Trial Title: Leveraging 5G and USVs for Enhanced Maritime Port Surveillance and Safety
Project Acronym: IMAGINE-B5G
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Contact Person: David Gomez-Barquero (dabogar@iteam.upv.es)
Project Website: **https://imagineb5g.eu/**
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 44
Geographical Location(s): Valencia, Spain
Supported testbed (s): Port of Valencia, Spain

Trial Overview

RESCUE-5G validates the use of an Unmanned Surface Vehicle (USV) connected over a private 5G network to support critical surveillance, search-and-rescue (SAR) and inspection operations in a real maritime port. The trial demonstrates real-time Full HD video streaming from the USV over 5G, AI-based video and sonar analytics at the edge, and an immersive Decision Support System (DSS) for port operators. It aims to reduce end-to-end latency, guarantee bandwidth for mission-critical services via network slicing and increase detection accuracy for threats and anomalies in the water surface and port infrastructure. As a large-scale trial, it exercises the full IMAGINE-B5G Spanish facility across extensive port areas, multiple use cases and multi-stakeholder operations.

Almost all technical KPIs have been measured and achieved. All KVIs targets have also been achieved.

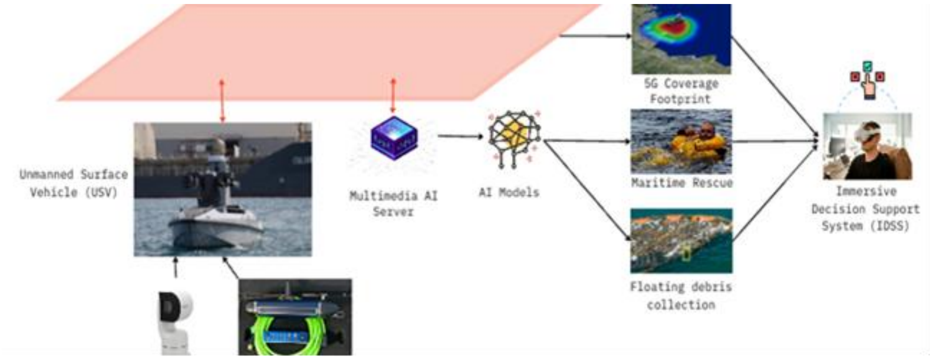


Figure 10: Architecture of the Enhanced Maritime Port Surveillance Trial

Trial deployment including integration with vertical solutions

The trial is deployed on the private 5G Standalone network at the Port of Valencia (Fundación Valencia port), a busy commercial seaport with complex infrastructure, vessel traffic and diverse operational zones (berths, breakwaters, basins). A USV equipped with PTZ Full HD camera, sonar, GNSS/IMU and a 5G UE navigates the port waters performing surveillance, SAR support and environmental monitoring. Video, telemetry and signal-strength data are transmitted over 5G to an edge node hosting AI analytics, KPI/KVI logging and data fusion, exposing results to an Immersive Decision Support System (web/XR) used by operators. APIs (REST/JSON, AMQP/TLS, WebRTC) provide integration points towards the IMAGINE-B5G facility and potential third-party systems. The trial leverages large-area over-water 5G coverage and real operational constraints (permits, safety, weather, vessel traffic) to emulate realistic port operations at scale.

Figure 11: Measurement and footage collected during the trial

Key 5G Technologies Used:

- 5G Standalone (SA) Rel-16-grade QoS / slicing (private NPN at Port of Valencia).
- Network slicing with guaranteed bandwidth for mission-critical video and alerts.
- Edge computing (on-prem edge node + GPU backend) for real-time AI inference.
- AI/ML computer vision: YOLO, Faster R-CNN, Mask R-CNN, Detectron2, EfficientDet.
- Unmanned Surface Vehicle (electric USV) with PTZ FHD camera and sonar.
- Immersive/xR Decision Support System (web + AR/VR visualisation).
- Secure media and data transport: WebRTC/SRTP, AMQP/TLS, Redpanda, PostGI

KPIs and KVIs

- **Technical KPIs:**
    - Video transmission latency (glass-to-glass)
    - Network Availability
    - Data throughput
    - 5G coverage (signal strength)
    - AI detection accuracy
    - Emergency Response Time (SAR)

- **Vertical KVIs:**
    - Operational Efficiency (Manual Effort Reduction)
    - Environmental Sustainability (Emission Reduction)
    - Time to Detect and Respond (Safety)
    - Cost Efficiency
    - Operator Cognitive Load / DSS Usability

- **Measurement Methodology:**

KPI measurements used a dedicated validation toolchain with synchronised timestamps across camera, USV, 5G network and DSS. Network-level counters (RSRP/RSRQ/SINR, UL/DL throughput, availability) from the 5G SA facility were correlated with system telemetry exported via AMQP/Redpanda from the USV and edge backend. Coverage mapping used a UE-based 5G probe on the USV mast, sampling radio metrics at 1–5 Hz and geo-referencing them via GPS to generate heatmaps. KVIs (efficiency, emissions, cost) combined time-series logs, USV telemetry (energy use), historical port baselines and operator feedback collected during high-maturity trials (SAR and debris scenarios).

Lessons learned

Technical insights:

- Early lab pre-validation (UPV campus) was essential to stabilise media/AI pipelines and avoid VPN-induced latency; migrating to secured public endpoints reduced jitter and improved QoS.

- Antenna placement and payload integration on the USV significantly affect radio performance and stability; iterative tuning was needed to achieve consistent coverage.

- Edge-based AI with CI/CD proved critical for rapid model updates (≤1 week, ≤30 min for urgent changes) and for coping with environmental variability (lighting, sea state).

Operational insights:

- Coordinating port permits, safety procedures and availability windows required close collaboration with Fundación Valencia port and harbour authorities.
- Weather and sea conditions (wind, swell) impacted USV behaviour and video quality; operational playbooks now include adaptive settings (e.g. bitrate, resolution) and safety thresholds.
- Operator feedback highlighted the risk of information overload; DSS layouts were simplified with configurable layers and clear visual hierarchy, improving usability.

Contribution to Standards / Open Source:

- Provision of open, facility-agnostic APIs and artefacts that can be reused by other IMAGINE-B5G experiments: REST/JSON control APIs, WebRTC/SRTP media interfaces, AMQP/TLS topics for events/telemetry, schemas and example clients; Coverage logging tools (PCI/RSRP/RSRQ/SINR+GPS), KPI exporters and dashboard templates for B5G experimentation.
- Selected software components (e.g., some AI/video processing modules) released as open-source under MIT licence to support broader community adoption.
- Contributions to IMAGINE-B5G objectives on KPI/KVI frameworks, business models and ecosystem analysis for maritime/PPDR verticals; results feeding into 6G-IA and SNS discussions on B5G facilities and vertical trials (via publications and working-group engagement).

References

Related Publications:

- Conference paper (under review): “RESCUE-5G: Leveraging 5G and USVs for Enhanced Maritime Port Surveillance and Safety”, submitted to Springer *Lecture Notes in Networks and Systems (LNNS)* series

Related Deliverables:

- IMAGINE-B5G Deliverable D2 – *Final Report and Results: Platform Extensions / Vertical Experiments – OC2-28 RESCUE-5G* (v2.0, 25/11/2025).
- IMAGINE-B5G Deliverable D1 – *Project Implementation Plan* (RESCUE-5G) – referenced in D2.

Links to Videos / Demos:

- Public demo video of RESCUE-5G trials and final pilot (USV operations, 5G streaming, AI detection, DSS):
  - YouTube: https://www.youtube.com/watch?v=5oFzVtF6wms
- Additional communication materials and photos of trials (LinkedIn posts by consortium partners, including deployment and final demo at Port of Valencia).

2.1.6 Leveraging 5G and USVs for Enhanced Maritime Port Surveillance and Safety

Trial Title: MC-SEAL: Mission Critical SEAL as enabler of AI-based emergency coordination and decision-making (MC-SEAL) - Field Trials Beyond 5G”
Project Acronym: MC-SEAL
Project Full Name: Field Trials Beyond 5G
Contact Person: Adrian Santiago (adrian.santiago@nemergent-solutions.com), Eneko Atxutegi (eneko.atxutegi@nemergent-solutions.com)
Project Website: https://fidal-he.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 53
Geographical Location(s): San Sebastián, surrounding area of the Reale Arena Stadium, and Donosti Municipal Guard Control Room and Crisis Room
Supported testbed (s): Victoria Network (Málaga's testbed)

Trial Overview

The Trial took place in San Sebastián (vicinity of the Anoeta stadium) and involved the PPDR and Railways sectors. Existing CCTV deployment around the station was used, to which an Unmanned Aerial Vehicle (UAV) footage was added, along with multiple MCX clients used as MCVideo sources in addition to MCPTT communications. Among the active participants (field and CCC San Sebastián Municipal Guard agents), the passive participants (sectoral authorities and Guardia commanders in the Crisis Management Room) and the members of the consortium in their different roles, no less than 25 actors were involved during the trial. The event illustrated law enforcement's

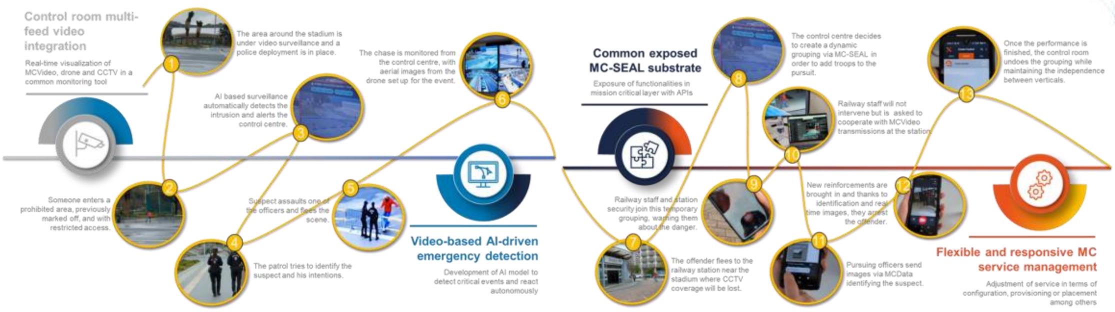


Figure 12: MC-SEAL Fidal trial diagram

Trial deployment including integration with vertical solutions

The MC-SEAL solution has been integrated into the FIDAL infrastructure. Notably, the Maestro orchestrator enabled cloud-native deployment and lifecycle management of MCX services. FIDAL's analytics module collected and processed experimental data, with MC-SEAL partners leveraging provided REST APIs to align with project requirements and report KPIs. Additionally, the FIDAL architecture included a local OpenCAPIF instance.

In terms of network interaction, while 3GPP SEAL APIs allow verticals to request enhanced 5G services like QoS directly from Network Functions (NF), the MC-SEAL initiative opted to rely on existing capabilities of the Victoria Network, such as prioritized Access Point Names (APNs) and Movistar SIMs. Movistar's national 5G coverage offered by Telefónica Innovación Digital (TID) enabled the trial relocation and, via specific APN, the participants in the San Sebastián trial have been able to connect to the MC-SEAL deployment in Málaga. TID's EDGE deployment in Málaga has also been used, which has been essential in assessing the prioritization of emergency communications in crowded environments.

The MCX service deployment has been made available through TID's private cloud based on OpenNebula where MC-SEAL can dispose of its own cluster adapted to its needs. This infrastructure environment based on OneKE, is a minimal hyper-converged Kubernetes (K8) platform provided by OpenNebula, providing load balancing for control-plane and ingress traffic, controlling nodes and managing storage. The FlexControl service, a video orchestration platform to monitor all different video sources together (CCTV, drone, MCVideo), and an AI based automatic surveillance and intrusion detection mechanism has been also integrated into the infrastructure.

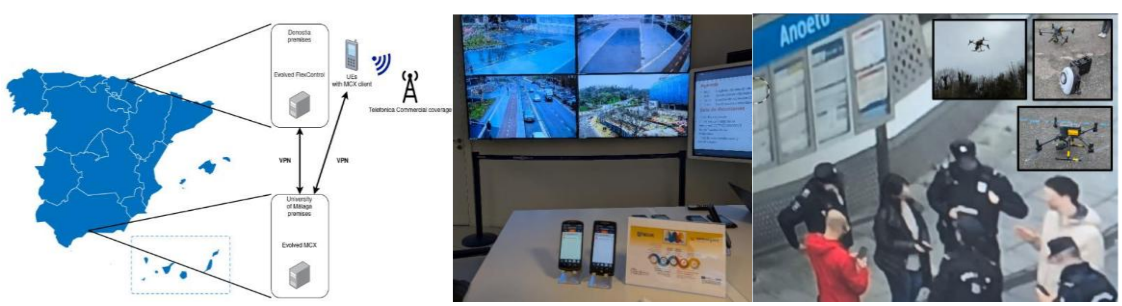


Figure 13: MC-SEAL Fidal trial location of deployments and captures of the operation

Key Technologies Used:

- 5G Standalone (SA) Network
- Network Slicing
- Cloud infrastructure based on RKE2
- SEAL API for vertical interaction with MCX capabilities (e.g. location, group management…)
- CAPIF deployment for secured API exposure and discovery (e.g. SEAL APIs)
- AI Based automatic surveillance and intrusion detection
- Nuuk's FlexControl Video orchestration supporting Nemergent's MCVideo as video source

KPIs and KVIs

- **Technical KPIs:**
  - End-to-End Latency (3GPP TS 22.261)
  - User Plane Latency (5G-PPP project/5G-MONARCH)
  - DL/UL Data Rate (5G-PPP project/5G-PICTURE)
  - Communication Service Availability (5G-PPP project/5G-PICTURE)
  - Access Time (3GPP TS 22.179)
  - End-to-End Access Time (3GPP TS 22.179)
  - Mouth-to-Ear Delay (3GPP TS 22.179)
  - Late Call Entry Time (3GPP TS 22.179)
  - Multi-agency Merged Talk Groups Creation (5G-PPP project/5G-EPICENTRE)
  - Reinstantiation time (5G-PPP project/5G-EPICENTRE)
  - Simultaneous Feed Handling
  - Simultaneous Feed Handling Complexity
  - Object Detection Mean Average Precision
  - Event detection (e.g fire) Accuracy

- **Vertical KVIs:**
  - Business Value: Stakeholder perceptions of problems solved.
  - Tackling economic inequality and economic sustainability
  - Waste Management: Reuse of existing equipment, unless it is too degraded.
  - Compliance Quality Standards
  - Knowledge: Impact on the sector, solution awareness, and events' relevance.
  - Open collaboration: To foster access to technology to smaller players
  - Flexibility: Ability of AI models to adapt to different conditions.
  - Transparency: Ability to trace actions
  - Security and privacy: Vulnerabilities
  - Data Protection: Personal Data Protection

- **Measurement Methodology:**

Technical KPIs were obtained from the MCX system itself and from the surrounding components of the infrastructure. Vertical KVIs were collected through structured questionnaires, internal and external economic, impact and security assessments, analysis of the reusability ratio of the equipment involved, ISO compliance, and detailed evaluation of results and outcomes.

Lessons learned

The final demonstration and dissemination activities confirmed the strong operational and strategic impact of the MC-SEAL approach. Third-party stakeholders reported clear benefits in operational efficiency, communication quality, and situational awareness, highlighting the potential of 3GPP-compliant MCX technologies to significantly enhance mission-critical operations, and expressed interest in continued collaboration beyond the project framework. Advanced 5G capabilities (such as assured QoS enabled by the FIDAL testbed and the UMA-enabled Victoria Network) were seen as highly relevant to addressing known limitations of commercial networks in crowded or mass-event scenarios. The speed of group management, clarity of communications, enhanced awareness, and AI-based automatic alerts for control room operators were consistently highlighted as key differentiators.

The trials also provided clear lessons for improvement and future evolution, such as tighter integration of MCVideo with Push-to-Talk workflows and enabling video transmission from control rooms to field teams. Data governance and handling proved to be a critical constraint when involving third parties in video-based demonstrations. Overall, the trial demonstrated how intelligent management of multiple video sources across different verticals can improve emergency response by enabling earlier detection, better situational understanding, stronger coordination, and faster alarm propagation, supporting quicker interventions, risk mitigation, and more effective protection of life and property.

Contribution to Standards / Open Source:

- Contribution to SDG OCF of OpenCAPIF invoker and provider clients (https://labs.etsi.org/rep/ocf/example-clients/clients-go)
- OpenCAPIF instance, which MC-SEAL actively contributed to, culminated on impactful demonstrations at key industry events (OpenCAPIF at SNS4SNS).

References

Links to Videos / Demos:

- MC SEAL FIDAL Video: https://www.youtube.com/watch?v=jFHpoVJWpig

2.1.7 Digital twin for first responders

Trial Title: Digital Twin for first responders
Project Acronym: FIDAL
Project Full Name: Field Trials Beyond 5G
Contact Person: papajohn@upatras.gr
Project Website: https://fidal-he.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: N/A
Geographical Location(s): Patras, Greece
Supported testbed (s): Patras5G Network (University of Patras and PNET)

Trial Overview

This trial demonstrates the automatic deployment of hazard detection and monitoring algorithms allowing for continuous updating of first responders about the future condition of the hazard evolution and short-term risk assessment, including situation monitoring of the fire, monitoring of the ground assets, predicting fire propagation against environmental conditions, and allowing for fire propagation disseminated to first responders, provided by SATWAYS. This trial was executed in cooperation with Open Call Wildlife and civilian Observation & Life-saving Framework (WOLF) which leverages Unmanned Aerial Vehicle (UAV) technology equipped with AI-powered video analytics to further enhance situational awareness.

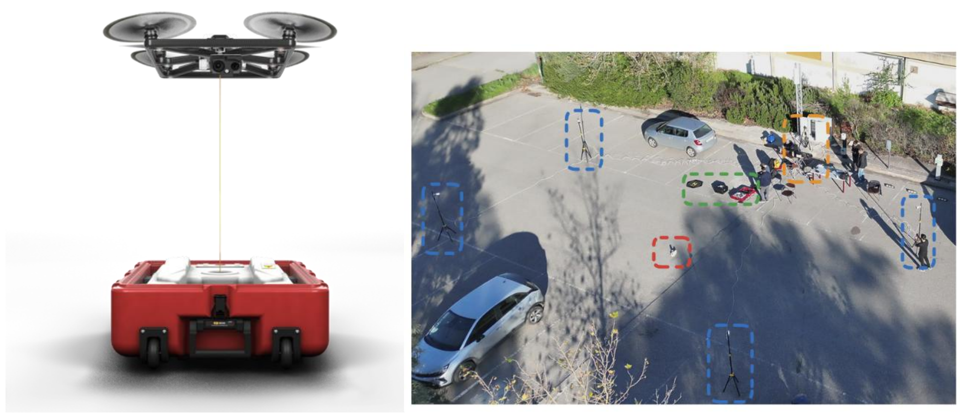


Figure 14.: Digital twin for first responders trial area

Trial deployment including integration with vertical solutions

The combined UC2 Open call trial was deployed on one of FIDAL's 5G infrastructure at the Patras5G testbed, leveraging technologies such as custom network slicing and Multi-access Edge Computing (MEC). The deployment integrated UAV (drones), 5G-enabled user equipment, cameras (optical and thermals), edge/cloud resources, and command-and-control systems, enabling end-to-end data flow and real-time processing.

The combined trial deployment consisted of two interconnected application architectures. UC2 developed by SATWAYS deployed cameras and drones for the smoke and fire for monitor detection while transmitting high resolution video to the Advanced Fire Detection (AFD) module that was deployed in compute infrastructure. The deployed WOLF architecture consisted of drones capable of integrating with AFD and receiving information while simultaneously using high-definition video to recognise possible dangers in the area that was being monitored. A Command centre was also deployed to facilitate the information exchange. Figure 2 shows this deployment.

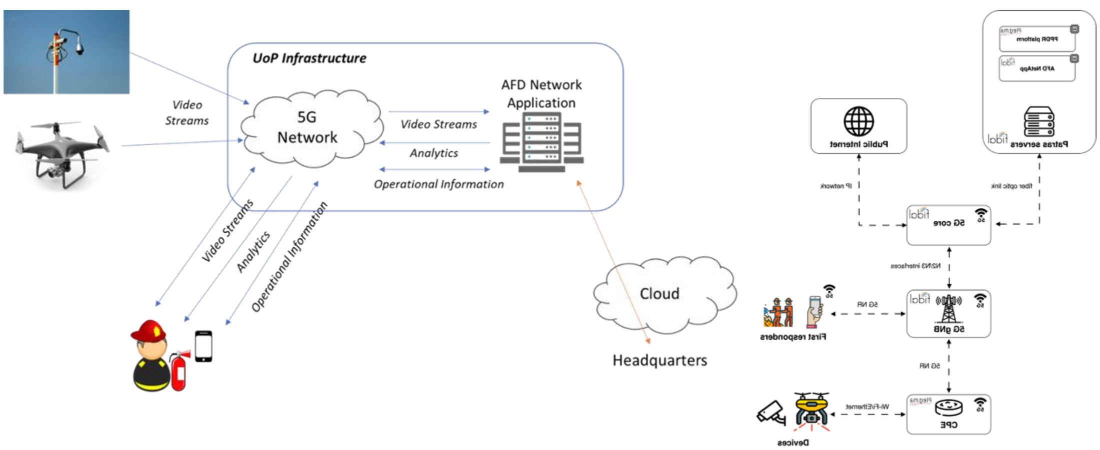


Figure 15: Digital twin for first responders trial deployment setup

Key 5G Technologies Used:

This trial leveraged key 5G and Beyond 5G technologies to support applications with demand for high uplink throughput to allow better situational awareness. A 5G Standalone architecture was used to ensure low latency, high reliability, and full control over network services.

Multi-access Edge Computing (MEC) enabled low-latency processing of the video streams uploaded form the various 5G enabled devices content by bringing computation closer to the end users. The high data rate requirements were supported through enhanced Mobile Broadband (eMBB) and RAN configurations specifically tailored for uplink communication. The system also supported multi-device connectivity, including 5G user equipment and cameras either static or mounted on drones.

In addition, the FIDAL framework incorporated Zero-Touch automation capabilities, enabling efficient and fast deployment and operation of the network applications needed and deplpyed by those use cases allowing for reduced deployment time, efficiency and scalability by rapid adaptation to various scenario parameters.

KPIs and KVIs

- **Technical KPIs:**

For UC2 (SATWAYS) the main KPIs were the uplink and downlink throughput measured at ~55 and 120 MBps respectively, the application latency, the video resolution (measured at ~60 FPS) and the time required for service network application deployment time which was measures at less than 2 minutes. All of the measured KPIs were deemed satisfactory.
Similarly, the WOLF project focused on Application Latency with an average RTT of 38 ms when operating within a GBR network slice, which met the target of <40 ms, which is critical for the real-time transmission of high-resolution video and situational alerts. Peak Throughput was also considered, with the 5G SA network
sustained an aggregate uplink throughput of 120 Mbps which was sufficient to support the simultaneous streaming of two drones and four static surveillance cameras. Complementing this, the system achieved a peak downlink throughput of 40 Mbps meeting the requirements of the command center.

- **Vertical KVIs:**

The UC2 part of this trial focused on the trustworthiness, safety enhancement energy efficiency and representation aspects regarding the KVIs, achieving very high grading in these areas.

Similarly, WOLF open call focused on system's ability to enhance community safety and preserve biodiversity and Inclusiveness / Equal Opportunity demonstrating 100% service availability for remote operators, ensuring that experts in distant command centers have the same quality of situational awareness as on-site teams. Other KVIs tackled include, Transparency, Business Value, Environmental sustainability etc.

- **Measurement Methodology:**

The measurement methodology followed the common experimentation framework defined within the FIDAL project deliverables, leveraging the FIDAL monitoring platform to ensure end-to-end observability across network, edge, and application layers. Performance data were collected in real time from multiple sources, including 5G network metrics, application-level indicators, and device measurements, enabling accurate correlation between network conditions and service performance. Technical KPIs were evaluated over multiple trial runs using statistical analysis, while KVIs were assessed through a combination of quantitative results and user feedback, ensuring a comprehensive evaluation of system effectiveness.

Lessons learned

Frequent testing in testbeds is essential to **identify issues early, validate stability, and detect configuration errors**. While 5G delivers **high bandwidth with low packet loss**, its ecosystem remains immature—**not all devices are fully compatible**, and some "5G-enabled" devices perform inconsistently across networks or require complex configurations.

The trials also showed flexibility in infrastructure, as **different antenna setups can be used without major reconfiguration**, but highlighted limitations such as the **lack of fully 5G-native devices (e.g., drones)**.

From a system perspective, **architecture adjustments may be needed for applications to operate as generic network services**, and although such solutions can support real operational use cases, **adoption is challenging due to the need to replace existing responder equipment and infrastructure with 5G-compatible alternatives**.

5G standalone networks are essential for reliable UAV-based PPDR operations, particularly through **network slicing**, which eliminates latency and jitter issues in real-time video analytics. It also highlighted that **uplink capacity is a key bottleneck**, requiring optimization for high-quality drone video streams.

From an operational perspective, **multispectral imaging (especially thermal cameras)** is crucial for detecting victims in challenging environments.

At the system level, **edge computing (MEC)** significantly improves response times, but **human decision-making remains critical**, with AI best used as a support tool rather than a replacement.

Finally, the trial showed that **custom, domain-specific datasets are necessary** to train reliable AI models for specialized emergency scenarios.

References

Related Deliverables:

- https://fidal-he.eu/sites/default/files/pd/file/2023-07/D2.1_FIDAL.pdf
- https://fidal-he.eu/sites/default/files/use-case/factsheet-pdf/2025-05/FIDAL%20UCs%20-%20FACTSHEET_A5_0.pdf

2.1.8 SAFERFLOW

Trial Title: SAFERFLOW
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Contact Person: David Gomez-Barquero <dagobar@iteam.upv.es>
Project Website: https://imagineb5g.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: PPDR, Media
Replicability: N/A
Geographical Location(s): Oporto, Portugal
Supported testbed (s): IMAGINE-B5G Portuguese facility

Trial Overview

SAFER-FLOW is a PPDR-oriented Vertical Experiment focused on ***urban flood warning and response***, strengthening ***situational awareness*** through the integration of ***IoT water-level sensors***, ***drones (video/observation)***, ***biometric wearables***, and ***analytics/AI***. The pilot uses ***Aveiro (Portugal)*** as the integration and demonstration environment, leveraging the ***IMAGINE-B5G Portuguese facility*** and a realistic flood-risk context to validate resilient communications and decision support during crisis events.

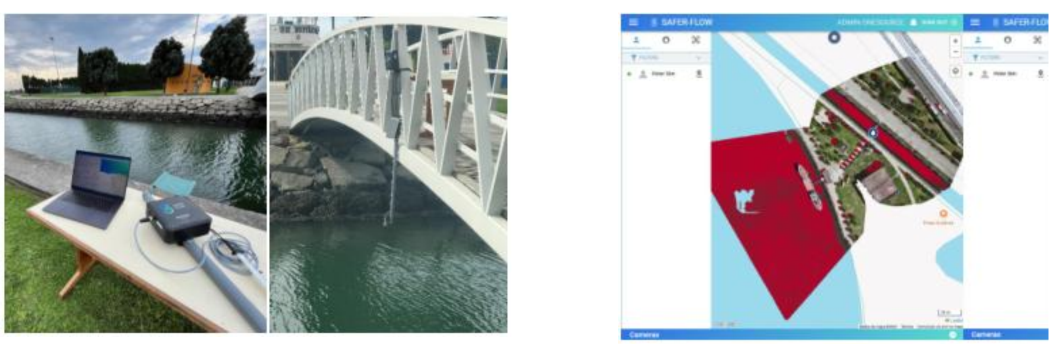


Figure 16. SaferFlow trials at test site. User interface on the right.

Trial deployment including integration with vertical solutions

The solution is deployed across multiple layers: (i) a **device layer** including water-level sensors and biometric wearables; (ii) a **network & connectivity layer** supported by 5G, leveraging a **PNI-NPN** approach and **network slicing** to ensure secured and prioritized communications; (iii) a **service/CCC layer** (e.g., message broker, video management components, etc.); and (iv) an **AI processing layer**, relying on containerized services (Docker) to process satellite/drone imagery and support risk assessment and operational decision-making. Integration with the facility followed a structured workflow including device installation in the field (Aveiro), 5G connectivity and slice configuration, and service deployment/management in Kubernetes through **OpenSlice/Helm**, including the possibility to dynamically adjust slicing and compute resources.

Key 5G Technologies Used:

- 5G connectivity through the IMAGINE-B5G Portuguese facility
- PNI-NPN (integration of private/non-public capabilities for dedicated communications)
- Network slicing with dedicated slices for different traffic classes, namely:
- Dynamic slicing (ability to create/modify slices and associate UEs through REST APIs and facility orchestration)
- Edge/Cloud deployment + containerization (Docker) for services and AI workloads
- Monitoring and KPI collection via KPI Manager + TICK stack (Telegraf/InfluxDB, etc.)

KPIs and KVIs

- **Technical KPIs:**
    - Round Trip Time (RTT)
    - Message delay (sensor request/response)
    - Throughput (DL/UL)
    - RSSI / RSRP / RSRQ
    - Accessibility (connectivity availability)
    - Availability (restarts/downtime)
    - Positioning accuracy
    - Battery life
    - Drone response time; drone reliability
    - Video streaming quality
    - End-to-end multimedia latency
    - Multimedia freezes / dropped frames / processing delay
    - AR reliability
    - AR Quality of Experience (QoE)
    - AI accuracy
    - AI inference speed

- **Vertical KVIs:**
    - Energy Efficiency
    - Minimization of Casualties (hard to validate in non-disaster conditions)
    - Open Collaboration
    - Societal Sustainability (hard to validate in limited pilot conditions)
    - Trustworthiness

- **Measurement Methodology:**

KPIs were validated using a systematic approach based on the OneSource KPI Manager and the TICK monitoring stack for real-time visibility and data analysis. The KPI Manager collects data from devices/sensors, processes it, and stores it in InfluxDB via Telegraf. Measurements were collected in both indoor and outdoor settings (including IT Aveiro facility and Jardim Oudinot), covering LoS/NLoS conditions and different loads (up to ~10 UEs). For KVIs, both automated evidence (e.g., sensor energy/battery evolution over time, including the use of solar panels to reduce consumption) and qualitative validation activities (e.g., feedback sessions/workshops) were used to assess collaboration and trust aspects.

Lessons learned

Technical insights:

AI is a key enabler to improve situational awareness (e.g., water detection from satellite/drone imagery) and should evolve to cover additional environmental conditions and data sources (e.g., weather data and flow simulations).

Network slicing proved useful to separate critical traffic (video) from periodic IoT traffic, improving predictability and prioritization.

Operational insights:

Real-world trials (e.g., Jardim Oudinot) are essential, but additional testing across diverse environments (urban/rural) would improve generalization and replicability.

Measurement insights:

Some targets (e.g., DL throughput) may be impacted by outliers and external conditions; controlled scenario repetition and careful analysis of deviations are important.

For KVIs, some indicators (e.g., casualty reduction) are inherently difficult to validate without large-scale simulations or real-event conditions.

Contribution to Standards / Open Source:

The main contribution was integration and validation with the facility (PNI-NPN, dynamic slicing, OpenSlice/Kubernetes) and KPI/KVI definition and assessment. Also, collaboration with stakeholders (e.g., Municipality of Ílhavo, Port Authority of Aveiro, Portuguese Civil Protection Authority) supported validation and adoption alignment.

References

Links to Videos / Demos:

- https://www.youtube.com/watch?v=5Hu9AduzMXA

2.2 SMART AGRICULTURE AND FORESTRY

2.2.1 5G Multi-Slice Connectivity for Precision Agriculture at La Mayora Experimental Farm

Trial Title: 5G Multi-Slice Connectivity for Precision Agriculture at La Mayora Experimental Farm
Project Acronym: 6G-PATH
Project Full Name: 6G Pilots and Trials Through Europe
Contact Person: Almudena Diaz Zayas (adz@uma.es)
Project Website: https://6gpath.eu/
Funding Programme: HORIZON-JU-SNS-2023-STREAM-D-01-01 - SNS Large Scale Trials and Pilots (LST&Ps) with Verticals – Focused Topic
Main Vertical(s) Addressed: Agriculture
Replicability: 60
Geographical Location(s): La Mayora Experimental Farm, Algarrobo (Málaga), Spain
Supported testbed (s): Victoria Network (University of Malaga)

Trial Overview

This trial demonstrates how a **private 5G Standalone network with multiple network slices** can support heterogeneous agricultural services at the La Mayora experimental farm. The use case focuses on the simultaneous operation of **drone-based crop monitoring, remote drone control, and agricultural sensor data collection**, each with different performance requirements.

The trial validates that **network slicing and edge computing** can guarantee service isolation, Quality of Service (QoS), and low latency in a real agricultural environment, enabling reliable and scalable precision farming operations.

Figure 17 Remote drone control used for fruit recognition

Trial deployment including integration with vertical solutions

The trial is deployed over a **private 5G Standalone (SA) network installed at La Mayora**. A **5G core network and an edge computing server are co-located on-site**, enabling low-latency data processing and local service execution.

Three **dedicated 5G network slices** are configured and simultaneously used:

- **Slice 1 – eMBB slice:** Used for the transmission of **4K video streams from UAVs** for real-time crop supervision and visual inspection.
- **Slice 2 – URLLC-like slice:** Used for **remote drone control**, ensuring low latency and high reliability during flight operations.
- **Slice 3 – mMTC-like slice:** Used for the **uplink of data captured by distributed agricultural sensors**, such as soil and microclimate sensors, with energy-efficient communication.

All devices (drones, controllers, and sensors) connect to the private 5G network using dedicated SIMs mapped to their corresponding slices. The **edge server deployed next to the 5G core** processes video and sensor data locally, reducing backhaul traffic and enabling near-real-time analytics.

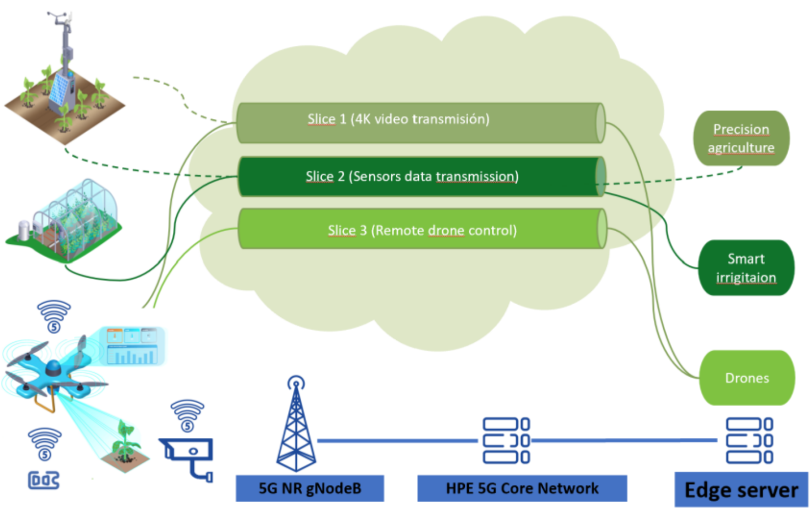


Figure 18: End-to-end trial architecture

Key 5G Technologies Used:

- Private 5G Standalone (SA) network
- Network Slicing (three parallel slices)
- Quality of Service (QoS) differentiation via 5G QoS Identifiers (5QI) and radio resources scheduling via API
- Edge Computing co-located with the 5G Core
- UAVs and IoT devices with native 5G connectivity

KPIs and KVIs

- **Technical KPIs:**
  - End-to-end latency for drone control communications
  - Sustained video throughput and resolution for 4K UAV video streaming
  - Packet loss and jitter for remote drone control
  - Radio quality indicators: SS-RSRP, SS-RSRQ, SS-SINR
  - MAC/RLC/PDCP layer performance metrics

- **Vertical KVIs:**
  - Cost savings (e.g., yield prediction).
  - Energy savings (reduced manual labour).
  - High data processing capabilities across the production chain.
  - Attracting younger generations to agriculture, countering the current trend of ageing orchard managers.
  - Addressing connectivity gaps in rural areas.

- **Measurement Methodology:**

Network KPIs are collected using **radio and network monitoring tools** integrated into the private 5G infrastructure, including slice and 5QI identification. Application-level metrics are gathered from the UAV video streaming system, drone control interfaces, and sensor data ingestion services running on the edge server.

Lessons learned

<u>*Technical insights:*</u> Network slicing in a private 5G agricultural environment enables effective separation of heterogeneous traffic types. Co-locating the edge server with the 5G core significantly reduces latency and improves service responsiveness, particularly for drone control and real-time video analytics.

<u>*Operational insights:*</u> The use of dedicated slices increases the reliability and safety of drone operations while allowing continuous sensor data collection. The architecture supports scalable farm monitoring without over-provisioning network resources.

<u>*Measurement insights:*</u> *Simultaneous multi-slice operation is essential to properly evaluate isolation and QoS guarantees. Field trials highlight the importance of stable radio coverage and careful slice configuration to meet diverse application requirements.*

Contribution to Standards / Open Source:

- Validation of GSMA OpenGateway initiative APIs in real-world public safety scenarios
- Input for future enhancements of network slicing for PPDR use cases

- Feedback to OpenGateway community on QoD API usage

References

Related Publications:

Chochliouros, I.P. *et al.* (2025). Water Saving for Modern Agriculture in the B5G/6G Framework. In: Papaleonidas, A., Pimenidis, E., Papadopoulos, H., Chochliouros, I. (eds) Artificial Intelligence Applications and Innovations. AIAI 2025 IFIP WG 12.5 International Workshops. AIAI 2025. IFIP Advances in Information and Communication Technology, vol 753. Springer, Cham. https://doi.org/10.1007/978-3-031-97317-8_22

Related Deliverables:

- https://6gpath.eu/wp-content/uploads/2025/12/6G-PATH-D2.2-Platform-architecture-and-verticals-midterm-v1.0_Final.pdf

Links to Videos / Demos:

- https://www.youtube.com/watch?v=oEUFEaiQeVQ

2.2.2 Artificial Intelligence for Forest

Trial Title: AI4FS (Artificial Intelligence for Forest). Open Call trial by iLink and Local AI **Project Acronym:** IMAGINE-B5G
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Contact Person: David-Gomez Barquero <dagobar@iteam.upv.es>
Project Website: https://imagineb5g.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Forestry & Smart Agriculture
Replicability: 46
Geographical Location(s): Fornebu and Jaren, Norway and Greece
Supported testbed (s): Telenor's B5G experimental platform/facility and Network-on-Wheels (NoW)

Trial Overview

This trial, carried out by iLink and Local AI, consisted of establishing a real-time monitoring system for critical forest metrics, including temperature, humidity, and potentially additional metrics that serve as vital indicators of forest health and sustainability. An integration of state-of-the-art technology components to create a holistic forest monitoring and surveillance system has been performed. The system operates in real-time, with immediate detection of changes in forest metrics and forest health threat identification. By harnessing 5G communication, edge computing, and deep learning, we established a proactive and responsive approach to forest management, conservation, and environmental protection.

Figure **19**: *AI4FS trials at Telenor's testbed*

Trial deployment including integration with vertical solutions

A Raspberry Pi 5 is combined with a Sense HAT sensor module used to measure forest environmental metrics. The Sense HAT is equipped with both pressure and humidity sensors and includes functionality to extract the temperature value from these sensors. The Raspberry uses a power bank, which is enough to keep it running for several days, and along with it, we have a ZTE 5G router for internet connection, powered by another power bank.

The drone integral to our proposed forest monitoring methodology, DJI Mavic 3 model, several solutions compatible with the DJI ecosystem were implemented, e.g., Keycloak, Minio, and DJI specificities such as pilot app and Cloud API.

The Raspberry Pi console received the IoT data at the far edge. In case a critical condition is identified, the edge server will utilise a 5G network to provide immediate notification to the authorities for further action. IoT data will be occasionally sent from the far edge device, over a 5G network, to the edge server for storage as well as further processing. More analytically, Raspberry Pi will communicate via a ZTE router, which offers the 5G capabilities of the far-edge node. IoT metrics will be visible on the web application, as an additional visual layer of information, combining spatial data from the drone (forest images), enriched with IoT metrics at specific forest locations. Combining drone images/video with IoT metrics will provide an integrated monitoring tool of the real-time conditions of the forest.

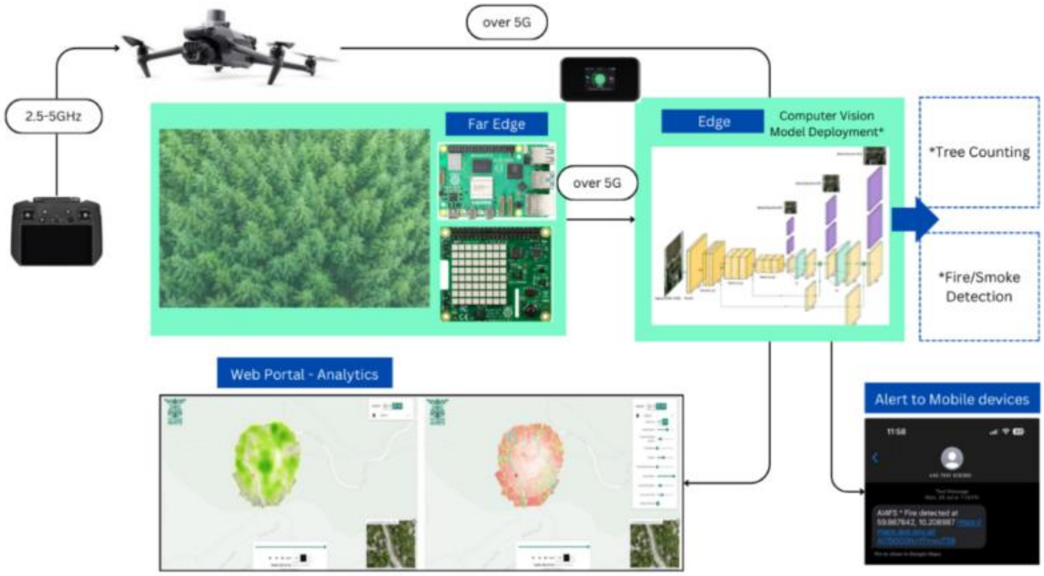


Figure 20 AI for forest trial architecture

Key 5G Technologies Used:

- 5G Standalone
- Network slicing
- Network-on-wheels
- Edge computing, AI/ML.

KPIs and KVIs

- **Technical KPIs:**
  - Downlink and Uplink throughput
  - Latency, Jitter
  - CV model performance
  - Fire/Smoke model performance
  - Service deployment time
  - Model inference time
- **Vertical KVIs:**
  - Societal sustainability
  - Innovation
  - Inclusiveness
  - Greenhouse emissions
  - Energy consumption
  - Forest surveillance efficiency

- **Measurement Methodology:**
  - KPIs measured by using data from the network, edge, and devices.
  - KVIs were analyzed by comparisons and assessments, user dialogues, observations, and subsequent reasoning.

Lessons learned

Technical and Operational insights:

- **Standalone 5G Connectivity with Network-on-Wheels**: Given that forestry areas often lack reliable 5G coverage, the IMAGINE-B5G platform's **Network-on-Wheels (NoW)** provides standalone 5G connectivity, enabling consistent, high-speed data transfer even in areas without traditional 5G infrastructure.
- **Ultra-Low Latency and High Bandwidth for Real-Time Processing**: The forestry monitoring use case relies on real-time image streaming, fire detection, and environmental metrics, which necessitate an ultra-low latency network. The IMAGINE-B5G platform's advanced capabilities allow UAVs to high-resolution, multispectral images and environmental data directly to the edge server.
- **Edge Computing Integration for Localized Processing**: The platform's support for edge computing nodes allows data to be processed closer to the source,
- **Massive Machine-Type Communications (mMTC) for Large-Scale Sensor Deployment**: The IMAGINE-B5G platform is optimized for massive machine-type communication, allowing the deployment of numerous IoT sensors throughout large forested areas. This capability supports the collection of diverse environmental metrics across a wide area, enabling comprehensive, high-resolution monitoring that would not be possible with conventional network technologies.

To meet the technical and operational demands of the forestry monitoring use case, the following advanced features of the IMAGINE-B5G platform were indispensable:

- **Network Slicing**: Dedicated network slices enable customised connectivity, prioritising specific data flows, such as UAV image streaming and critical IoT sensor data.
- **High Mobility Support**: The platform's high mobility support enables seamless connectivity with UAVs and ground sensors in constantly changing locations,
- **Self-Healing and Automated Management**: With self-healing capabilities and automated network management, the B5G platform ensures minimal downtime and quick restoration in case of network disruptions, which is crucial for real-time applications operating in remote, difficult-to-access areas.

Contribution to Standards / Open Source:

- Validation of GSMA OpenGateway initiative APIs in real-world public safety scenarios
- Input for future enhancements of network slicing for PPDR use cases
- Feedback to OpenGateway community on QoD API usage

References

Related Deliverables:

- G. Tsironis (iLink) & G. Vlachodimitropoulos (Local AI), Deliverable D2 Final report and Results

Links to Videos / Demos:

- https://www.youtube.com/watch?v=VED5x07QfJM
- https://www.linkedin.com/posts/imagine-b5g_norwegian-facility-open-call-1-of-imagine-b5g-activity-7310260926677450752-kpYU?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAGM-WkBfsT3IyTY84bBVECp2kVnGHKwq_I

2.2.3 Environment protection and sustainable agriculture leveraging on 6G infrastructure and enablers by means of APIs

Trial Title: Environment protection and sustainable agriculture leveraging on 6G infrastructure and enablers by means of APIs
Project Acronym: SUSTAIN-6G
Project Full Name: SUSTainability Advanced and Innovative Networking with 6G (The European Sustainability Lighthouse Project)
Contact Person: Panagiotis Demestichas (pdemest@wings-ict-solutions.eu), Sokratis Barmpounakis (sbarmpounakis@wings-ict-solutions.eu)
Project Website: https://sustain-6g.eu/
Funding Programme: SNS-JU Horizon Europe
Main Vertical(s) Addressed: PPDR (Environmental monitoring / wildfire detection, Agriculture)
Replicability: 50
Geographical Location(s): Athens, Greece
Supported testbed (s): WINGS ICT Solutions testbed (Athens, Greece)

Trial Overview

The objective of this trial is to demonstrate how 6G-native exposure APIs and event-driven orchestration enable energy-efficient environmental protection and precision agriculture services. It validates a shift from always-on monitoring to on-demand activation of network and compute resources, reducing energy consumption while maintaining low-latency response. The trial is deployed in environmental and agricultural monitoring settings, combining farmland and sensitive areas. Ultra-low-power IoT sensors continuously monitor conditions, while high-consumption resources (e.g., cameras, drones, edge compute) are activated only upon anomaly detection. The use case that is demonstrate comprises a Wildfire Early Warning UC, in which air-quality anomalies trigger activation of cameras, edge analytics, and data sharing with authorities.

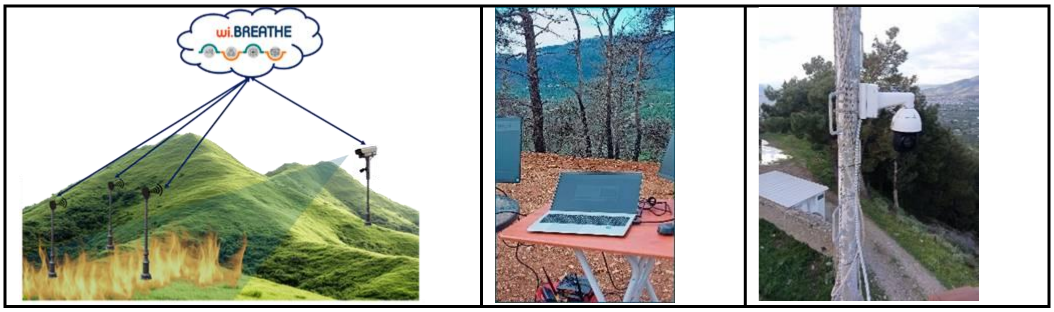


Figure 21: Wildfire Early Warning Trial images from trial

Trial deployment including integration with vertical solutions

The architecture follows a sense–process–act paradigm, where ultra-low-power sensors generate event triggers processed by a central orchestrator. Upon detection, network and compute resources are dynamically activated via exposure APIs, enabling edge analytics and high-bandwidth data acquisition. Resources are released after event resolution to minimise energy consumption.
Vertical applications, including WINGS **wi.BREATHE** and **wi.GROW**, interface with the infrastructure through exposure APIs, allowing programmatic control of connectivity and compute resources based on service intent and detected events.

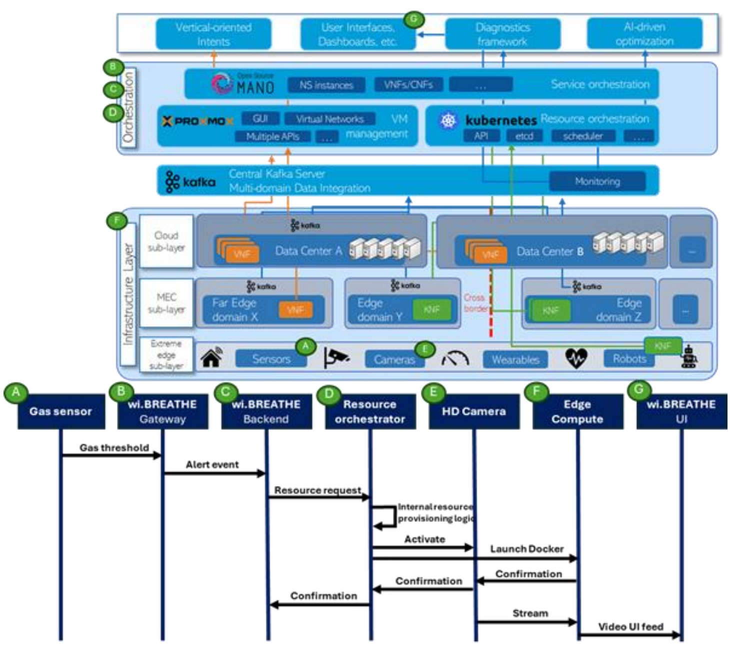


Figure 22: Experimental Platform / Testbed Used: WINGS B5G NPN Testbed

KPIs and KVIs

- **Technical KPIs:**
    - End-to-end latency from event detection to resource activation
    - QoD orchestration success rate (%)
    - Network throughput during event-driven data transmission
    - Energy consumption per incident (kWh)
    - Reliability of API-based resource provisioning

- **Vertical KVIs**
    - Energy savings compared to always-on monitoring (%)
    - Carbon emissions per handled incident (gCO_2)
    - Time-to-response for environmental incidents
    - Reduction of unnecessary data acquisition and processing
    - Improved protection of crops and natural areas

Measurement Methodology: KPIs are measured via network tools, orchestrator logs, and application timestamps, comparing event-driven operation against always-on baselines. KVIs are derived from energy consumption, resource utilisation, and scenario-based assessments.

Lessons learned

Technical insights: Event-driven orchestration and API-based resource control enable energy-efficient operation while maintaining responsiveness, but require careful coordination between sensing, orchestration, and infrastructure layers.
Operational insights: On-demand activation of high-consumption resources significantly reduces unnecessary processing and improves sustainability, while maintaining effective environmental monitoring and response capabilities.
Measurement insights: Evaluating energy efficiency requires comparison with baseline configurations and integration of measurements across network, compute, and application layers.

References

Related Publications/Deliverables:

- SUSTAIN-6G Deliverable D5.1 (Use Case ID1.4)
- SUSTAIN-6G Deliverable D3.2 (R&I Topic 6.2)

2.2.4 Phenology and Innovation for Vegetation

Trial Title: Phenology and Innovation for Vegetation (FI-VEG)
Project Acronym: IMAGINE-B5G
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Contact Person: David Gomez-Barquero <dagobar@iteam.upv.es>
Project Website: https://imagineb5g.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Smart agriculture and forestry
Replicability: 83.38 %
Geographical Location(s): Soria, Spain
Supported testbed (s): Matanza de Soria, Spain

Trial Overview

The trial uses the 5G platform to connect different devices oriented to the management and care for vineyards. The experiment bases slice management to optimize the use of the resources of the 5G platform allowing to optimize the energy consumption, critical in self-powered stations as the one used.

The objectives referring to the vertical layer are:

- Monitoring the ripening stage of grapes using multispectral cameras
- Monitoring of the wildlife in the crop lands
- Remote monitoring using AGVs and drones connected through the 5G network.

Figure 23: FI-VEG trials at the test site

Trial deployment including integration with vertical solutions

The FI-VEG architecture follows a three-layer design:

- **Device Layer:** Comprises IoT multispectral sensors (visible–NIR range) for grape maturity monitoring, PTZ cameras for phenological tracking, and onboard camera modules integrated into AGVs (XAG-R150). Each device is equipped with a 5G modem for low-latency communication (< 10 ms) and supports synchronisation via the B5G network slicing framework

- **Edge Computing Layer:** Edge nodes deployed locally at the vineyard process raw sensor and video data in near real time. This ensures fast inference for grape maturity classification, anomaly detection, and object recognition. AI models (e.g., CNNs for fruit detection, ANN for ripeness stages) are executed at the edge, reducing cloud-to-device delays and bandwidth demands.
- **Cloud & Management Layer**: The central IMAGINE-B5G cloud stores datasets, provides visualisation dashboards, and manages API-based service orchestration. It enables remote access for researchers who can control PTZ and drone units via web interfaces, collaborate in virtual sessions, and validate processed data. Integration is supported through open APIs (REST/JSON) compliant with IMAGINE-B5G SDK standards.

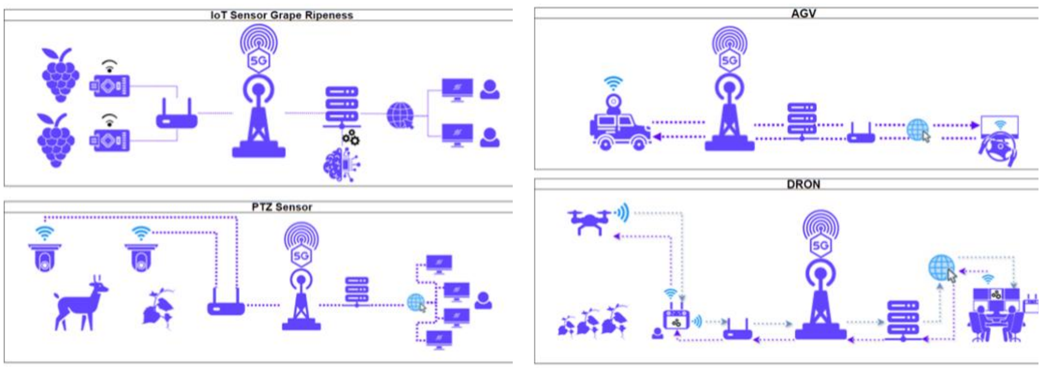


Figure 24. System general architecture

Key 5G technologies used:

- 5G Standalone (SA) network
- Edge/cloud infrastructure IoT

KPIs and KVIs

- **Technical KPIs:**
    - Latency
    - Jitter
    - Throughput (downstream/upstream)
    - Bandwidth
    - Connection density
    - PDU session establishment time
    - Mobility
    - Energy Efficiency
    - Reliability

- Availability
- Positioning accuracy
- Positioning latency
- Spectral efficiency

- **Application KPIs:**
  - Service deployment time
  - Precision of Maturity Monitoring
  - Power Consumption of IoT Sensors
  - Data Integration Efficiency

- **Vertical KVIs:**
  - Economic Growth
  - Innovation
  - Good Health and Safety
  - Environmental Sustainability

- **Measurement Methodology:**

The tools used were iPerf3, Speedtest, Nokia's LoadCore network simulator, System logs, MQTT broker and Power analyzers. All collected data was centrally stored and aggregated using PathWave Test Automation Cloud, enabling robust statistical post-processing in Excel to compute KPI mean values, distributions, and compliance margins.

The validation of Key Value Indicators (KVIs) in FI-VEG was achieved through a combination of automated sensor data logging, project documentation audit, and carefully designed operational trials under real vineyard conditions.

Lessons learned

The FI-VEG project successfully validated a private 5G-enabled platform for smart viticulture, integrating real-time IoT sensors, drones, AGVs, and PTZ cameras across a working vineyard. The system demonstrated robust data fusion, high connection density, and rapid service deployment, while also delivering measurable environmental benefits—reducing CO_2 emissions by 656 kg through remote operations. Although some KPIs like latency, energy efficiency, and availability were not fully met, detailed analysis has identified improvements in edge architecture and firmware that will enable future compliance. The results showcase FI-VEG's strong potential to accelerate digital transformation and operational sustainability for precision agriculture in Europe.

References

Related Publications/Deliverables:

- Event webpages: https://www.itacyl.es/-/demovina2025, https://demoviña.es/
- Media link: Facebook – Revista Campo Comunicación
- BOOK OF ABSTRACTS OF ALL THE POSTERS: https://ecpa2025.upc.edu/wp-content/uploads/2025/06/Book-of-posters_ECPA2025-comp.pdf
- POSTER PRESENTATIONS: https://ecpa2025.upc.edu/wp-content/uploads/2025/06/Posters-Program-ok.pdf
- Project page: https://imagineb5g.eu/fi-veg-in-imagine-b5g-open-call-2/

Presentation sessions:

- https://www.youtube.com/watch?v=a88GbT5_0sk

2.3 AUTOMOTIVE AND TRANSPORTATION

2.3.1 Port logistics and transport optimisation and safety

Trial Title: Port logistics and transport optimisation and safety
Project Acronym: AMAZING-6G
Project Full Name: Amazing Large-Scale Trials and Pilots for Verticals in 6G
Contact Person: Andreas Georgakopoulos (andgeorg@wings-ict-solutions.eu)
Project Website: **https://amazing6g.eu/**
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Transport and Logistics
Replicability: 48
Geographical Location(s): Thessaloniki, Greece
Supported testbed (s): CERTH/Port of Thessaloniki testbed, Acromove connectivity equipment, WINGS private testbed

Trial Overview

This use case aims to foster operational efficiency, safety, and human-machine interaction, and to reduce the environmental footprint of port logistics and transport operations. This is achieved by enabling real-time, massive twinning by extending a Digital Twin platform developed for process monitoring and tele-operation. The platform is tested in a pilot that covers an end-to-end port process, i.e., from vessel unloading to loading trucks. The pilot implementation is broken down into two Subcases. The Digital Twin is developed in a virtual environment with a series of avatars of vehicles, containers, and machines (cranes, etc.) that utilise real-time data. To achieve this result, the AnyLogic Simulation Software is instrumented as it contains an explicit UI for 3D representations that replicate the real world, as well as capabilities for discrete event and agent-based modelling, along with the integration of custom optimisation routines.

Trial deployment including integration with vertical solutions

The WINGS testbed provides E2E 5G/B5G functionality, along with extensive cloud and edge computing capabilities, leveraging the 3GPP (Release-16 and beyond) Public Network Integrated Non Public Network (PNI-NPN) with shared CP (at a first phase) and isolated, Stand-alone Non-Public Network (SNPN), with all NFs (UP and CP) inside WINGS premises, isolated from the public network in the final phase. The site offers a range of 5G/B5G services and will gradually evolve to 6G. It supports various vertical domains, with WINGS providing the necessary HW, software, and configurations to enable the testbed to handle diverse use cases. WINGS testbed serves as a testing ground for services, equipment, and new features before they are commercially released. WINGS has progressively extended the existing software, HW, and network functionality to support Cloud, Mobile Edge Computing (MEC), Extreme Edge and IoT functionalities. WINGS has demonstrated advanced use cases on digital twins, Collaborative Robots with native-AI B5G/6G capabilities of the system. Also, the required frameworks to build, test, and validate innovative 6G applications are part of the overall infrastructure.

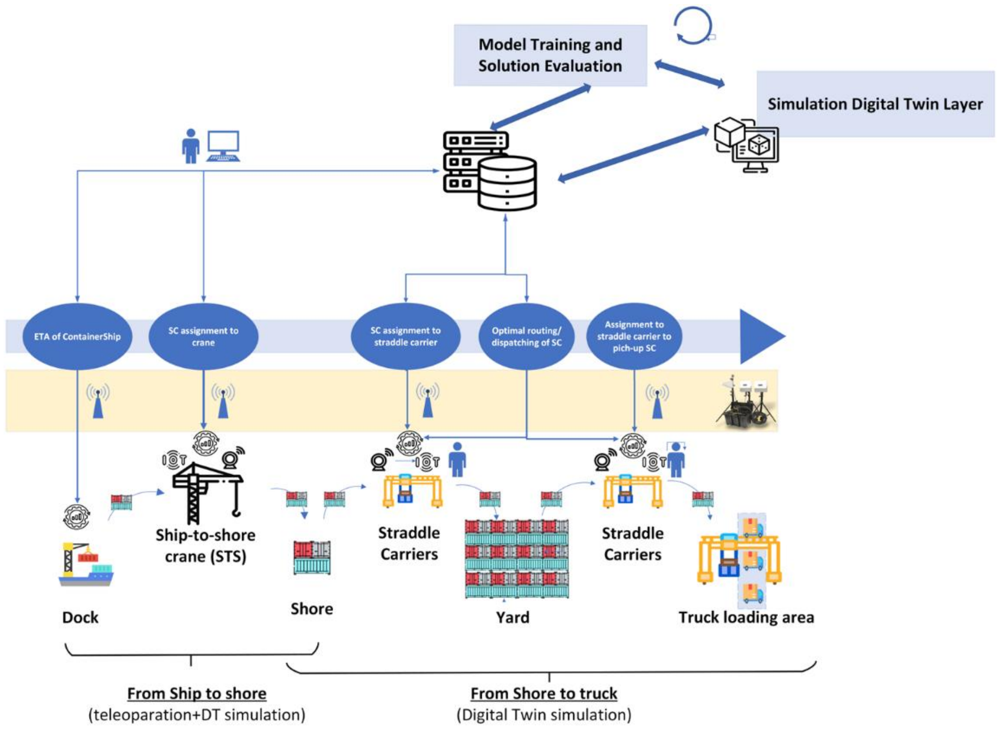


Figure 25 Port logistics and transport optimisation and safety use case overview

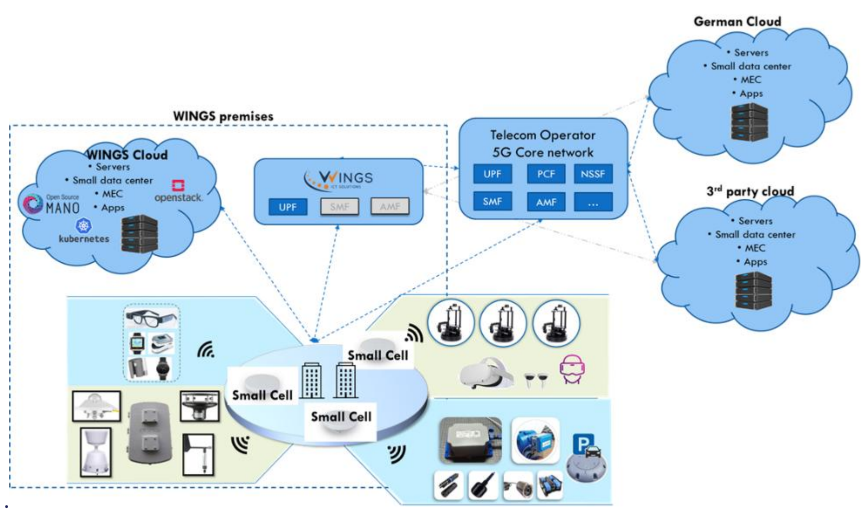


Figure 26 WINGS testbed architecture for experiments

Port logistics and transport operations will be tested through Use Cases developed in the port of Thessaloniki (Thessaloniki Port Authority-ThPA) in cooperation with

CERTH/HIT. ThPA provides the 'physical' site of operations and infrastructure facilities (ships, equipment, etc.) as well the testbed of current applications used to monitor the port operations. CERTH/HIT provides the research capacity and infrastructure to develop the platform needed for the UCs, and monitor and assess the outcomes. Acromove provides connectivity equipment and WINGS provides AI functionality and private testbed facilities.

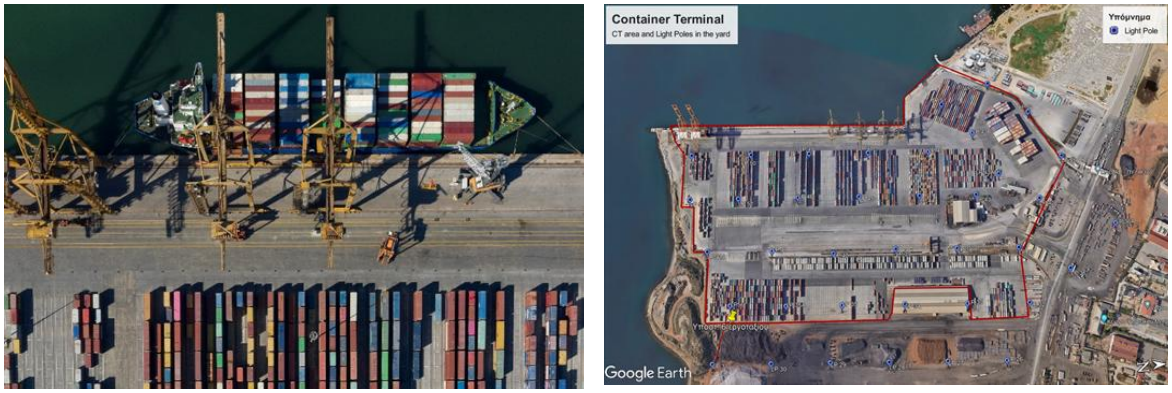


Figure 27: Overview of the Port of Thessaloniki container terminal.

Key 5G Technologies Used:

- Private and Public 5G testbeds.
- Proprietary equipment

KPIs and KVIs

- **Technical KPIs:**
  - Network service latency
  - Network reliability
  - Network availability

- **Vertical KVIs:**
  - Environmental
    - Improve environmental footprint (reduced emissions) of port transport operations through optimal use of resources.
  - Societal
    - Create a safe working environment through reduced human-machine interaction (automation and teleoperation).
    - Raise workforce skills through competence building in the use of new technologies.
  - Economic
    - Reduced cost through port operations (time) optimization i.e., turnaround times (ship, truck), (un)loading times (ship, container, truck).

- Reduced downtime and cost of maintenance through optimal use of resources and predictive maintenance.

Lessons learned

<u>*Technical and Operational insights:*</u>

- Real-time collection, monitoring and analysis of data combining digital twin, B5G/6G, AI/ML, simulation and IoT technologies.
- Orchestration of seamless tele-operations.
- Integration and exposure of sensing capabilities, from the network to the end user. Use of sensors, cameras, etc., integrated through B5G/6G.

<u>*Challenges:*</u>

- Enhanced connectivity, reliability and data rates, enabling real-time massive twinning, data processing and analytics. This is crucial for the synchronization of operations in a port, where milliseconds can affect logistics and supply chain efficiency.
- Massive twinning and seamless IoT Integration: B5G/6G's ability to connect a vast number of devices per square kilometer enables comprehensive IoT deployment. In a port setting, this means everything from cranes, vehicles, containers, to sensors can be interconnected, providing a seamless flow of information and automation in near-real time.
- Sustainability (environmental, societal, and economic): Port operations pose a wide range of challenges related to severe environmental impacts, security, congestion, and conflicts over land use. The digital transformation offers an opportunity to confront those challenges, however most ports are struggling to keep up with the implementation of digital services and technology; while at the same time they face difficulties in following the demanding sustainability agendas leading towards climate neutrality.
- Limitations: (a) from the cranes side, (b) from the communications side (ultra-low E2E latency, high bitrate, reliability), (c) of the human factor.

Contribution to Standards / Open Source:

Contributed to international standardization activities through engagements with 3GPP SA1 and GSMA. Two submissions to 3GPP SA1 introduced and advanced a new 6G medical applications use case, developed in collaboration with TNO and co-signed by Telefónica. The first contribution (August 2025) proposed the use case and was officially noted, while the second submission (November 2025) refined the proposal and achieved agreement within the working group. In parallel, a contribution to the GSMA IoT and Open Gateway activities (November 2025), developed with NXW, presented an example implementation of a CAMARA API for smart transport use cases, supporting interoperability and open network service exposure initiatives.

References

Related Deliverables:

- https://amazing6g.eu/wp-content/uploads/AMAZING-6G_D2.1_v1.0.pdf

2.3.2 Real-Time Road Digital Twin with AI Vision and 5G Edge Connectivity

Trial Title: Real-Time Road Digital Twin with AI Vision and 5G Edge Connectivity
Project Acronym: TARGET-X
Project Full Name: Trial Platform for 5G evolution cross industry on large scale
Contact Person: Hacı Mehmet Güzey (info@adaguzey.com)
Project Website: https://target-x.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 85%
Geographical Location(s): Barcelona, Spain
Supported testbed (s): IDIADA (Barcelona, Spain)

Trial Overview

RTwin-CAV delivered a real-time road digital twin pipeline that detects road hazards using AI vision (YOLOv10), estimates object distance via RGB + depth sensing, geolocates detected events, and updates a Unity-based 3D digital twin with minimal latency using 5G and edge computing. Building on the HybridCAVs autonomous vehicle platform, RTwin- CAV integrated new sensors (RGB and depth cameras), updated embedded electronics (custom STM32-based PCBs), and implemented a vehicle–server–digital twin architecture. A key validation milestone was achieved through testing in IDIADA (Barcelona), where the end-to-end delay from detection to digital twin update over 5G edge was observed to be approximately 24 ms, whereas cloud-based processing required roughly an order of magnitude longer under comparable conditions. The trial demonstrates a practical foundation for B5G-to-6G transition by stressing low-latency, secure, and edge-native components required for cooperative safety services.

Figure 28 RTwin-CAV trial at IDIADA in Barcelona (Spain)

Trial deployment including integration with vertical solutions

The RTwin-CAV trial was deployed as an end-to-end connected automated vehicle (CAV) safety demonstrator that integrates an automotive vertical solution with a real-time road digital twin. A prototype electric vehicle carried an onboard mini-PC, STM32-based control electronics, GPS, LiDAR, and synchronized RGB+depth cameras. Onboard perception executed a YOLOv10 model to detect road hazards (e.g., cones, boxes, tires, logs), while depth fusion estimated object distance and relative direction. Perception outputs were formatted as lightweight messages (object class, confidence, GPS position, timestamp, and range) and transmitted through the vehicle's 5G router to the edge platform at IDIADA, where secure networking and low-latency forwarding were available. The edge service relayed updates to a central workstation running Unity, which instantiated corresponding 3D objects and updated the vehicle pose in the virtual road scene in real time. The same channel supported supervisory commands (speed limits, stop, and mode changes) from the digital twin back to the vehicle, enabling closed-loop remote intervention. Integration with the vertical therefore covered sensing, AI inference, edge communication, and digital-twin visualization, providing a reproducible workflow for CAV R&D teams to validate perception pipelines, network KPIs (latency and reliability), and safety responses under realistic field conditions. Streams were logged for offline analysis.

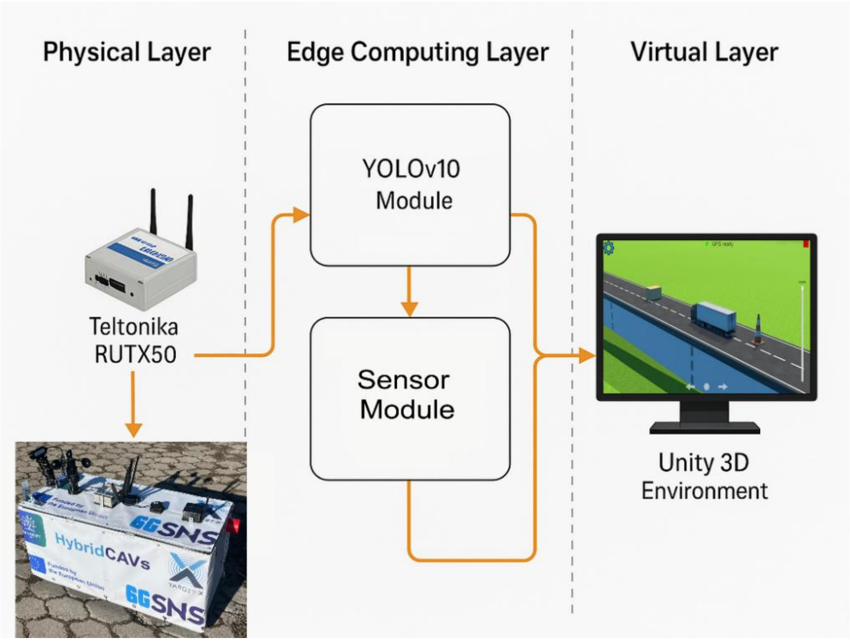


Figure 29 RTwin-CAV End-to-end trial architecture

KEY TECHNOLOGY USED:

- AI perception on vehicle: YOLOv10 object detection (trained with ~2000 labeled images), real-time inference on onboard mini-PC.
- Multi-sensor fusion: RGB + depth camera fusion for distance estimation; GPS used to geo-tag detected objects for placement in the digital twin.
- 5G connectivity: Teltonika RUTX50 5G router on the vehicle, transmitting event messages to back-end services.
- Edge computing (MEC): 5G edge platform used to forward events to the digital twin with very low latency; measured end-to-end detection→digital twin update around ~23–24 ms, compared to ~106 ms via 4G + cloud/AWS baseline.
- Digital Twin platform: Unity-based road digital twin updating vehicle pose and detected objects in real time.
- Back-end software stack: Python services for data handling, logging, and forwarding; secure communication mechanisms as required by the test environment.

KPIs and KVIs

- **Technical KPIs:**
  - **End-to-end latency (vehicle → edge → digital twin):** ~24 ms (5G + edge at IDIADA); **baseline:** ~106 ms (4G + cloud/AWS).
  - **Object detection accuracy (YOLOv10):** mAP ≈ **95%+** on average across trained classes (best on box/cone/wheel; lower on wood-like items).

- **Real-time inference throughput: 4–7 FPS** on onboard computing during live runs.
- **Localization & digital twin synchronization rate:** real-time pose updates with continuous GPS streaming; stable object-placement updates without noticeable drift in typical test runs.
- **Communication reliability:** continuous streaming under 5G coverage with maintained JSON messaging; disconnections mainly linked to VPN/authentication constraints in specific server modes.

- **Vertical KVIs:**
  - **Safety awareness improvement:** hazards detected and visualized in the digital twin fast enough to support proactive operator/vehicle response.
  - **Operational responsiveness:** low-latency edge pipeline enables near-real-time supervision and remote intervention capability compared to cloud-based routing.
  - **Replicability for CAV R&D:** modular architecture (AI perception + depth fusion + 5G/edge + Unity twin) reusable for other vehicles/sensors with minimal adaptation.
  - **Technology readiness advancement:** validated “vehicle + edge + digital twin” workflow in a representative automotive test environment, supporting progression toward higher TRL/field pilots.

Lessons learned

The RTwin-CAV trial showed that end-to-end system performance depends as much on integration choices as on individual components. Deploying the perception-to-twin pipeline over 5G with edge computing reduced round-trip latency by an order of magnitude versus cloud routing, which is essential for timely situational awareness and remote intervention. Yet operational overhead (VPN authentication, session drops, firewall policies) can erode these gains unless connectivity management is streamlined. On the perception side, YOLO-based detection was robust for well-defined classes, but sensitivity to vibration, motion blur, and illumination changes highlighted the need for better mechanical mounting, exposure control, and augmentation during training. Depth-RGB alignment proved to be a practical bottleneck: small calibration errors translate into large distance errors at longer ranges, so periodic calibration checks and confidence reporting are necessary. System engineering lessons were equally important: modular PCB redesign and clear message formats (timestamped JSON, unit conventions, coordinate frames) simplified debugging and enabled rapid iteration. Finally, ethical and data-governance considerations must be addressed early; sending only object type and location (not raw video) supported privacy-by-design while still delivering value to the digital twin. Overall, the trial validated an architecture, but emphasized rigorous validation, logging, and fault-handling for reliable deployment in real driving conditions.

Contribution to Standards

RTwin-CAV contributes practical implementation insights and KPI evidence relevant to ongoing standardization work in connected mobility and edge-enabled services. In particular, our trial experience supports:

3GPP 5G System / MEC deployment considerations: evidence on end-to-end latency improvements when moving from cloud routing to 5G edge computing, useful for URLLC-like safety services and deployment guidelines.

ETSI MEC: lessons learned on application placement at the edge, service exposure, and operational aspects (authentication/VPN, security policies) that affect latency and reliability in real trials.

V2X / cooperative perception message design: we implemented a lightweight event-based message structure (object type + GPS position + timestamp + distance) rather than streaming video, providing a scalable approach aligned with V2X cooperative perception concepts and privacy-by-design principles.

While RTwin-CAV did not submit a formal standards change request during the project, the above results can be shared as concrete trial evidence and recommendations for these standardization domains.

References

Related Publications:

- https://iopscience.iop.org/article/10.1088/1402-4896/ad69e4/meta

Links to Videos / Demos:

- https://www.youtube.com/watch?v=XVt76J2W3jg
- https://www.youtube.com/shorts/ORt2ZGPrqO0

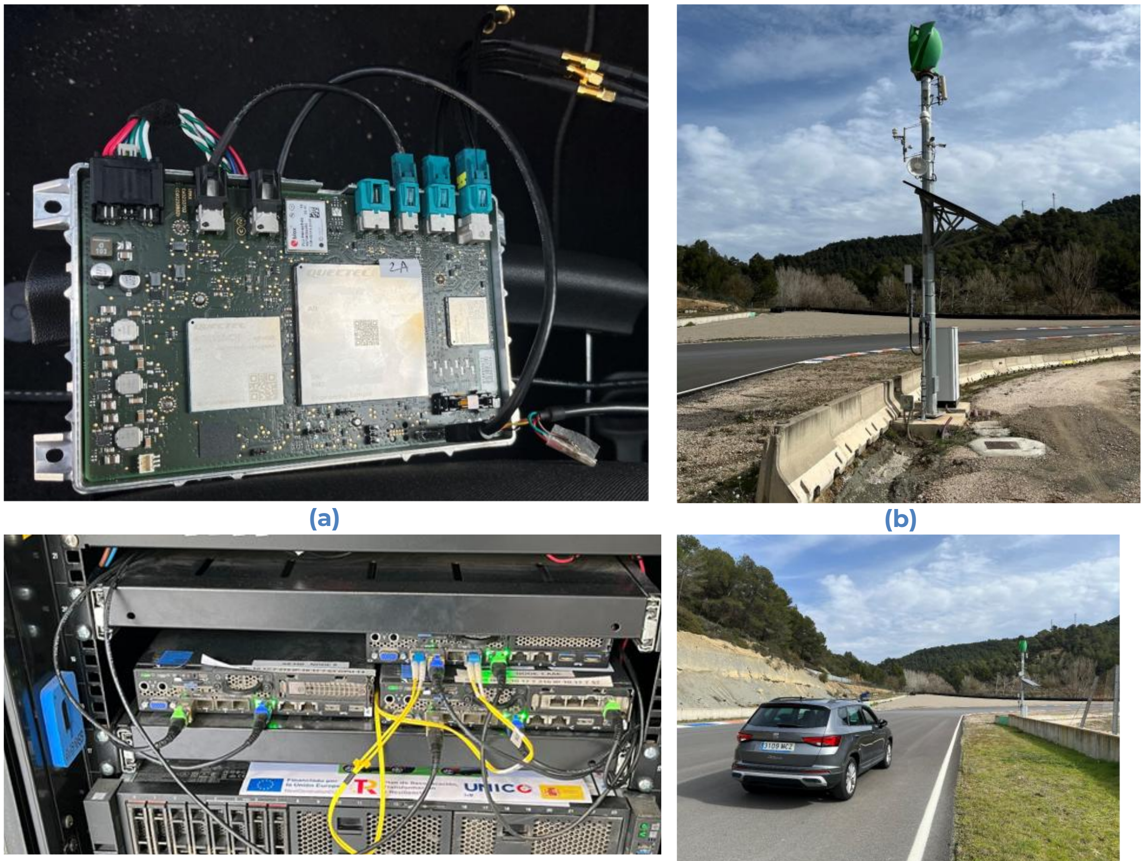
2.3.3 AI-Driven Vehicle Condition Monitoring with Cell-Aware Edge Service Migration

Trial Title: AI-Driven Vehicle Condition Monitoring with Cell-Aware Edge Service Migration
Project Acronym: SUCCESS-6G
Project Full Name: Towards robust, secure, and computationally efficient vehicular services in 6G
Contact Person: Charalampos Kalalas (ckalalas@cttc.es), Miquel Payaro (mpayaro@cttc.es)
Project Website: https://success-6g-project.cttc.es/
Funding Programme: UNICO 5G I+D (Funded by the Spanish National Call)
Main Vertical(s) Addressed: CCAM
Replicability: 41
Geographical Location(s): Castelloli and Barcelona, Catalunya, Spain

Trial Overview

The real-world tests of the SUCCESS-6G project, conducted at the Cellnex Mobility Lab at Circuit Parcmotor Castelloli in February and March 2025, aimed to demonstrate and assess the performance of an AI-based condition monitoring system for real-time vehicular anomaly detection at the edge. The experimental validation focused on replicating realistic vehicular scenarios, including handovers across the edge monitoring infrastructure, varying vehicular speeds and network conditions, to rigorously challenge the system's capabilities in a controlled but dynamic environment. To ensure seamless service continuity during vehicle handovers, the system was enhanced with closed-loop service orchestration, which dynamically triggered service migration in response to real-time network events. Key elements of the condition monitoring service, such as edge-based data processing, service orchestration, communication interfaces, and advanced analytics, were assessed in terms of their responsiveness, reliability, and overall impact on service quality.

Figure depicts various elements of the monitoring infrastructure. A SEAT Ateca R4 2.0 TDI vehicle, equipped with monitoring sensors, continuously transmitted operational status data via its cellular vehicle-to-everything (C-V2X) on-board unit (OBU) to the edge monitoring infrastructure that featured two different 5G Stand Alone (SA) base-stations (gNB) that provided mobile connectivity. The 5G SA mobile network utilized the Raemis™ Druid software solution, a 3GPP-compliant 5G core with REST API and additional functionalities. The edge computing infrastructure consisted of two servers, each associated with a gNB, hosting virtual machines (VMs) for the Dockerized services. The vehicle's trajectory involved multiple handovers between the gNBs and their respective edge servers. Service orchestration was managed by the NearbyOne[1] orchestrator.



(a) (b)

(c) (d)

Figure 30:: Experimental setup at the Circuit Parcmotor Castelloli: (a) On-board unit used in the trials, (b) 6G SA gNB, (c) Edge servers in the control room, (d) Vehicle approaching the gNB.

Trial deployment including integration with vertical solutions

Figure ***31***9 illustrates the considered trial deployment architecture, where an edge monitoring infrastructure was deployed to monitor the vehicle condition across its trajectory. The vehicle was equipped with monitoring sensors that acquired status information related to various vehicular operations. Transmission to the edge infrastructure occurred with the aid of a vehicular OBU, which aggregated information from the sensors. Network connectivity was provided by C-V2X technology, offering scalable and seamless wireless communication between the vehicle and the two available gNBs. The transmitted measurement streams were then processed at the edge monitoring nodes, which offer computational resources close to the vehicle for real-time condition monitoring.

[1] https://www.nearbycomputing.com/wp-content/uploads/2021/09/Product-Data-Sheet-NBYCOMP.pdf

A service orchestrator (NearbyOne) was further deployed to provide lifecycle management functionalities to the vehicular condition monitoring service at the edge. In the case of handovers, the service orchestrator performed service migration across the available edge nodes based on events originating from the 5G core network. Based on the knowledge extracted and with the help of appropriate visualization tools, instructive and actionable insights could be derived, e.g., flag whether a fault has occurred and diagnose its type in event-detection operations.

Each edge node was associated with a gNB and comprised i) a dedicated VM for hosting the distributed user plane function (UPF) of its associated gNB; ii) a VM reserved for the condition monitoring service; and iii) a third VM, isolated from all others, used for the 5G network application programming interface (API) and network event calls. Specifically, the condition monitoring service involved two microservices: i) a Mediator service which adapts the OBU messages into the appropriate inference request format; and ii) a KServe inference service enabling scalable and low-latency real-time inference directly from vehicle measurement streams.

The local cloud provided a cluster of VMs that support different services. The 5G core network was deployed within a dedicated VM, isolated from all other services. Another isolated VM hosted all backend components, including Grafana, a visualization tool that creates dashboards to monitor system performance and model behavior. The Redis database for storing vehicular data was deployed in a third VM, while a fourth VM was allocated for network measurement tools.

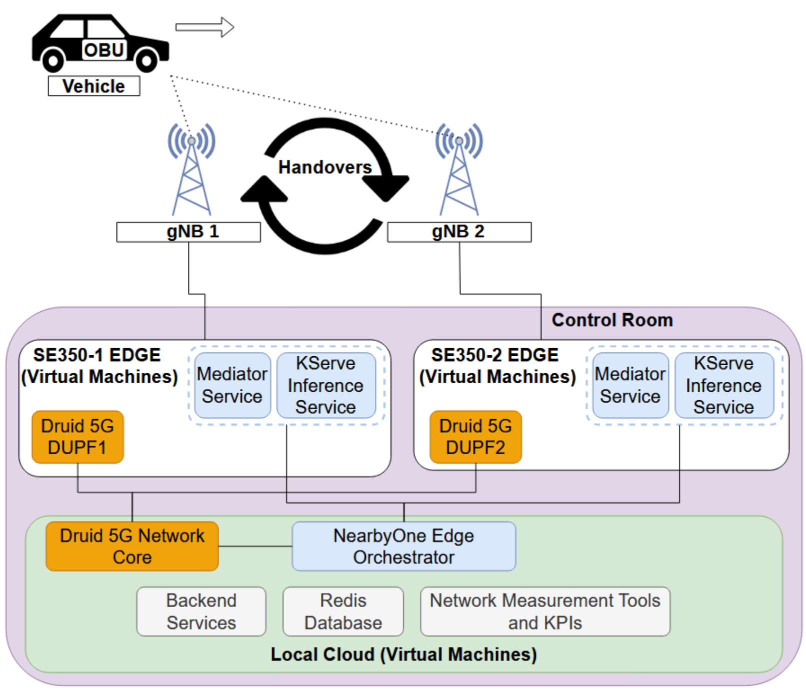


Figure 31: Edge infrastructure for vehicle condition monitoring system with C-V2X connectivity and associated services. Services related to the 5G standalone network are highlighted in orange, while all other services are relevant to the condition monitoring use case.

KEY TECHNOLOGY USED

- 5G standalone network for ultra-reliable low-latency connectivity
- Cellular V2X (C-V2X) for real-time vehicle-to-edge data transmission
- Multi-access edge computing for localized low-latency processing
- AI-based anomaly detection (LightGBM classifier) for real-time vehicle condition monitoring
- KServe-based edge AI serving for scalable low-latency inference
- Closed-loop orchestration with cell-aware service migration for seamless mobility support
- Containerized microservices and Kubernetes orchestration for flexible deployment and lifecycle management

KPIs and KVIs

- **Technical KPIs:**
  - KServe inference time
  - Service migration time (with and without the Mediator module)
  - Anomaly detection performance: precision, recall, F1-score
  - Network latency, throughput
  - Radio quality: Reference Signals Received Power (RSRP) and Reference Signal Received Quality (RSRQ), Signal-to-Noise Ratio (SNR)
  - OBU downtime and uptime

- **Vertical KVIs:**
  - Operational efficiency: Unplanned downtime can be avoided via component failure provisioning, while vehicle maintenance can be performed only when necessary
  - Service availability: Service continuity is guaranteed during vehicle handovers
  - Situational awareness: Vehicular equipment's lifespan can be optimised to its fullest with a minimisation of the number of unexpected breakdowns
  - User satisfaction: Safer driving experience

- **Measurement Methodology:**

The vehicle data acquisition architecture is depicted in *Figure*. The deployment of the applications involved migrating the V2X data parser and receiver from the vehicle and deploying a Redis database on the server side. Network KPIs were collected from the dashboard of the Raemis™ Druid software. Condition monitoring metrics were collected and stored in InfluxDB, allowing precise and systematic analysis of inference behaviour by visualising in real-time the condition of vehicle assets during the trials. Orchestration metrics were reported both on the NearbyOne dashboard and the edge node's resource orchestration platform (e.g., Kubernetes). Finally, KVIs were defined prior to the deployment phase, and operational feedback was reported during the trials.

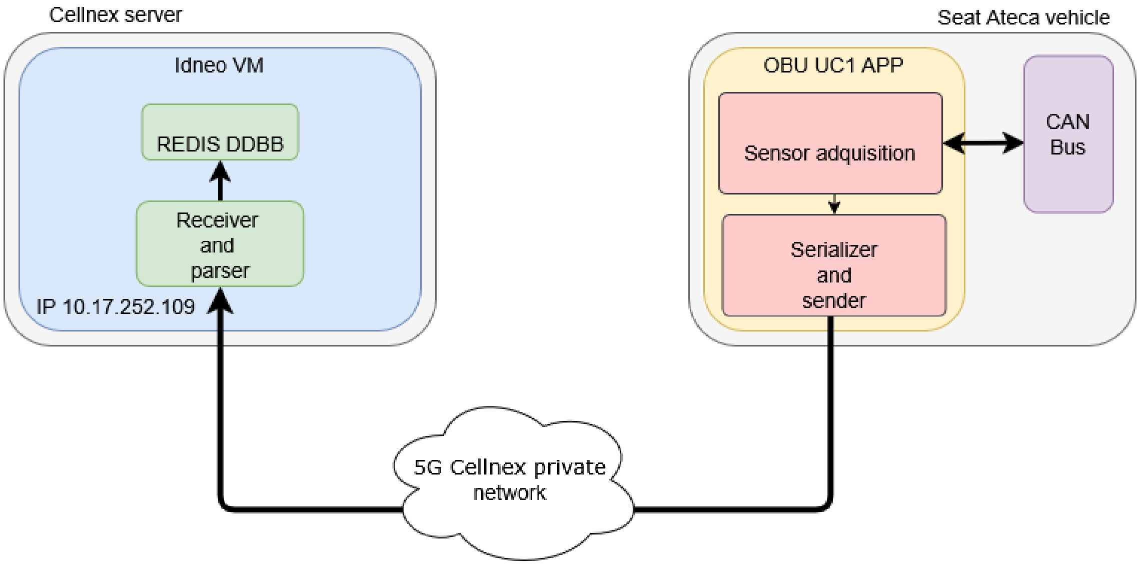


Figure 32: Vehicle data acquisition architecture

Lessons learned

Technical insights: Low-latency inference time for condition monitoring and service continuity was achieved across the edge infrastructure. While the detection of collective anomalies in contiguous time windows was effectively performed, the efficacy in detecting isolated anomalies was limited. The insights gained from the trials not only confirmed the feasibility of the solution in a near-real-life-deployment environment but also helped identify opportunities for fine-tuning specific components, such as optimizing the data ingestion pipeline, improving predictive maintenance algorithms, or enhancing V2X link reliability.

Operational insights: The testing activities served as a vital step toward demonstrating the readiness of the condition monitoring service for further integration into broader intelligent transportation systems, paving the way for scalable deployments in 6G-enabled vehicular networks.

Measurement insights: The Mediator micro-service, a Redis consumer that adapts OBU messages for inference and forwards responses to the observability backend, was observed to negatively impact the migration duration. Thus, service migration can benefit from an AI-based vehicular trajectory system and thus guarantee service continuity.

Contribution to Standards / Open Source:

- Open-source software for vehicle condition monitoring service: https://github.com/5uperpalo/success6g-edge
- Documentation: https://5uperpalo.github.io/success6g-edge/

References

Related Publications:

- C. Kalalas *et al.*, "AI-Driven Vehicle Condition Monitoring with Cell-Aware Edge Service Migration," 2025, *arXiv:2506.02785*. [Online]. Available: https://arxiv.org/abs/2506.02785

Related Deliverables:

- https://success-6g-project.cttc.es/images/deliverables/E10-EXTEND.pdf
- https://success-6g-project.cttc.es/images/deliverables/E11-EXTEND-Final%20testing%20and%20validation%20of%20service%20KPIs.pdf

2.4 EHEALTH & EDUCATION

2.4.1 5G/6G for Elderly Monitoring

Trial Title: 5G/6G for Elderly Monitoring
Project Acronym: 6G-PATH
Project Full Name: 6G Pilots and Trials Through Europe
Contact Person: MCS Datalabs - Gregor Liebscher (gregor.liebscher@mcs-datalabs.com)
Charité Geriatric Research - nils.lahmann@charite.de, Fraunhofer FOKUS - andreea.ancuta.corici@fokus.fraunhofer.de
Project Website: https://6gpath.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Healthcare, Elderly Care, Rehabilitation
Replicability: 59
Geographical Location(s): Berlin, Germany
Supported testbed(s): Fraunhofer FOKUS Testbed

Trial overview

The UC HEALTH 2 trial aims to demonstrate how 5G/6G technology, specifically edge computing and Quality of Service (QoS) capabilities, can enable continuous monitoring and rapid emergency response for elderly populations in care facilities. The trial validates the reliability of real-time vital signs transmission, fall detection alerts, and telehealth video consultations, even under varying network conditions.

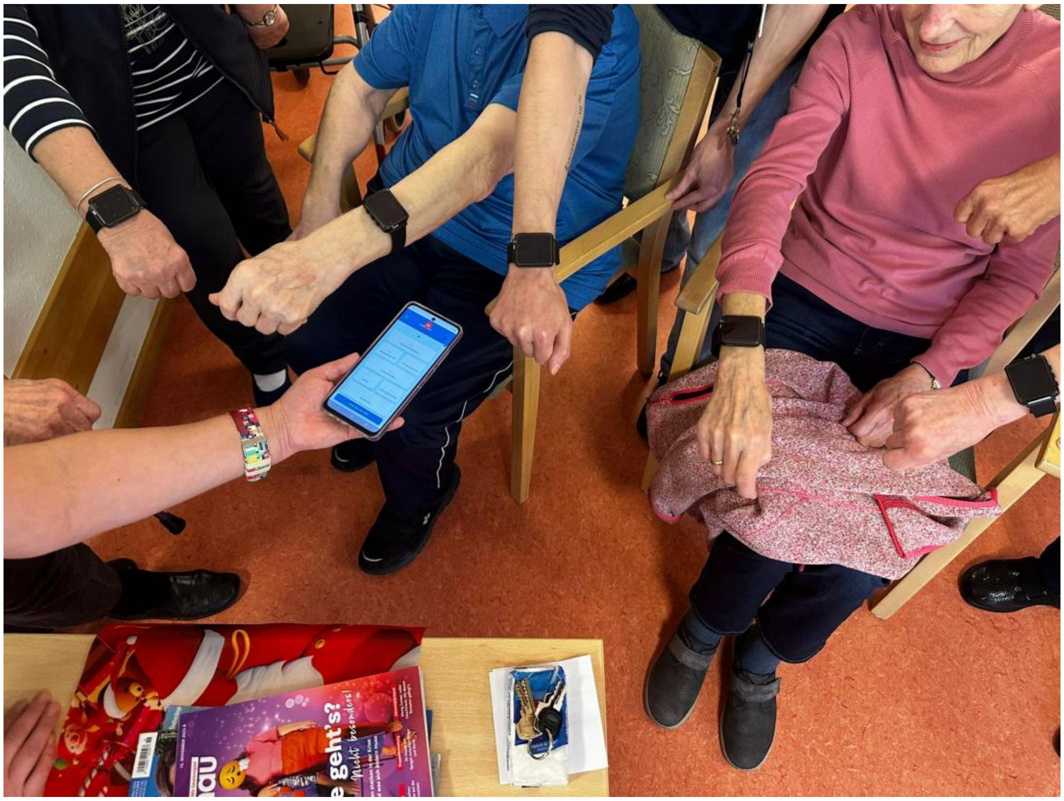


Figure 33: Elderly participants wearing smartwatches during the UC HEALTH 2 kick-off session in the nursing home

Trial deployment including integration with vertical solutions

Fraunhofer FOKUS's Open5GCore testbed with microservices architecture was used during the trial. The vertical domain systems (smartwatch monitoring, pain detection algorithms, meineReha Coaching App, telehealth platform) are connected to the 5G/6G network via the edge-core split architecture. The edge handles time-critical operations locally, ensuring fall alerts receive immediate processing, while the central core manages device profiles and longitudinal data. The QoD service is integrated through Telefonica's OpenCAPIF, enabling dynamic QoS requests for prioritized traffic. MCS Data Labs provides the smartwatch analytics, while geriatrics research group from Charité - Universitätsmedizin Berlin delivers the clinical validation environment and the meineReha rehabilitation application.

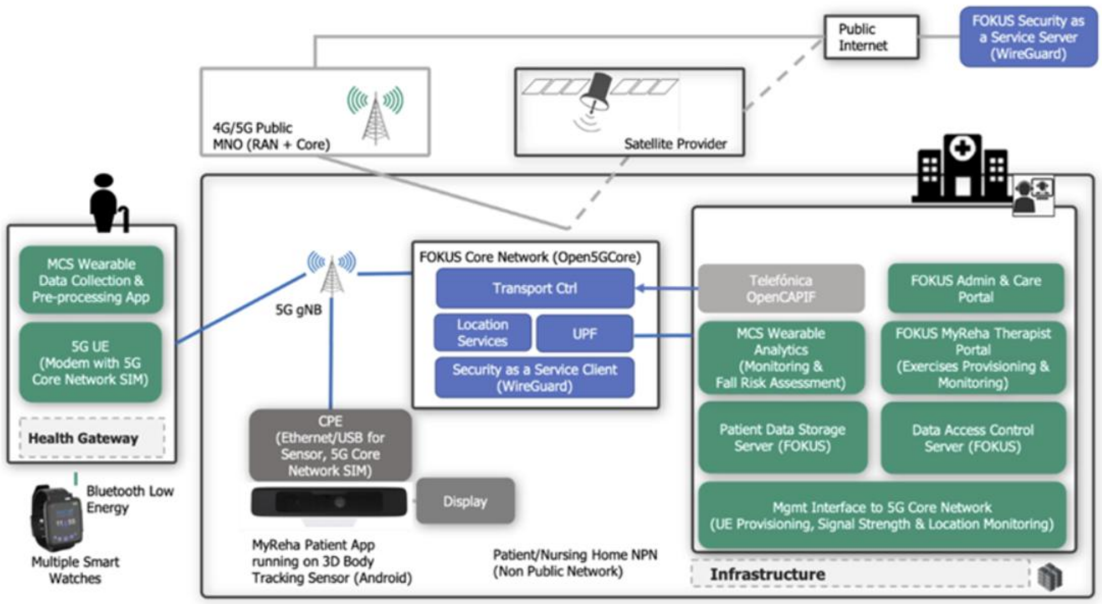


Figure 34: End-to-end trial architecture for UC HEALTH 2

The architecture comprises a Health Gateway connecting multiple smartwatches via Bluetooth Low Energy to a 5G UE (modem with 5G Core Network SIM). The MCS Data Labs Wearable Data Collection & Pre-processing App runs on the gateway. Data flows through the 5G gNB to the FOKUS Core Network (Open5GCore), which includes Transport Control, Location Services, UPF, and Security as a Service Client (WireGuard). The infrastructure side hosts Telefonica OpenCAPIF, MCS Wearable Analytics (Monitoring), FOKUS MyReha Therapist Portal, Patient Data Storage Server, and Data Access Control Server. The MyReha Patient App runs on a 3D Body Tracking Sensor (Android) connected via CPE to the Patient/Nursing Home Non-Public Network.

Figure 35: MeineReha Coaching App demonstration with 3D body tracking avatar during group exercise session.

Key 5G/6G Technologies Used:

- 5G/6G Core Network (Open5GCore with microservices architecture)
- Edge Computing for local data processing
- Network Slicing (prioritized traffic for fall detection events)
- Quality on Demand (QoD) / Dynamic QoS enforcement via OpenCAPIF
- Device Location Services (TS23.273 compliant)

KPIs and KVIs

- **Technical KPIs:**
    - Edge-to-Central Connectivity Establishment
    - End-to-End Connectivity Establishment
    - Device Scalability
    - Data Upload Capacity
    - Packet Loss Rate
    - Prioritized Message Latency (fall events)

- **Vertical KVIs:**
  - Operational Efficiency: Improvement in caregiver workflow and resource allocation
  - Quality of Care: Evidence-based rehabilitation through data-driven insights
  - Emergency Response: Fast reaction to fall events through detection and QoS enforcement
  - Communication Reliability: Percentage of time critical communications are maintained
  - User Satisfaction: Feedback from elderly participants and nursing staff on system usability

- **Measurement Methodology:**

Network KPIs were measured through monitoring tools integrated into the Open5GCore testbed. The smartwatch and telehealth services under test were instrumentalised to report application performance metrics. Application metrics have been integrated into the 6G-PATH Monitoring Analytics and are visualised in real time during the trials. KVIs were collected through semi-structured interviews with health care students and geriatric care experts at Charité-Universitätsmedizin Berlin (June 2025), followed by operational feedback from nursing home staff via questionnaires and post-trial debriefings (December 2025 - February 2026).

Lessons learned

Technical insights: Edge-core split architecture on the Open5GCore testbed requires careful coordination between network components and application services. Dynamic QoS through OpenCAPIF provides valuable flexibility for prioritizing alerts but needs well-defined policies for automatic activation. Data pipeline integration between MCS smartwatch analytics and the FOKUS backend required iterative debugging using isolated InfluxDB instances before full integration.

Operational insights: Elderly participants and nursing staff appreciated the reliability of fall detection and vital signs monitoring, but emphasized the importance of simple, intuitive interfaces for daily use. Training and familiarization with technology proved essential for effective deployment. On-site support during initial sessions built trust and confidence among users.

Contribution to Standards / Open Source:

- Validation of Open5GCore microservices architecture in real-world healthcare scenarios

References

Related Publications:

- Andreea Ancuta Corici, Simone Kuntz, Mareike Jansen, Anne Grohnert, Gregor Liebscher, Benny Häusler, Marius Corici, Nils Lahmann, Hemant Zope, Fabian Eichhorn, Tim Bormann, Celin Mousa, Zak Seridarian, Sulaiman Shamasna: Employing 5G Mobile Networks in Keeping Elderly Healthy and Active. HealthCom 2024: 1-4
- Fernandes, J. et al. "Paving the Path to 6G: The 6G-PATH Project's Vision for Advanced Telecommunications' Infrastructure and Use Cases." IEEE, 2024. https://ieeexplore.ieee.org/document/11028780/

Related Deliverables:

- https://6gpath.eu/
- https://6gpath.eu/vertical-3-health/uc-health-2-elderly-monitoring/

Links to Videos / Demos:

- https://www.youtube.com/@6gpath/video

2.4.2 Chronic Wounds Management with Personalized 3D-Hydrogel Patch

Trial Title: Chronic Wounds Management with Personalized 3D-Hydrogel Patch
Project Acronym: 6G-PATH
Project Full Name: 6G Pilots and Trials Through Europe
Contact Person: Charité Geriatric Research Group and Fraunhofer FOKUS
(nils.lahmann@charite.de, andreea.ancuta.corici@fokus.fraunhofer.de)
Project Website: https://6gpath.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: eHealth
Replicability: 61
Geographical Location(s): Fraunhofer FOKUS Testbed

Trial Overview

Chronic wounds are a growing challenge in elderly care, requiring both treatment of underlying diseases and stage-specific wound assessment. Improved technology for high-quality imaging and reliable remote data transmission is essential to support effective digital wound therapy, particularly in rural areas.

The trial addresses this gap by employing a B5G-enabled medical service supported by nomadic micro-networks in a vehicle, which provides secure and dependable connectivity at the patient's location, as well as computational resources and bioprinting capabilities. The approach aims to combine 3D wound scans analysis for digital wound documentation and generating on-site personalised bioprinted patches, e.g. using bioinks like hydrogel for wound dressings.

The objective is to develop a custom-made 3D-printed hydrogel patch derived from a digital wound model, ensuring an exact fit to the wound bed, edges, and surrounding tissue (*Figure* This process will improve the quality of care for patients with chronic wounds, particularly in underserved rural areas where mobile connectivity is limited.

Figure 36 Chronic Wounds Management with Personalized 3D-Hydrogel Patch use case overview

In the implementation, a 3GPP aligned prototype of the Core Network, the Open5GCore Edge Router enables the connectivity reliability over available backhauls from mobile operators and satellite providers. The application-level data access requirement is fulfilled by employing OAuth2.0 authentication and authorization framework and the HL7 FHIR standard for storing the patient data. As end devices, the smartphone or tablet are used to scan the wounded area and the Nurse Care App is used to send the data and ask for wound analysis. The prototype was validated with a do-it-yourself 3D bio-printer, based on a 3D printer that can be connected via a 5G Customer Premises Equipment (CPE) (see Figure).

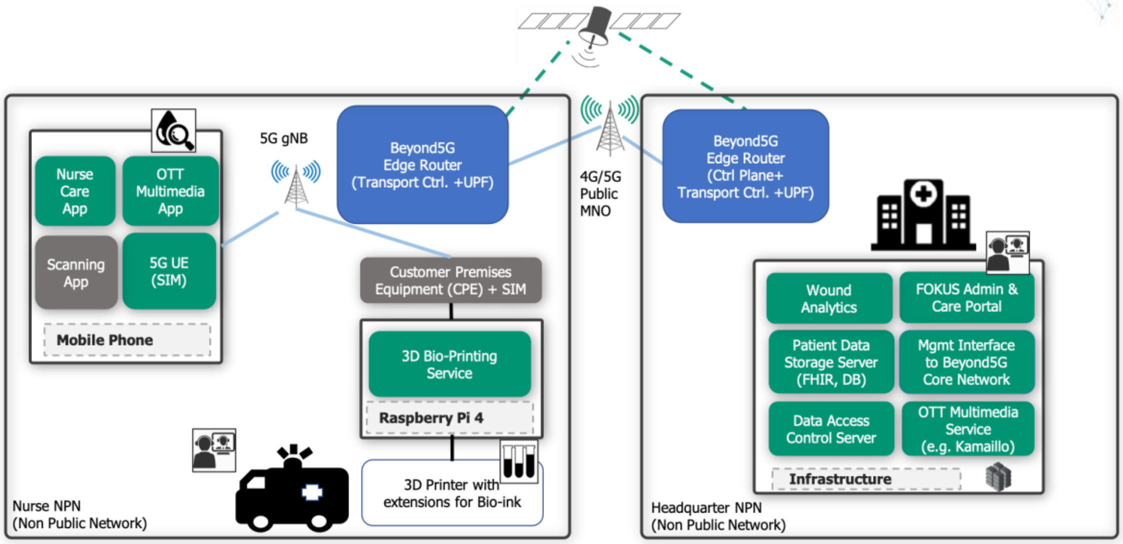


Figure 37 6G-PATH - 3D Hydrogel Patch usecase topology

Trial deployment including integration with vertical solutions

The trial utilised the Fraunhofer 5G/6G testbed integrating Open5GCore and Amarisoft gNB components, connecting mobile devices to the healthcare digital platform and integrating the Charité clinical infrastructure.

Mobile devices and 5G tablets were running the Nurse Care App, which connected to the FHIR-based backend over a 5G network; real-time data processing enabled local storage and transformation for hydrogel patch preparation.

Vertical integration enabled automated wound segmentation, dimensional analysis, and data transformation to 3D-printable formats. The eHealth components interface via REST APIs with secure HL7 FHIR Store endpoints, ensuring interoperability and clinical data integrity.

KPIs and KVIs

- **Technical KPIs:**

The KPIs identified that are required for the trial and current piloting activities include:

- **Network KPIs:** latency in connectivity establishment, capacity for upload and download of data, system-connected devices capacity and reliability
- **Vertical KPIs:** time to perform, as well as 2D wound segmentation and 3D measurements accuracy

- **Vertical KVIs:**

By analysing the trial use case, the identified KVIs include:

- Economic KVIs: operational cost savings, productivity and efficiency gains, resource efficiency gains
- Social KVIs: improved public health and safety, digital inclusion and accessibility, enhanced quality of life, improved digital skills and competency, increased technology adoption and digital uptake, improved emergency response and preparedness, improved social connectivity and participation, enhanced user satisfaction and perceived value
- Service Quality KVIs: perceived system reliability, perceived responsiveness, perceived data security and privacy

Lessons learned

Experts confirmed high accuracy and usability of the integrated wound care platform and endorsed its potential for clinical deployment. Participants reported high perceived value in telehealth-enhanced wound care and strong support for digital solutions in clinical workflows.

Lessons learned include the need for system reliability, integration with clinical IT and potential for AI-assisted wound recognition.

Outcomes contribute to European best practices for connected healthcare and future 6G-enabled telemedicine deployments.

References

Related publications:

- A. Corici, M. Hocquel-Hans, K. Chaudhary, S. Kuntz, M. Corici, B. Häusler, H. Zope, A. Deter, A. Grohnert, N. Lahmann. "Implementation Design and Validation Results of a Chronic Wound Management System Powered by Beyond 5G Private and Nomadic Networking". Artificial Intelligence Applications and Innovations. AIAI 2025 IFIP WG 12.5 International Workshops. AIAI 2025. IFIP Advances in Information and Communication Technology, vol 753. Springer, Cham. https://doi.org/10.1007/978-3-031-97317-8_14

- A. Corici, N. Lahmann, M. corici, M. Hocquel-Hans, S. Kuntz, A. Deter, A. Grohnert, B. Häusler, H. Zope. "5G Wound Management System for Remote Areas". 4th edition of the IEEE Conference on ICT Solutions for eHealth (ICT4eHealth) 2024, https://6gpath.eu/wp-content/uploads/2024/07/5g_Wound_Management_ICTS4eHealth2024.pdf

Deliverables:

- D2.1 Platfrom architecture and verticals-initial, D3.1 6G-PATH experimentation environment – initial, D4.1 – Verticals experiments -initial, D6.1 6G trials and pilots validation and evaluation – initial from: https://6gpath.eu/public-deliverables/

Videos and an overview of the trial use case:

- URL: https://6gpath.eu/vertical-3-health/uc-health-1-3d-hydrogel-patches/

2.4.3 CLASSROOM OF THE FUTURE

Trial Title: Classroom of the Future (XR-based Higher Education on B5G)
Project Acronym: 6G-PATH
Project Full Name: 6G Pilots and Trials Through Europe
Contact Person: Qi Wang (qw96@leicester.ac.uk) and Jose Maria Alcaraz Calero (j.alcarazcalero@aston.ac.uk)
Project Website: https://6gpath.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2023-STREAM-D-01-01
Main Vertical(s) Addressed: Education
Replicability: 36
Geographical Location(s): Leicester, Aston and Paisley, UK

Trial Overview

The Classroom of the Future trials aim to demonstrate the creation of an immersive teaching and learning environment based on eXtended Reality (XR) for higher education with a specialized topic on realistic 5G and beyond infrastructure over a beyond 5G testbed. The trial validates the operation of the XR application and the delivery of the topic on 5G and beyond infrastructure to students in a university setting.

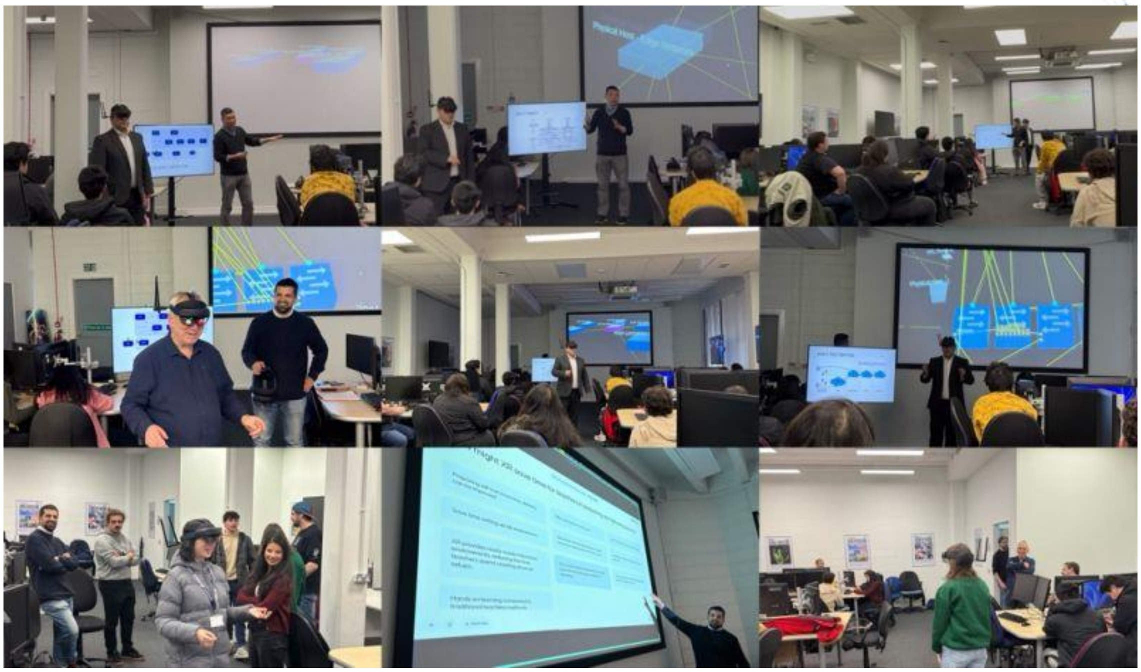


Figure 38. Classroom of the Future trial

Trial deployment including integration with vertical solutions

The Three commercial 5G network and the Aston Testbed are used during the trial. The vertical domain systems (XR application, and XR devices) are connected to the 5G network, and the backend services that provide the beyond 5G infrastructure information are located in the Aston Testbed, which also offers network slicing based on data path programmability.

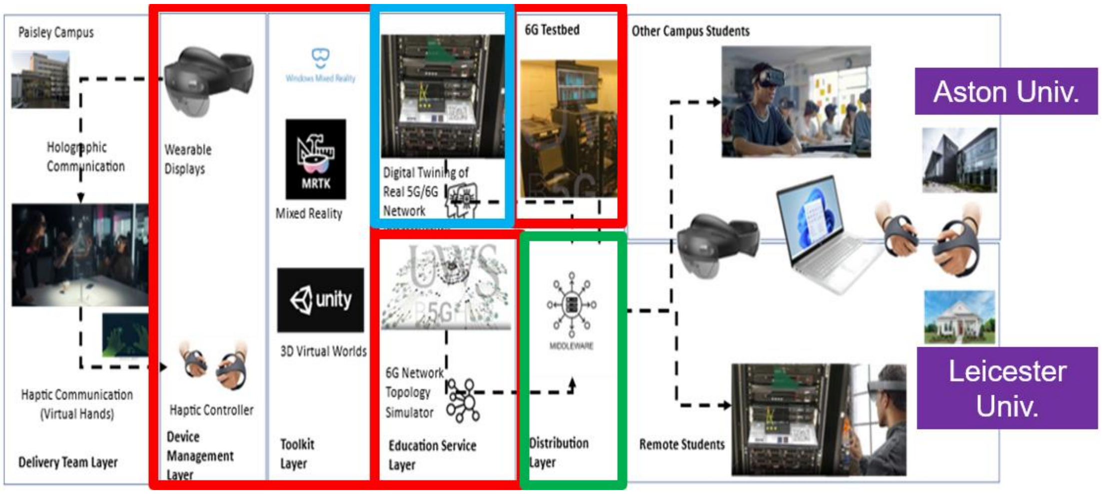


Figure 39. Classroom of the Future end-to-end architecture

Key 5G and Beyond Technologies Used:

- 5G Network,
- Topology awareness in complicated virtualized network infrastructure,
- Network Slicing based on data path programmability.

KPIs and KVIs

- **Application Technical KPIs:**
    - Newly developed XR app: Develop new XR teaching and learning materials to deal with one of the pain points on the lack of XR-based teaching & learning materials for higher education.
    - Visualised devices: Number of supported networked devices visualised in the same topology in the subject domain (5G and beyond) to deal with one of the pain points on the lack of large-scale visualisation for complex 5G and beyond networking infrastructure representation for higher education.
    - Visualised connections: Number of supported connections among devices visualised in the same topology in the subject domain (5G and be-yond) to deal with one of the pain points on the lack of large-scale visualisation for complex 5G and beyond networking infrastructure representation for higher education
    - Key techno-logical concept visualization: Number of visualised key technological concepts in the subject domain (5G and beyond) to deal with one of the pain points on the lack of visualisation of virtualisation-based concepts in 5G and beyond networking infrastructure representation for higher education.

- **Vertical KVIs:**
    - Operational Cost Savings: Long-term operational costs reduction.
    - Resource Efficiency Gains: Improvement of utilisation of digital learning resources.
    - Productivity and Efficiency Gains: Gains in productivity and efficiency.
    - Improved Digital Skills & Competency: Enhancement of practical and theoretical skills.
    - Enhanced Quality of Life (via learning outcomes): Improvement of academic performance.
    - Digital Inclusion & Accessibility: Improvement of accessibility and collaboration across locations.
    - User Satisfaction: Satisfaction with the learning environment.
    - Interactive Experience Quality: Improvement of interactivity and engagement.
    - Content Quality: Improvement of content relevance and quality.
    - Perceived Ease of Use: Ease of use of the XR system.
    - Perceived Responsiveness: Learning efficiency.

- **Measurement Methodology:**

Application KPIs are measured in the XR application. KVIs were collected through feedback from students and teaching staff via questionnaires and focus groups.

Lessons learned

Technical insights: Visualisation of a complicated real-world 5G and beyond infrastructure with a large number of network devices, connections and virtualisation technologies has proven to be challenging in an XR application.

Operational insights: Teaching staff reported that XR can replace expensive physical labs and reduce equipment wear, though high initial development and setup costs were highlighted. Students acknowledged cost benefits from virtualisation and shared access, but noted that differences in learning styles and preparation effort may affect efficiency.

Measurement insights: In-app measurement of application KPIs are useful under the condition of limited capacity of rendering of 3D objects in the XR application. KVIs collection require significant efforts in recruiting students and teaching staff and organising the trials.

Contribution to Standards / Open Source:

- Input for future deployment and trials of XR-based use cases especially in the higher education sector.
- Informed the ITU-T Focus Group on Artificial Intelligence Native for Telecommunication Networks (FG AINN) through invited talks at ITU-T AI for Good Summit - AI and Machine Learning in Communication Networks Workshop 2024 and 2025.

References

Related Deliverables:

- https://6gpath.eu/wp-content/uploads/2025/12/6G-PATH-D2.2-Platform-architecture-and-verticals-midterm-v1.0_Final.pdf.

Links to Videos / Demos:

- https://www.linkedin.com/feed/update/urn:li:activity:7398412526834720768/

2.4.4 Enhanced Healthcare Education

Trial Title: Enhanced Healthcare Education	
Project Acronym: 6G-PATH	
Project Full Name: 6G Pilots and Trials Through Europe	
Contact Person: Anna Brunstrom (anna.brunstrom@kau.se)	
Project Website: https://6gpath.eu/	
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2023-STREAM-D-01-01	
Main Vertical(s) Addressed: Education. eHealth	
Replicability: 41	
Geographical Location(s): Karlstad, Sweden	

Trial Overview

The trial illustrates how the use of a private 5G Standalone (SA) network can enhance the training of prehospital nurses. Practical training with manikins in simulated environments is a crucial part of their education. During manikin-based training, the manikin is usually laying in a bed in a classroom with the instructor situated in an adjacent room, providing voice responses and controlling certain reactions based on the students' actions.

The trial demonstrates how 5G SA with network slicing and edge compute provides the quality of service and flexibility required to relocate the manikin from its fixed classroom to locations that offer a more authentic medical scenario, also allowing students to follow the scenario from a distance. This paves the way for more realistic, scalable and cost-efficient training.

Figure 40. Enhanced Healthcare Education trial

Trial deployment including integration with vertical solutions

The trial was conducted over a private 5G SA network at the Karlstad University campus, with local breakout and edge compute capabilities. The manikin was placed at a simulated medical accident scene, and remotely controlled over the 5G network. In order to support remote control of the manikin, the site was equipped with multiple cameras for high-quality video and microphones/speakers for audio input and output. The manikin control and video feeds were sent over a dedicated network slice to ensure the required quality. To reduce latency, a streaming server deployed at the edge managed the video feeds. Additionally, the medical scenarios that took place could be viewed from a remote training site and the videos were also collected for KPI and KVI evaluations.

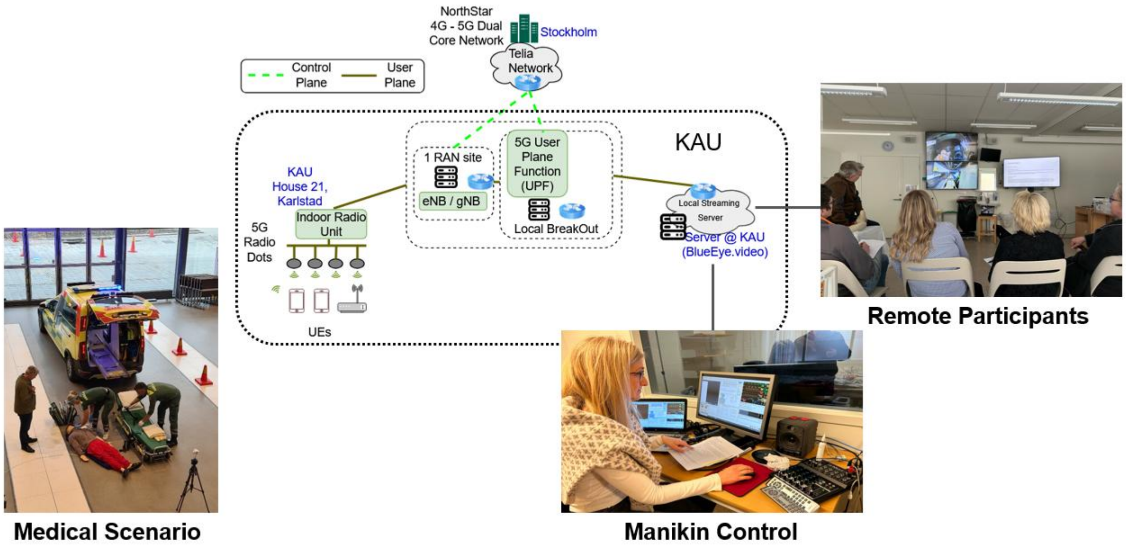


Figure 41. Trial architecture representing the manikin and cameras connected over a 5G slice. A local edge streaming server distributes the video.

Two medical scenarios were simulated during the trial. The first medical scenario involved a Patient with COPD and heart failure being treated for suspected UTI without improvement. When the simulation starts the patient has already been loaded into an ambulance on a stretcher. The patient is dizzy and nauseous, and is given various treatments in the ambulance.

The second medical scenario involved a Patient who was walking with his son and collapsed outside the house. It looked like he was having a short seizure. The simulation starts as the ambulance is arriving at the scene. According to the son, who is on site, the patient has previously had a heart attack and is taking medication after this. The ambulance nurses carry out various actions before the patient is loaded into the ambulance. In connection with loading, Patient again has what is interpreted as a seizure, about 5 seconds and becomes unconscious. Treatment of the patient continues inside the ambulance.

Key 5G and Beyond Technologies Used:

- Private 5G Standalone (SA) network
- Network Slicing (three parallel slices)
- Quality of Service (QoS) differentiation via 5G QoS Identifiers (5QI) and radio resources scheduling via API
- Edge Computing co-located with the 5G Core
- IoT devices with native 5G connectivity

KPIs and KVIs

- **Technical KPIs**
    - E2E latency for manikin control: RTT
    - Video performance: Video quality and video latency
    - Radio coverage: RSRP, RSRQ
    - Network latency: RTT

- **Vertical KVIs**
    - Reduced training costs
    - Enhanced health education.
    - Increased student engagement.
    - Increased support for diversity and inclusion in training.
    - User satisfaction with the training solution.

- **Measurement Methodology:**

To evaluate latency, we used ICMP ping between the manikin NUC and the server in the control room. To assess the video quality, we employed the Video Spatial-Temporal Feature Aggregation (VSFA), which is a deep learning-based architecture designed for no-reference subjective video quality evaluation. VSFA utilizes spatial and temporal feature aggregation to predict human-perceived video quality on the Mean Opinion Score (MOS) scale from 1 to 5. To measure the video delay we inserted a send timestamps in the video and calculated the delay at the receiver. To collect the KVIs we used a set of questionnaires along with a small focus group discussion.

Lessons learned

Technical insights: Network slicing and edge compute capabilities provide the latency and reliability required, but video quality is still a challenge. It involves many aspects that are not related to the network. This poses the risk that aspects that are not related to the 5G/6G infrastructure impacts the results.

Organizational insights: Focus group discussions provide valuable insights on how to improve the use case. It was for example suggested that the video views of the medical trial scenario could be complemented with additional information about the scenario, maybe as pop-up windows. It illustrates the importance of integrating the end users early in the design process.

Operational insights: It is challenging to assess all metrics at the same time, both logistically and to avoid a technical issue jeopardizing the user studies. Careful planning is needed for what KPIs and KVIs to collect in the same trial. Some KPIs may better be collected in dedicated technical trials.

References

Related Publications:

- M. Rajiullah et al., "Enhancing Healthcare Remote Education with 6G and XR Technologies," 2024 3rd International Conference on 6G Networking (6GNet), Paris, France, 2024, pp. 216-220, doi: 10.1109/6GNet63182.2024.10765675.

Related Deliverables:

- https://6gpath.eu/wp-content/uploads/2025/09/6G-PATH-D4.1-Verticals-Experiments-Initial_v1.0.pdf

Links to Videos / Demos:

- https://youtu.be/s4jogA86GXc

2.5 IMMERSIVE MEDIA, EXTENDED REALITY (XR) and JCAS/ISAC

2.5.1 5G XR Gamming competition

Trial Title: 5G XR gaming competition (Media)
Project Acronym: IMAGINE-B5G
Project Full Name: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe
Coordinator: Universitat Politecnica de Valencia (UPV)
Contact Person: David Gomez-Barquero <dagobar@iteam.upv.es>
Project Website: https://imagineb5g.eu/
Project Duration: 27 months (January 2023 - March 2026)
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Media
Replicability: 35
Geographical Location(s): Valencia, Spain
Supported testbed (s): UPV Campus Site of the IMAGINE-B5G Facility, Valencia, Spain

Trial Overview

This trial aimed at deploying a novel edge/cloud-based XR platform into the IMAGINE-B5G project infrastructure at UPV, where resource-intensive tasks are offloaded, while delay-critical tasks are executed on the head-mounted display, which includes a dynamic object detection and tracking service. The app is a multi-player car soccer game, where real and virtual cars are tracked in real-time and play with a virtual ball, achieving true XR. Real-world experiments consisted of a student gaming competition with 19 participants to test the application and gather data. Results show that network slicing and edge/cloud are beneficial for real-time XR applications. Also, B5G infrastructure has proven able to support XR applications in real-time. Users highly rate the XR application for gaming, although few improvements must be made to solve key usability issues.

Figure 42. XR application snapshot with virtual car, ball and part of the field. Real car and green field (left). Tracking iPhone on the center. Spectator view on the right.

Trial deployment including integration with vertical solutions

During the experiments a remotely controlled toy car was detected and tracked in real-time, interacting with a virtual ball which moved according to the collisions. Based on instantaneous events in the game, special effects were also triggered and displayed at event-specific positions. To solve the two-car tracking limitation, it was decided to combine one physical and one virtual car into a common game where both users are equipped with HoloLens 2 HMDs watching the same field; one of the users controls a physical car while the other user plays with a virtual one similarly driven. The remotely rendered images, including the virtual ball and special effects, were sent to the client devices.

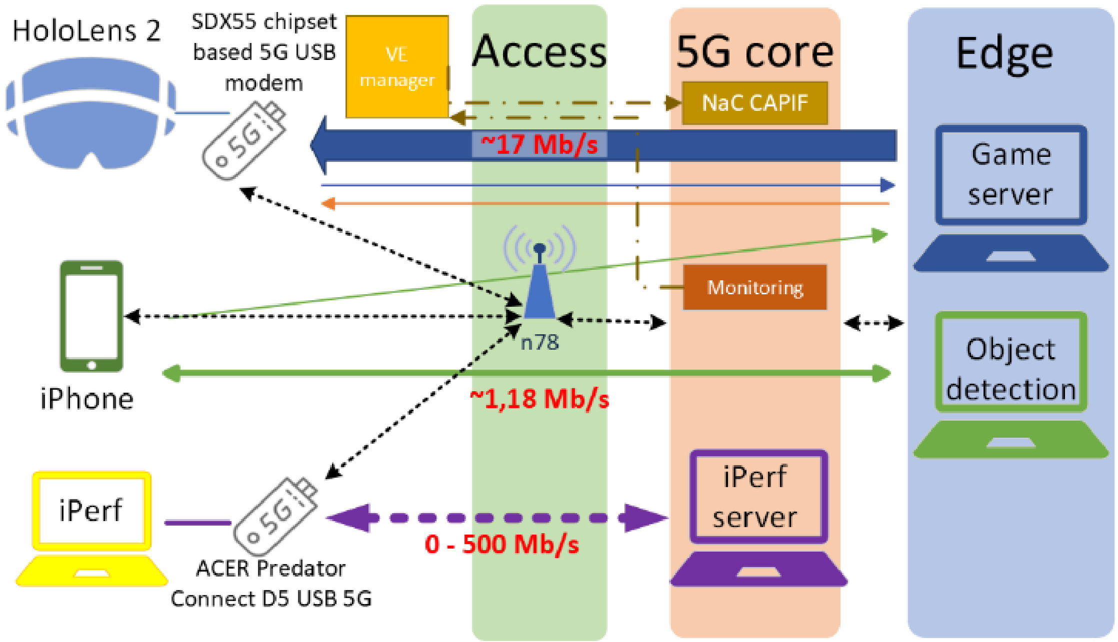


Figure 43. XR application trial deployment.

Figure 43 shows the integration of individual components into the 5G network. The object detection server and the game server were directly connected to the 5G Core network as edge computing nodes via Ethernet cables. The tracking iPhone was 5G-capable. The Hololens devices were connected using several modems. The UEs were connected to UPV's radio network in the n78 band. The UEs prioritization was achieved by assigning different 5QIs. The gNodeB of the network identifies the 5QI parameter and applies a different schedule weight for its MAC scheduler depending on its value.

Key 5G Technologies Used:

- 5G Standalone (SA) network
- Network slicing (one default slice + one prioritized media slice)
- Private 5G Edge-cloud computing (two app servers directly running connected to the network core)
- Internet of Senses (True XR application with interaction between real and virtual elements)

KPIs and KVIs

- **Technical KPIs:**
    - Network: latency, jitter, throughput (downstream/upstream)
    - Application: latency, jitter, throughput (downstream/upstream)

- **Vertical KVIs:**

  - Multi-user XR applications improvement: true XR interaction was achieved, in which the user was presented with a blend of virtual and real elements that can interact with each other.
  - Communication Reliability: network impairments (delay, jitter, etc.) mitigation by using advanced techniques and precise component synchronization. Network slicing to mitigate effect of network congestion.
  - User satisfaction: feedback from students on system quality, usability, enjoyment, future use of the technology, etc.

- **Measurement Methodology:**

During the application and network measurements, no other relevant traffic occurred on the network. If network traffic was needed during the measurements, it was generated with several devices using iperf. We defined a dedicated measurement methodology in detail focusing on the quantitative characterization of the user experience. We monitored infrastructure level metrics using influxDB and Grafana. KVIs were collected through user surveys, filled out during the open-call student gaming competition. These surveys had several questions about user experience (audio and image quality, ease of use, latency, etc.) and usefulness and potential future of XR technology.

Lessons learned

Technical insights: network slicing requires careful coordination between network operators and service providers. Also, we found out that the remote-rendered video stream has the greatest impact on the user experience. The results show that the latency and jitter characteristics can be managed efficiently together by a network-level control mechanism (prioritizing network slices including the HMDs) and a dynamic jitter buffer at the application level.

Operational insights: connecting the HoloLens to the B5G network turned out to be challenging. Several USB dongles are not supported by HoloLens. However, we can opt for other 5G modems with WiFi, which introduces significant jitter to the system, thereby skewing the measurement results, or we must connect the HoloLens through an Ethernet cable, requiring an additional conversion (Ethernet-to-USB-C adapter).

Measurement insights: (i) Network slicing proved to improve application and latency figures when network congestion is present, (ii) B5G architecture and functionalities can support real-time XR applications, (iii) latency and jitter figures can greatly vary depending on the utilized 5G UE, (iv) overall, subjects enjoyed using the application, even though most users are not entirely familiar with immersive technologies (most of them only tried few times before). They were intuitive enough to start using without much difficulty, (vi) most subjects evaluated the response time of ball collision to be acceptable and (vii) the image quality was scored average.

References

Related Publications/Deliverables:

- J. Dóka, B.Gy. Nagy, D. Jocha, B. Formanek, I. Viciedo, A. Rodrigo, D. Gomez-Barquero, B. Sonkoly. "Enablers of low-latency immersive interaction in future remote-rendered Mixed Reality applications". ACM Multimedia Systems Conference (MMSys), 2025 https://dl.acm.org/doi/pdf/10.1145/3712676.3714448

Links to Videos / Demos:

- https://netsoft.gsuite.tmit.bme.hu/projects/democrats
- https://www.youtube.com/watch?v=E-PlOqMP8Zo

2.5.2 5G-Enabled AR Network Application for Public Safety

Trial Title: 5G-Enabled AR Network Application for Public Safety
Project Acronym: FIDAL
Project Full Name: Field Trials Beyond 5G
Coordinator: NOVA TELECOMMUNICATIONS & MEDIA SINGLE MEMBER SA
Contact Person: George Margetis (gmarget@ics.forth.gr), Eva Milolidaki (milolid@ics.forth.gr)
Project Website: https://fidal-he.eu/
Project Duration: January 2023 - June 2026
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: Public Safety, Emergency Services, Public Protection and Disaster Relief (PPDR)
Replicability: 39
Geographical Location(s): Patras, Greece
Supported testbed (s): UoP/PNET

Trial Overview

The purpose of the present trial was to demonstrate and validate the operation of a Network Application that provides real-time Augmented Reality (AR) support for public-safety and disaster relief operations. The trial focuses on enhancing situational awareness for first responders by combining AR visualization, AI-based video analysis, and low-latency 5G connectivity.
The trial scenarios are designed to simulate real-world operational conditions, where participants receive real-time visual data, through AR devices, and have to act based on it in dynamic environments. The trial aimed to evaluate the effectiveness and usability

of the AR visual feedback and how communication and coordination in operational incidents is enhanced. Moreover, during the trials the reliability of live video streaming under increased mobile network load was also assessed.

Figure 44. AR glasses view with real-time overlays.

Trial deployment including integration with vertical solutions

The proposed system follows an end-to-end architecture optimized for real-time AR support in public-safety environments. AR devices capture live video from the field and transmit it over a 5G network to edge computing resources. The Network Application is deployed at the edge, where video streams are processed in real time using AI-based analysis to detect and segment people and objects of interest. Based on this analysis, relevant information is filtered and transformed into lightweight AR annotations, which are transmitted back to the AR devices and displayed directly in the user's field of view. By performing computationally intensive processing at the edge, the system enables the use of lightweight AR devices or smartphones while maintaining low latency and stable performance.

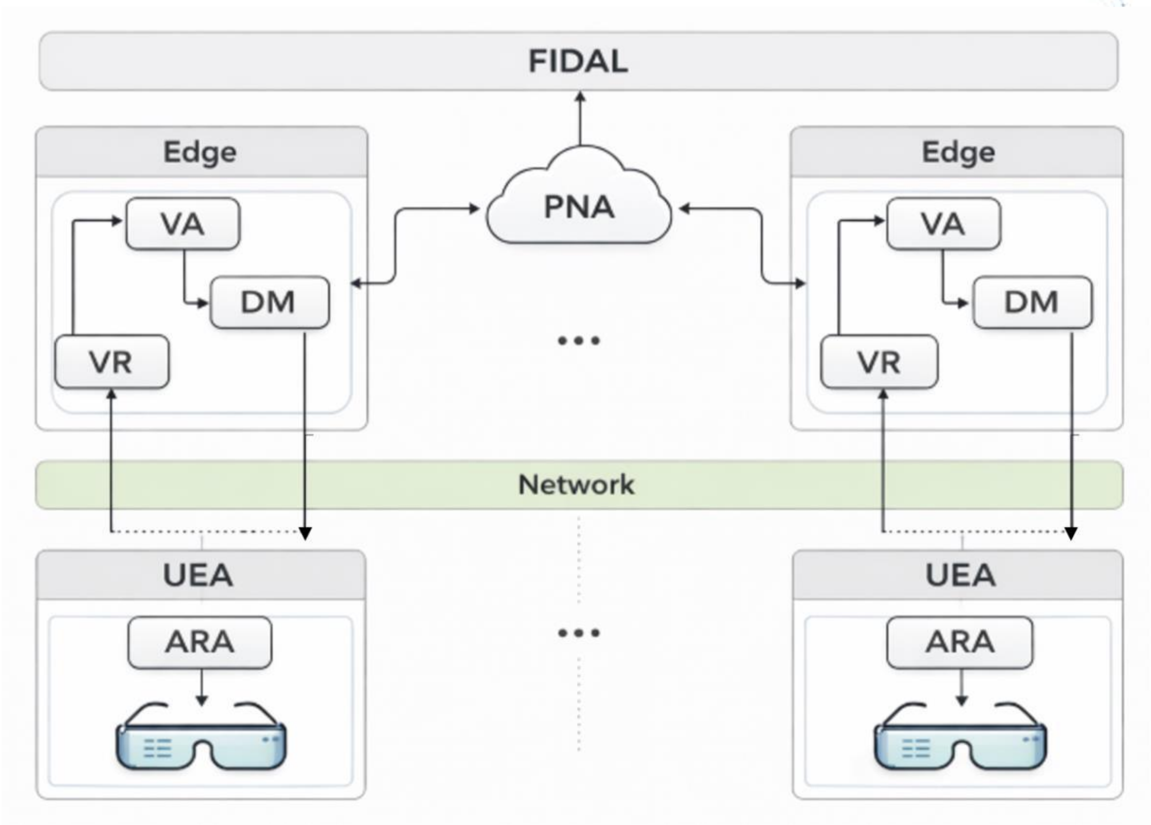


Figure 45. Architecture for 5G-Enabled AR Network Application for Public Safety

KEY TECHNOLOGY USED

- 5G Standalone (SA) Network
- 5G uplink video streaming
- Edge computing with GPU acceleration
- Containerized orchestration
- Real-time AI inference (YOLOv11)

KPIs and KVIs

- **Technical KPIs:**
    - End-to-end latency (ms)
    - Video frame rate (FPS)
    - Throughput (Mbps)
- **Vertical KVIs:**
    - **Flexibility:** scalable operation across emergency scenarios

- **Protection of humans:** improved awareness and risk mitigation
- **Security:** confidential and secure communications
- **Trustworthiness:** reliable mission-critical services
- **Operational safety: low cognitive and operational burden**

- **Measurement Methodology:**

Technical KPIs were measured by the Network Application and the 5G testbed during the trials and transmitted in real-time to the FIDAL Monitoring Analytics platform, where live visualization and post-trial analysis are feasible. KVIs were collected through questionnaires and debriefing sessions with the Hellenic Rescue Team, who participated as end users in the trials. In some cases, this feedback was considered together with relevant KPI results to better reflect the experience of using the system in real operational conditions.

Lessons learned

The trial confirmed the successful operation of the AR-based Network Application in realistic public-safety scenarios. The system provided stable real-time AR overlays, supported by edge-based processing and 5G connectivity, enabling low-latency visual feedback during active operations. Performance remained smooth at around 30 FPS, with end-to-end latency between 30–40 ms, even when multiple devices were connected.

<u>Technical insights:</u> The trial showed that low latency and sufficient bandwidth are critical for real-time scene analysis and AR visualization. Performing heavy processing at the edge proved essential for maintaining stable performance, especially when multiple devices were active at the same time. Network configurations that allowed slicing resulted in more consistent latency, higher throughput, and stable frame rates compared to shared network conditions.

<u>Operational insights:</u> The acceptance rate among participants was high, since they considered the real-time visual feedback not distracting, provided added value, and supported easier task execution. Training and short familiarization sessions were considered important for the effective use of the system during operations.

References

Related Deliverables:

- https://fidal-he.eu/sites/default/files/pd/file/2023-07/D2.1_FIDAL.pdf
- https://fidal-he.eu/sites/default/files/use-case/factsheet-pdf/2025-06/FIDAL%20UCs%20-%20FACTSHEET_A5_BOTH.pdf

Links to Videos / Demos:

- https://www.youtube.com/watch?v=vkSXgqaK-Q4

2.5.3 XR assisted services for public safety

Trial Title: XR assisted services for public safety
Project Acronym: FIDAL
Project Full Name: Field trials beyond 5G
Contact Person: papajohn@upatras.gr
Project Website: https://fidal-he.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-D-01-01
Main Vertical(s) Addressed: XR assisted services, Public Protection and Disaster Relief (PPDR)
Replicability: 39
Geographical Location(s): Patras, Greece
Supported testbed (s): Patras5G Network (University of Patras and PNET)

Trial Overview

The trial focused on the integration of Extended Reality (XR) technologies, including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR), with advanced 5G and Beyond 5G network capabilities to improve situational awareness, operational efficiency, and decision-making in emergency response scenarios. The trial was structured into two complementary sub-use cases and further enhanced through the integration of the ISAFECO open call use case, which provided real-time video streaming and multi-source situational awareness.

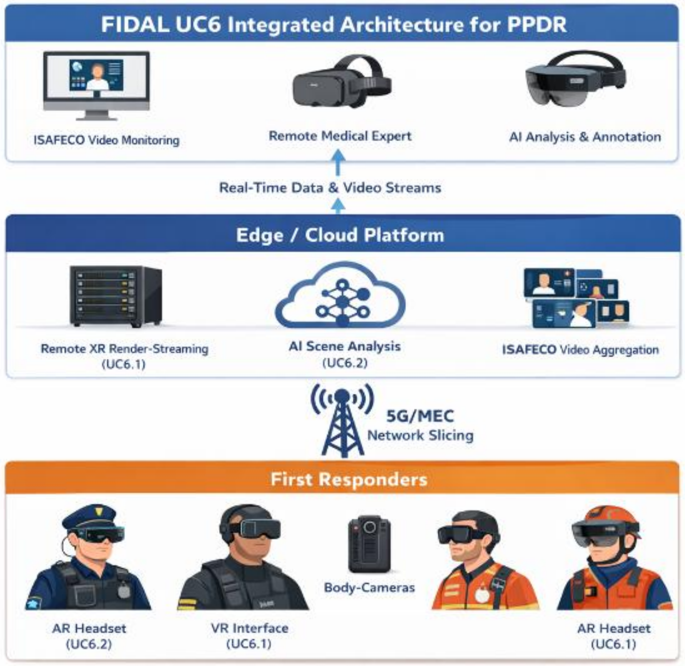


Figure 46. XR-assisted services for public safety integrated architecture

This trial integrated two different XR solutions. The first one focused on XR-assisted on-site emergency operations, where first responders used AR headsets to receive real-time guidance from remote experts using VR headsets. The second one focused on AI-enhanced situational awareness for law enforcement, enabling real-time scene analysis and AR-based annotations of potential threats. These sub-use cases were complementary, combining immersive XR collaboration with intelligent visual analysis to enhance decision-making in complex emergency scenarios.

The combined system was validated through a large-scale, multi-phase scenario based on a major traffic accident involving multiple casualties. First responders including police officers, firefighters, and rescue teams were deployed to the scene and equipped with 5G-enabled devices, XR headsets, and body-worn cameras. The ISAFECO network application enabled continuous streaming of real-time video from the field to the Command and Control (C2) centre, where incident commanders monitored the situation and coordinated response actions. In parallel, XR technologies and AR-based analytics enhanced the responders' perception of the environment and enabled remote collaboration. This integrated approach demonstrated the potential of combining XR, AI-based analysis, and 5G connectivity to provide a unified and real-time operational picture.

Trial deployment including integration with vertical solutions

This trial was deployed on one of FIDAL's 5G infrastructure at the Patras5G testbed, leveraging technologies such as custom network slicing and Multi-access Edge Computing (MEC). The deployment integrated XR devices, 5G-enabled user equipment, body-worn cameras, edge/cloud resources, and command-and-control systems, enabling end-to-end data flow and real-time processing.

The deployment consisted of two distinct application architectures. The first XR solution, developed by ORAMA, relied on a distributed XR architecture including a Remote XR Render-Streaming (RRS) service deployed at the edge and a Physics Server (PhyS) deployed in the cloud (see *Figure*). This architecture enabled real-time rendering and synchronization of multi-user XR environments, while lightweight XR devices acted as thin clients receiving rendered streams and transmitting user interactions.

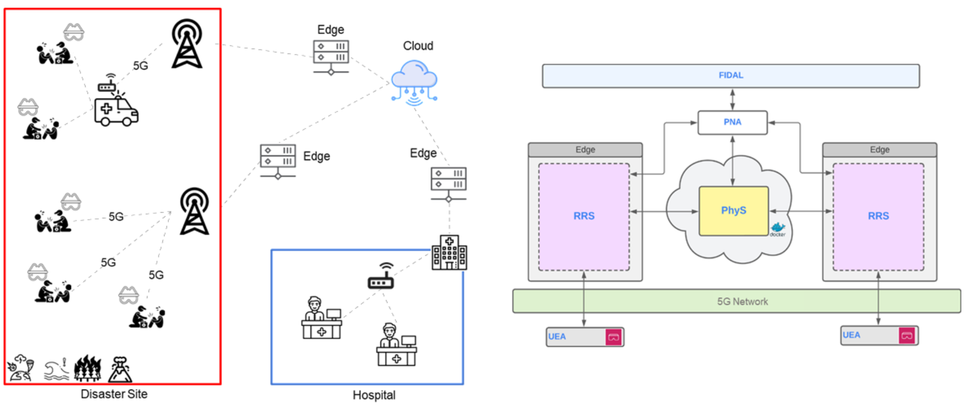


Figure 47. XR-assisted services for public safety integrated architecture

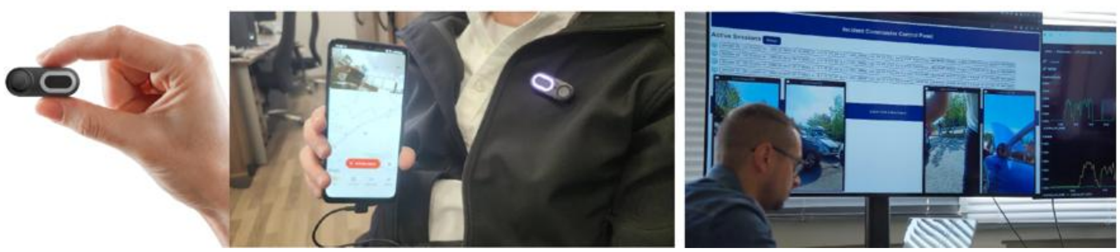


Figure 48. XR-assisted services trials at Patras Private 5G Infrastructure

Technical Architecture

The proposed system follows an end-to-end architecture optimized for real-time AR support in public-safety environments. AR devices capture live video from the field and transmit it over a 5G network to edge computing resources. The Network Application is deployed at the edge, where video streams are processed in real time using AI-based analysis to detect and segment people and objects of interest. Based on this analysis, relevant information is filtered and transformed into lightweight AR annotations, which are transmitted back to the AR devices and displayed directly in the user's field of view. By performing computationally intensive processing at the edge, the system enables the use of lightweight AR devices or smartphones while maintaining low latency and stable performance.

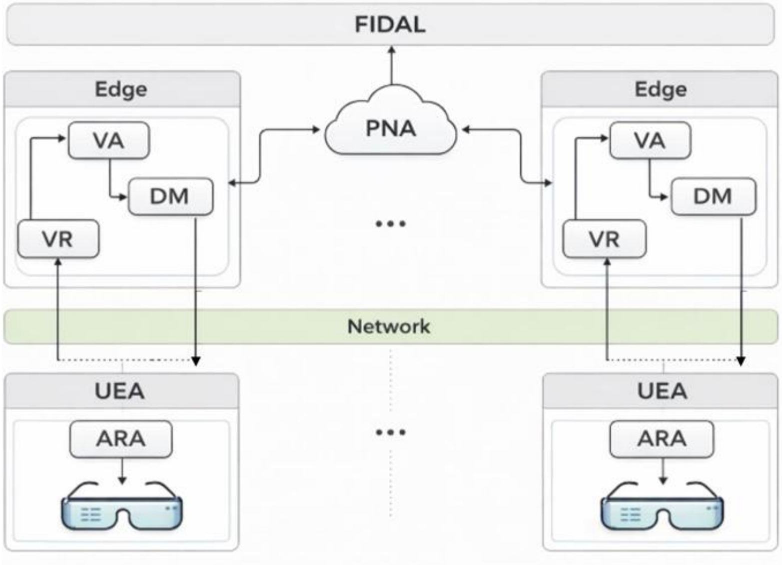


Figure 49. Conceptual architecture

Key Technologies Used

- 5G Standalone (SA) Network
- 5G uplink video streaming
- Edge computing with GPU acceleration
- Containerized orchestration
- Real-time AI inference (YOLOv11)

KPIs and KVIs

The trial scenarios involved more than multiple concurrent XR users and up to seven simultaneous video streams.

The measured results demonstrated that low latency levels, combined with network slices providing guaranteed bitrates and XR-specific 5QI, were sufficient to preserve user immersion in XR environments. However, different connectivity configurations, driven by the unavailability of 5G-ready devices in certain cases (e.g., USB vs. WIFI tethering through smartphones or 5G CPEs), had a direct impact on performance and Quality of Experience (QoE).

Frame rates reached approximately 30 FPS, while latency values ranged between 30–70 ms under optimized configurations. Under congested network conditions, network slicing with custom and isolated resources proved essential to support such applications over public networks.

KVIs assessed improvements in situational awareness, operational efficiency, and decision-making. The integration of real-time video, AI-based analysis, and XR visualization enhanced coordination among responders and improved overall response effectiveness.

- **Measurement Methodology:**

The measurement methodology followed the common experimentation framework defined within the FIDAL project deliverables, leveraging the FIDAL monitoring platform to ensure end-to-end observability across network, edge, and application layers. Performance data were collected in real time from multiple sources, including 5G network metrics, application-level indicators, and device measurements, enabling accurate correlation between network conditions and service performance. Technical KPIs were evaluated over multiple trial runs using statistical analysis, while KVIs were assessed through a combination of quantitative results and user feedback, ensuring a comprehensive evaluation of system effectiveness.

Lessons learned

This trial demonstrated that the combination of XR technologies, AI-based analysis, and 5G connectivity significantly enhances situational awareness and operational coordination in public safety scenarios. The layered integration of ISAFECO, UC6.2, and UC6.1 enabled a comprehensive operational view, combining raw data, intelligent processing, and immersive visualization.

From a technical perspective, the trials confirmed the importance of edge computing and low-latency connectivity. Network slicing improved performance under load, while different deployment configurations revealed trade-offs between latency, throughput, and stability.

The trials also highlighted challenges related to device limitations, particularly the lack of native 5G XR devices, requiring the use of tethering or CPE solutions. Performance was also influenced by real-world conditions such as network variability and user density.

Finally, the results demonstrated that combining AI-based scene analysis with XR interaction provides significant benefits for public safety operations, enabling faster decision-making and improved coordination in complex emergency scenarios.

References

- https://fidal-he.eu/sites/default/files/pd/file/2023-07/D2.1_FIDAL.pdf
- https://fidal-he.eu/sites/default/files/use-case/factsheet-pdf/2025-05/FIDAL%20UCs%20-%20FACTSHEET_A5_0.pdf

2.5.4 JCAS/ISAC people detection

Trial Title: JCAS/ISAC people detection
Project Acronym: 6G-SANDBOX
Project Full Name: Supporting Architectural and technological Network evolutions through an intelligent, secured and twinning enabled Open eXperimentation facility
Contact Person: Pablo Herrera (pabloherreradiaz@uma.es)
Project Website: https://6g-sandbox.eu/
Project Duration: January 2023 - June 2026
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals HORIZON-JU-SNS-2022-STREAM-C-01-01
Main Vertical(s) Addressed: Safety and Security, Smart spaces
Geographical Location(s): Poznan, Poland (EUCNC 2025)
Supported testbed (s): Victoria Network

Trial Overview

This trial Demonstrate the feasibility of Integrated Sensing and Communications (ISAC/JCAS) in FR1 using commercial O-RAN 5G NR equipment and SRS-based sensing combined with AI/ML. The trial targets real-time detection and coarse positioning of people in a highly dynamic, crowded public venue, and identifies performance boundaries under dense, uncontrolled pedestrian traffic conditions.

The trial was conducted during EuCNC & 6G Summit 2025 in Poznań, Poland, over the full exhibition period (3–6 June 2025). The sensing area was a standard open corridor between the 6G-SANDBOX and ITRI booths, allowing normal attendee flow with occasional stops to observe the live dashboard. The sensing region was constrained to approximately 4 m (length) × 1 m (width), while equipment remained inside the respective booths.

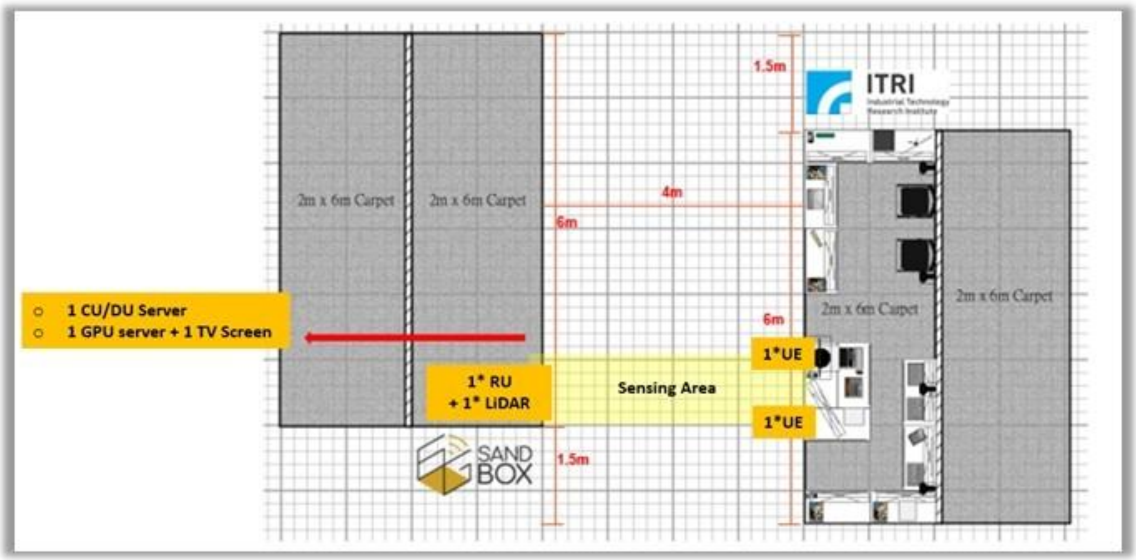


Figure 50. JCAS/ISAC demonstration setup

Figure 51. JCAS/ISAC demonstration: heatmap and hourly presence detection statistics

Trial deployment including integration with vertical solutions

The deployment used a commercial O-RAN 5G NR system with local compute for sensing inference: (i) RAN: IS-Wireless O-RAN solution with Benetel RAN650 RU, configured as 4×4 MIMO; (ii) DU/CU on a local server; (iii) Core: Open5GS running locally; (iv) Two commercial UEs (Crosscall Z5), both transmitting SRS and spatially separated to increase channel observability; (v) Time synchronization via PTP using a Falcon RX Grandmaster; (vi) Real-time inference on a Windows GPU PC (NVIDIA RTX 4080); (vii) Camera and LiDAR used for ground-truth labeling and accuracy benchmarking. The public project description highlights an O-RAN RU with 100 MHz and AI/ML processing based on SRS channel estimation signals for corridor detection.

Key Technologies Used

The demonstration implemented an FR1 ISAC/JCAS system on top of a commercial 5G NR O-RAN setup, exploiting SRS-based sensing via CSI/channel-variation features and

an AI/ML Transformer model to enable near real-time people detection, coarse counting, and coarse positioning.
Key components included: Benetel RAN650 RU (4×4 MIMO), IS-Wireless DU/CU, local 5G Core (Open5GS), two commercial UEs (Crosscall Z5) transmitting SRS, PTP synchronization (Falcon RX grandmaster), real-time inference on a Windows GPU PC (NVIDIA RTX 4080), and camera + LiDAR used as ground truth for training/validation and accuracy estimation displayed on a live dashboard (heatmap, counter, metrics).

KPIs and KVIs

- **Technical KPIs:**
  - Detection rate (recall)
  - Precision / false alarm behaviour
  - Coarse positioning consistency within the sensing region
  - End-to-end responsiveness (near real-time), assessed via dashboard update behaviour. (PoC-focused KPI set.)

- **Vertical KVIs:** Not formally collected (proof-of-concept deployment).

- **Measurement Methodology:**

The system operated continuously across the full exhibition period. Accuracy/precision were estimated by comparing RF-based detections with camera/LiDAR ground truth, aggregated in time windows and visualised in the dashboard (prediction vs ground truth and accuracy %).

Lessons learned

Technical lessons: (i) FR1 bandwidth limits spatial/range resolution and can cause target merging in dense crowds; (ii) the short 4 m × 1 m corridor region increases multi-target ambiguity; (iii) multi-UE SRS improves observability, but dense clustering remains challenging.

Operational lessons: (i) a public venue corridor is a strong stress test due to uncontrolled motion and variable density; (ii) keeping equipment inside booths simplifies logistics but constrains geometry.

Contribution to Standards

No direct contributions to standardization bodies (e.g., 3GPP, ETSI) were produced within this proof-of-concept trial (i.e., no formal submissions such as change requests, work items, or liaison statements). However, the trial generated practical experimental insights on the feasibility and limitations of FR1 ISAC/JCAS using commercial O-RAN equipment in a dense public-venue environment, which were disseminated to the research community through EuCNC 2025 technical activities (including Workshop 10 on ISAC).

References

- 6G-SANDBOX at EuCNC 2025 & 6G Summit (Press Release PDF) – https://6g-sandbox.eu/wp-content/uploads/2025/05/6G-SANDBOX-at-EuCNC-2025-6G-Summit.pdf
- EuCNC 2025 Exhibitions and Demos page (ITRI + partnered FR1 ISAC People Positioning) – https://www.eucnc.eu/2025/www.eucnc.eu/patrons-exhibitors/exhibitions-and-demos/index.html
- SNS JU event listing – EuCNC & 6G Summit 2025 (delegate magnitude) – https://smart-networks.europa.eu/event/eucnc-6g-summit-2025-in-poznan-poland-3-to-6-june-2025/
- EuCNC 2025 Workshop 10 – Integrated Sensing and Communications initiative – https://www.eucnc.eu/programme/workshops/workshop-10/

2.6 SMART CITIES and INDUSTRY

2.6.1 5G Tracking of Circular Facade Elements

Trial Title: 5G Tracking of Circular Facade Elements
Project Acronym: 5CADE
Project Full Name: 5G Tracking of Façade Greening System
Coordinator: University of Technology Dresden
Contact Person: Annika Herdan (Annika.herdanätu@desdren.de)
Project Website: http://target-x.eu/open-calls/
Funding Programme: TAEGET-X Open Call
Main Vertical(s) Addressed: Smart Cities, Construction
Replicability: 41
Geographical Location(s): 5G-Industry Campus Europe, Campus Melaten RWTH Aachen University

Trial Overview

The objective of the present trial is to demonstrate the potential of 5G technology in conjunction with an automated, gravity-based irrigation system to establish a Low-Tech Facade Greening System. It is vital to emphasise the significance of primary resources in this context. The objective of the trial is to demonstrate that the plants of the greening system can be watered in a controlled manner through effective monitoring and an internal water reservoir, thereby ensuring minimal wastage of water. Furthermore, the system incorporates a series of linear planters, thereby enabling the greening system to be adapted for subsequent reuse and repurposing. It is therefore evident that the use case that will be validated is that of a modular, linear planter system in conjunction with a low-tech irrigation system, which is monitored by 5G temperature and humidity sensors. The demonstrator façade has been installed at the 5G-Industry Campus Europe, which is located at the Campus Melaten of RWTH Aachen University. A the campus a demonstrator building has been built with a sub-structured manufactured for our systems sub-structure. The installation of an additional demonstrator is scheduled for the first quarter of 2026 in Borna.

Figure 52. Demonstrator in Aachen

Trial deployment including integration with vertical solutions

The proposed system follows a layered end-to-end architecture for smart irrigation control, specifically optimized for integration into a 5G campus network. At the field level, the irrigation sensors communicate with a central gateway via the 868-MHz frequency band, utilizing the energy-efficient Lemonbeat protocol to ensure long-range connectivity and high penetration in outdoor environments. The gateway performs data aggregation and protocol translation, converting the 868-MHz proprietary signals into IP-based data packets. Unlike conventional consumer setups, the gateway is integrated into a dedicated 5G campus network, which serves as the primary local area network (LAN). By utilizing 5G mobile connectivity for the backhaul, the system benefits from industrial-grade reliability, low latency, and high security, enabling seamless bidirectional data exchange between the gateway and the cloud infrastructure even across expansive corporate or industrial premises. The cloud layer hosts device management, data storage, and advanced analytics, as well as the control logic that generates precise irrigation commands. Control signals are transmitted downstream from the cloud via the 5G network to the gateway and further via the 868-MHz link to the irrigation control units. Simultaneously, sensor data is transmitted upstream for real-time monitoring, analysis, and optimization of water usage.

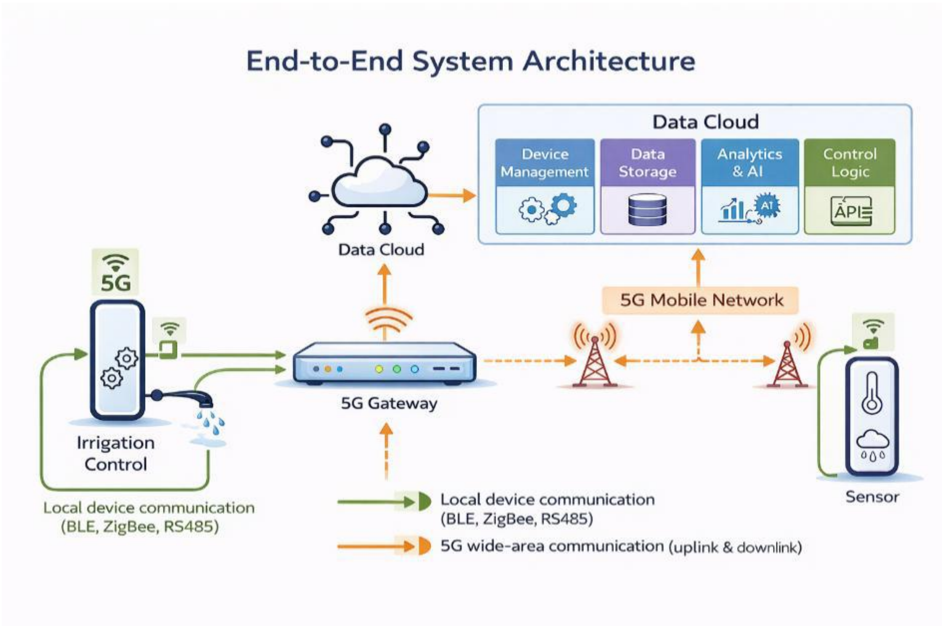


Figure 53. ACADE end-to-end architecture

Key Technologies Used

- 5G router connected to sensor technology
- Sensor technology within the substrate and the water reservoir

KPIs and KVIs

- **Technical KPIs:**
    - Low end-to-end latency via gateway
    - High data transmission rates
    - High reliability through 5G Industry Campus network
    - High energy efficiency through water reservoir and energy efficient water pump
    - Humidity target within sensors to prevents over irrigation: target > 50 %

- **Vertical KVIs:**
    - Resource efficiency: minimal wastage of water
    - Modularity: subsequent reuse and repurposing
    - Cost reduction: minimized operating costs through optimised usage of water, fertilizer and energy

- **Measurement Methodology:**

The measurement of humidity was achieved through the utilisation of seven sensors, with some sensors being installed within the substrate and the remaining sensors within the water reservoir. The irrigation system is activated twice daily, at 6am and 6pm, provided that the target has not been fulfilled. The data is transmitted to the cloud via the 5G network and stored there for subsequent analysis. The installation of the intelligent system was undertaken to measure all data, and this was subsequently double-checked through real-time data access. KVIs were meticulously planned prior to the installation stage, and subsequent data were collected through operational feedback from the multidisciplinary target-X research team in Aachen, as well as from the medical team during their stay at the campsite.

Lessons learned

The primary outcomes of the 5CADE project illustrate a fruitful convergence of circular design, 5G automation, and ecological optimisation. The project's qualitative outcomes included the establishment of a high-precision 5G sensor network, which enabled real-time monitoring of substrate moisture and water levels. This, in turn, facilitated fully automated, demand-based irrigation. The system's market readiness was further validated through its compliance with key EU regulatory frameworks, including the EU Green Deal, the Ecodesign for Sustainable Products Regulation (ESPR), and the EU Taxonomy, effectively advancing the technology to a readiness level between TRL 6 and TRL 7.

Quantitatively, design iterations significantly improved the system's biological capacity by nearly doubling the available substrate volume from 8,649 cm^3/m to 14,625 cm^3/m, thereby enhancing nutrient buffering and plant vitality. Operational tests demonstrated the efficacy of the integrated irrigation logic, which maintained stable substrate moisture levels between 65% and 85%. Furthermore, the logic demonstrated environmental responsiveness by automatically overriding scheduled cycles during an 8 L/m^2 precipitation event. These outcomes were operationalised through the deployment of a demonstrator facade in Aachen, consisting of 12 units populated with diverse species such as Vinca minor, Epimedium, and Luzula, providing a robust foundation for long-term technical and ecological validation.

<u>Technical insights:</u> The utilisation of a 5G router within the 5G network, in conjunction with the gateway, engenders low latency transmission. However, the unidirectional

communication between the sensors and the gateway is vulnerable to interference from third parties, which poses a risk to redundancy

within the connectivity infrastructure, particularly in a context such as a building campsite, as evidenced by the example of the campsite in Aachen.

Operational insights: The selection of plants was made in conjunction with a professional landscaping gardener. Following an eight-month period and one autumn and winter season, it was determined that one species of plant, out of a total of four, was not conducive to the desired orientation and dimensions of the façade. The remaining three species (Epimedium, Vinca minor and Luzula sylvatica) are exhibiting vigorous growth and retaining their colouration typical of evergreen plants.

Measurement insights: Following the initial prototype, the volume of the water reservoir and the substrate has been augmented from 8.649 cm^3 to 14.625 cm^3. It is particularly during the summer months that this additional space has been found to be essential for the growth and vitality of the plants. In addition, the initial target of the irrigation system was set at 70%, however, it was determined that this could be reduced to 50%. This adjustment was necessitated by the observation that, in the initial stages of cultivation, the plants exhibited signs of being slightly too wet. Consequently, a significant amount of water was being expended through the system.

Contribution to Standards/ Open Source:

- Open data for long-term data of humidity and temperature dynamic
- Open data for a new facade greening system
- Main Results: (Quantitative and qualitative outcomes of the trial – include data if available.)
- Lessons Learned: (Summarize technical, organizational, or operational insights gained.)
- Contribution to Standards / Open Source: (List any inputs to standardization bodies or open repositories.)

References

Links to Videos / Demos: https://youtu.be/deCWjdtgnlM?si=sHkdq2qw0iEebYwu

2.6.2 Connected and Sensing City Trials

Trial Title: Connected and Sengins City Trials
Project Acronym: 6G-PATH
Project Full Name: 6G Pilots and Trials Through Europe
Contact Person: Anna Brunstrom (anna.brunstrom@kau.se)
Project Website: https://6gpath.eu/
Funding Programme: SNS Large Scale Trials and Pilots (LST&Ps) with Verticals
HORIZON-JU-SNS-2023-STREAM-D-01-01
Main Vertical(s) Addressed: Smart Cities, Automotive
Replicability: 48
Geographical Location(s): Aveiro, Portugal

Trial Overview

The trial aimed to demonstrate the capabilities of a 5G-6G platform in supporting connected and sensing city use cases, leveraging the Aveiro testbed to showcase real-time information exchange between vehicles, people, and sensors. It validated beyond-5G technologies for urban mobility and services, gathering feedback on societal relevance and technological evolution. Expected outcomes included proof of service continuity, low-latency data processing, and participant insights via surveys and interviews.

Specifically, the trial had as its main purpose the demonstration of two scenarios centered around Beyond-5G concepts. The first scenario (Figure) had as its primary goal the demonstration of the integration of Digital Twin technologies with 5G network emulation, providing digital representations of the city merged with realistic network behavior to enable traffic simulations that can support improved urban and network decision-making, which was transçated into an indoor simulation using SUMO for mobility and parallel 5G network emulation to demonstrate traffic scenarios and network decision-making.

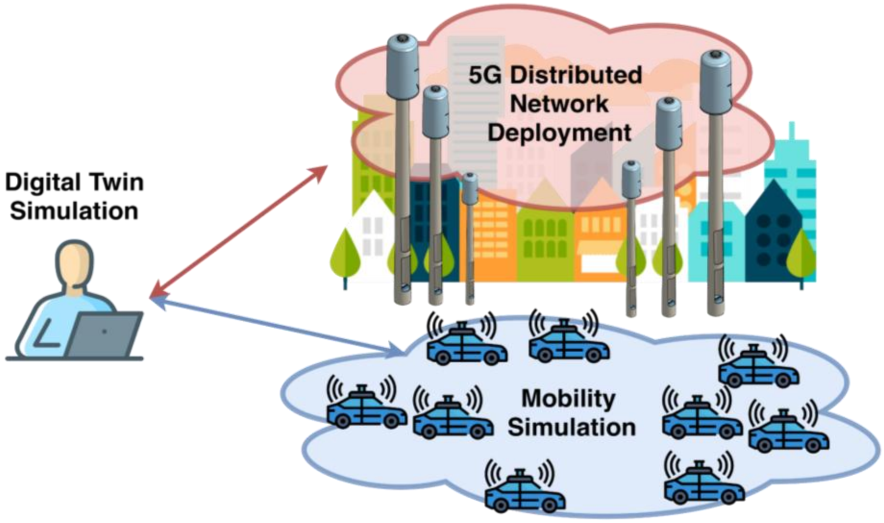


Figure 54. DT and 5G Network Emulation

The second scenario (*Figure*) focused on demonstrating dynamic and proactive resource management mechanisms at both the edge platform and network levels, aiming to ensure intelligent resource distribution that maximizes platform utilization while avoiding quality-of-service degradation for end-users and platform overload. Accordingly, the scenario was divided into two phases. The first phase aimed to demonstrate smart edge orchestration mechanisms and their ability to react to user mobility and edge platform conditions, whereas the second phase showcased the dynamic capabilities and programmability of the 5G network in adapting to network congestion. It consisted of an outdoor live demonstration of autonomous vehicle integration with city sensors for real-time services.

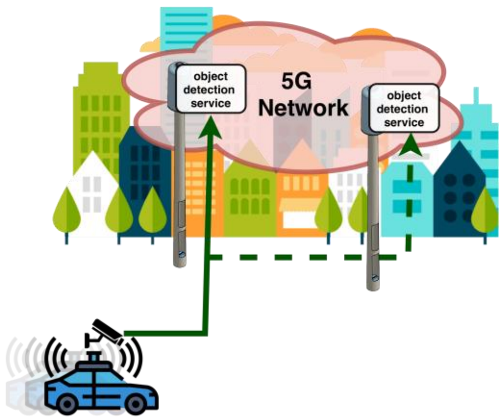


Figure 55. Perception offloading with resource management for autonomous mobility scenario overview

Trial deployment including integration with vertical solutions

The system (see *Figure*) combined private and public 5G/6G networks (IT and Altice Labs cores) for roaming and service continuity, with vehicles, sensors, and a digital twin for simulations and a MEC platform for edge computing orchestration. It included IoT devices, edge computing, and a data platform for unifying heterogeneous sources. The communication infrastructure of the system built on fiber and millimetre-wave (mmWave) links, integrates a communication network with radio terminals (WiFi, ITS-G5, C-V2X, 5G, and LoRaWAN), supporting multiple protocols, and is deployed across public facades and smart lampposts throughout the city. The ALB testbed integrates with the city's infrastructure, extending its technological capabilities to the company campus. The system includes user equipment, radio access technologies, core network entities, and management and orchestration functionalities. Additionally, it features a data management and analytics platform that enables the collection and integration of data from heterogeneous sources and presents them in a unified format.

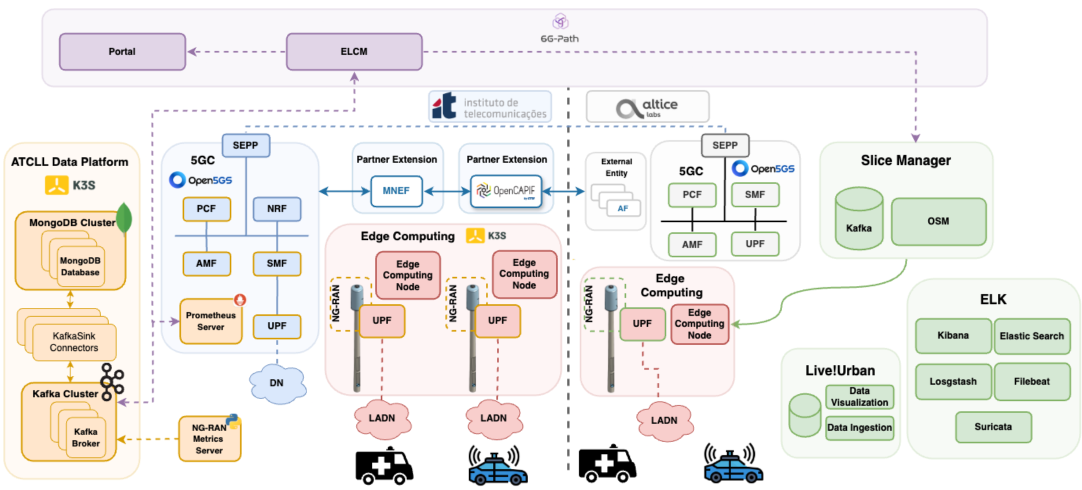


*Figure **57**. Perception offloading with resource management for autonomous mobility architecture*

The Radio Access Network (RAN) infrastructure is made up of various solutions, including OpenAirInterface (OAI) and srsRAN, open-source solutions deployed in Ettus Research USRPs, and CableFree 4G/5G Small Cell n78 indoor/outdoor, commercial solutions. Both open-source solutions are O-RAN compliant gNB with CU/DU split and interconnect with RAN Intelligent Controllers (RICs) for RAN monitoring. User equipment options include SIM cards, modems (e.g., Quectel, SIMCom, Sierra Wireless), customer premises equipment (CPEs), and smartphones (e.g., Google Pixel, Xiaomi, OPPO, and Samsung). The core network is implemented with Open5GS in standalone (SA) mode.

The MEC system deployment is considered to address smart city scenarios with edge nodes spread out at various locations, with a B5G edge-enabled deployment to address user mobility and dynamic nature of the edge environment, while improving quality of service (Quality of Service (QoS)). This is accomplished with extensions to the base edge architecture through the appropriate plug-ins, custom resources, and components to address the dynamic nature of this environment and the mobility of the users.

On ALB's testbed Slice Manager provides operations on microservices available in the service manager of Open Source MANO (OSM). Those operations include the retrieval of information about the services and the creation, update and deletion of slices from those services. The slice manager interface receives messages from Kafka; it relays the information received onto the OSM, which uses underlying components to configure the raw network to obtain/release resources for the requested slices.

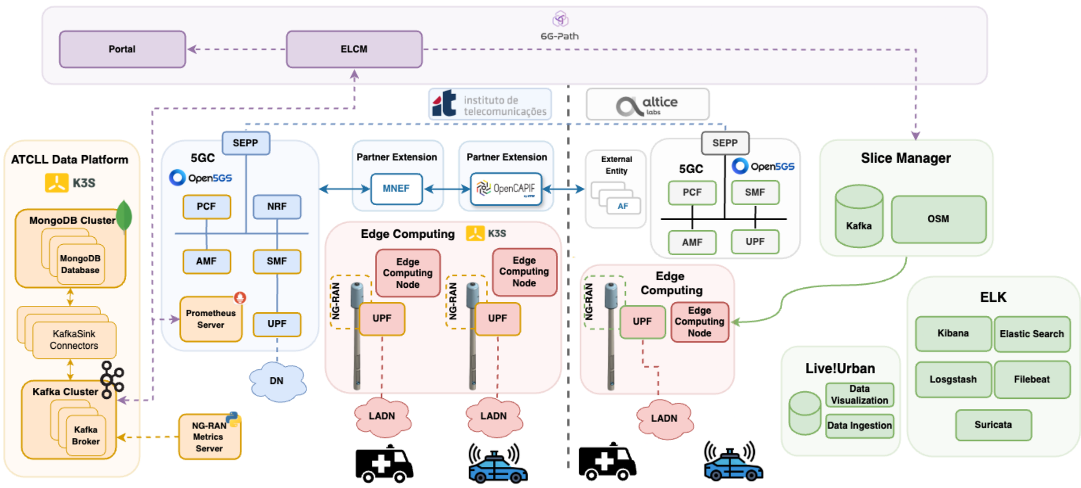


Figure 57. Perception offloading with resource management for autonomous mobility architecture

All of these capabilities and these services depend on a monitoring platform that constantly leverages ATCLL's measurement tools and data collection systems across MEC, 5G network, and mobility platforms. The ATCLL data platform is composed of a Kafka cluster that receives information updates published in real-time that can be accessed in real-time by applications and by a MongoDB database allowing for complex analysis, and processing bulks of historical data by querying it from the platform's databases. It contains metrics servers that monitor the RAN's gNBs and Prometheus configured in the edge computing cluster configured to monitor the status of the cluster's nodes, the running applications and containers, the network interfaces, etc.

Vertical systems present in this trial include autonomous vehicles (e.g., PIXKIT) and city sensors (radars, cameras) interfaced via 5G networks, with data routed through UPFs, managed by Open5GS and service orchestration at the edge platform, data collection by ATCLL data platform (real-time mobility and sensing data) and the NEF for network actions.

Key Technologies Used:

- 5G SA, network slicing,
- Edge computing,
- AI/ML (via RICs),
- Orchestration (OSM),
- O-RAN compliant RAN (OAI, srsRAN, CableFree small cells),
- MEC (K3S Kubernetes),
- Digital twin with emulated network simulations (SUMO, Kubernetes,UERANSIM).

KPIs and KVIs

- **Technical KPIs:**
  - Latency (e.g., perception offloading, edge handover),
  - Throughput (e.g., real-time data collection, video streaming bitrate),
  - Reliability (e.g., QoS during congestion, service continuity during roaming and handovers),
  - Energy efficiency (implied via optimized edge deployment),
  - Resource allocation efficiency (e.g., via network slicing).

- **Vertical KVIs:**
  - Safety improvement (e.g., traffic avoidance),
  - Cost reduction (e.g., efficient resource management),
  - Productivity gain (e.g., enhanced city services, improved traffic avoidance),
  - Societal relevance (e.g., impact on urban mobility and safety),
  - Institutional value (e.g., connection to 5G technologies).

- **Measurement Methodology:**

KPIs via ATCLL Kafka cluster, RAN WebSocket scraping, Prometheus for MEC monitoring, ELCM for multi-source collection (Kafka, MQTT, InfluxDB). KVIs through stakeholder discussions, questionnaires, and interviews on urban needs, technological relevance, and societal impact.

Lessons learned

Hands-on interaction enhanced understanding; integration of simulations with real hardware proved effective for replicating urban scenarios; feedback highlighted needs for scalable beyond-5G solutions in mobility.
Stakeholder input revealed needs for urban-specific adaptations; broad representation highlighted national scalability; organizational insights on integrating city hall expertise for practical deployments.

Contribution to Standards / Open Source:

Alignment with ETSI (ITS-G5), 3GPP (C-V2X); open-source contributions via tools like Open5GS and FlexRIC.

References

- João Gameiro, Pedro Valente, Francisco Ribeiro, José Oliveira, Pedro Rito, Duarte Raposo, Susana Sargento, Carlos Marques, Miguel Mesquita, Filipe Pinto, "Poster: 6G-PATH Project Connected and Sensing City 6G Testbed" 2025 EuCNC & 6G Summit, 3-6 June 2025, Poznan, Poland.
- Tiago Mostardinha, João Gameiro, Pedro Valente, Pedro Rito, Duarte Raposo, Susana Sargento, Carlos Marques, Miguel Mesquita, Filipe Pinto, "Perception Offloading for Autonomous Mobility in a Beyond-5G Edge-enabled Environment", IEEE Future Networks World Forum 10–12 November 2025, Bangalore, India.
- Links to Videos / Demo 28th May: https://www.youtube.com/watch?v=caWi0xwSSK4
- Links to Videos / Demo 25th July: https://www.youtube.com/watch?v=-4GHgNh4D6I
- News: https://6gpath.eu/6g-path-showcases-uc-cities-1-at-the-automotive-summit-in-aveiro/ https://6gpath.eu/6g-path-at-nato-vip-day-in-aveiro/ https://6gpath.eu/uc-cities-1-trial-showcases-connected-and-sensing-city-scenarios-at-aveiro-testbed/ https://6gpath.eu/open-demonstration-event-showcases-uc-cities-1-and-uc-cities-3-in-aveiro-portugal/

2.6.3 TRAP-5G-enabled Remote-controlled Assembly Process for Digital Construction

Trial Title: TRAP – 5G-enabled Remote-controlled Assembly Process for Digital Construction
Project Acronym: TARGET-X
Project Full Name: Trials for Advanced 5G-based Technological Solutions
Contact Person: Roberto Ruggiero (University of Camerino)
Project Website: https://target-x.eu/
Funding Programme: Horizon Europe – SNS JU - TARGET-X (5G/6G Large-Scale Trials and Pilots)
Main Vertical(s) Addressed: Construction Industry, Industry 4.0, Smart Manufacturing, Digital Construction
Replicability: N/A
Geographical Location(s): Aachen, Germany

Trial Overview

The objective of the TRAP trial is to validate a 5G-enabled cyber-physical workflow for the design, robotic production, and on-site assembly of prefabricated construction components. The trial aims to demonstrate how low-latency connectivity, real-time data synchronization, and mixed reality (MR) technologies can improve precision, adaptability, and traceability in construction processes. A further goal is to assess the performance and limitations of public and private 5G networks in supporting AR/MR-assisted assembly and remote supervision.

The trial is deployed in controlled laboratory and testbed environments simulating real construction workflows. The scenario includes distributed design offices, and on-site assembly contexts, connected through public and private 5G infrastructures. The concrete building components were 3D printed in Italy and subsequently shipped to the Aachen testbed for assembly and testing.

Trial deployment including integration with vertical solutions

The TRAP end-to-end architecture integrates parametric design environments, robotic fabrication systems, and mixed reality devices within a unified 5G-enabled digital infrastructure. Design data and block identifiers are managed through a BIM-based digital twin, synchronised in real time with production and assembly phases. Mixed reality headsets receive live instructions and stream on-site activities to remote servers for supervision and analysis.

Vertical systems, including parametric design tools, robotic control software, and BIM environments, are interfaced through the 5G network to enable bidirectional data exchange. The integration ensures continuous synchronisation between digital models, production data, and assembly instructions.

Key 5G Technologies Used:

- Public and Private 5G Networks
- VPN-based logical local networking
- Mixed Reality (HoloLens 2, Meta Quest 3)
- Robotic 3D Concrete Printing
- BIM-based Digital Twin (Speckle)
- Parametric and Generative Design Tools
- IoT-based Production Monitoring

KPIs and KVIs

- **Technical KPIs:**
    - End-to-end network latency
    - Uplink and downlink throughput
    - Packet rate stability
    - Video streaming quality
    - Data synchronization reliability
    - MR device responsiveness

- **Vertical KVIs:**
    - Assembly precision and reduction of placement errors
    - Productivity gains in assembly operations
    - Reduction of on-site supervision requirements
    - Process traceability and data availability
    - Operator safety and usability

- **Measurement Methodology:**

Technical KPIs were measured through application-level traffic monitoring and network performance testing across WiFi, public 5G, and private 5G scenarios. Vertical KVIs were assessed through observational analysis, task execution metrics, and qualitative feedback from operators involved in the trials.

Lessons learned

The trial highlighted the importance of low-latency and predictable network performance for MR-based construction workflows. Environmental factors and device ergonomics influence MR usability on site. Further standardization of interfaces between BIM, parametric design, robotics, and MR systems is required to fully exploit the potential of the workflow.

Contribution to Standards / Open Source:

- Validation of 5G-enabled MR workflows for construction use cases
- Contribution to best practices for cyber-physical construction processes within SNS JU projects
- Feedback on interoperability between BIM, parametric, and MR systems

References

Related Publications/Deliverables:

- The linked preprint presents the TRAP experimentation in the context of related research topics. A dedicated paper focusing on the TRAP trial is currently under review for an international conference and is planned for submission to an international Elsevier journal.
- Links to Videos / Demos: https://youtu.be/j7xhT36S13w?si=Fo_9BHmfBxlmJJHZ
- Official site: https://target-x.eu/

2.6.4 Resilient, cobot-powered warehouse inventory management leveraging trustworthy flexible topologies and beyond communication aspects

Trial Title: Resilient, cobot-powered warehouse inventory management leveraging trustworthy flexible topologies and beyond communication aspects
Project Acronym: HEXA-X-II
Project Full Name: European level 6G Flagship project
Contact Person: Panagiotis Demestichas, pedemest@wings-ict-solutions.eu , Sokratis Barmpounakis, sbarmpounakis@wings-ict-solutions.eu
Project Website: https://target-x.eu/
Funding Programme: Horizon Europe – SNS JU
Main Vertical(s) Addressed: Smart Manufacturing, Logistics, Collaborative Robots
Replicability: 41
Geographical Location(s): Athens/Attica Region, Greece

Trial Overview

The objective of this trial is to evaluate and validate key 6G enablers developed in Hexa-X-II at system level, assessing their alignment with the 6G system blueprint. It demonstrates how advanced orchestration, beyond-connectivity services (e.g. Compute-as-a-Service, AI-as-a-Service), and intent-driven automation support complex multi-domain industrial scenarios.

The trial is deployed in a distributed warehouse environment with multiple sites connected through an emulated multi-domain network. It includes cobots, autonomous devices, energy-harvesting sensors, and edge/cloud resources, supporting latency-sensitive and compute-intensive services. The following use cases are demonstrated:

- **Cobot-Powered Warehouse Inventory Management:** Real-time shelf monitoring using energy-harvesting sensors, edge analytics, and digital twinning.
- **Cobot-Powered Video Surveillance:** Latency-sensitive video streaming and object detection across sites.
- **Multi-Site Monitoring and Orchestration:** Intent-driven deployment, dynamic bandwidth adaptation, and workload migration between sites.

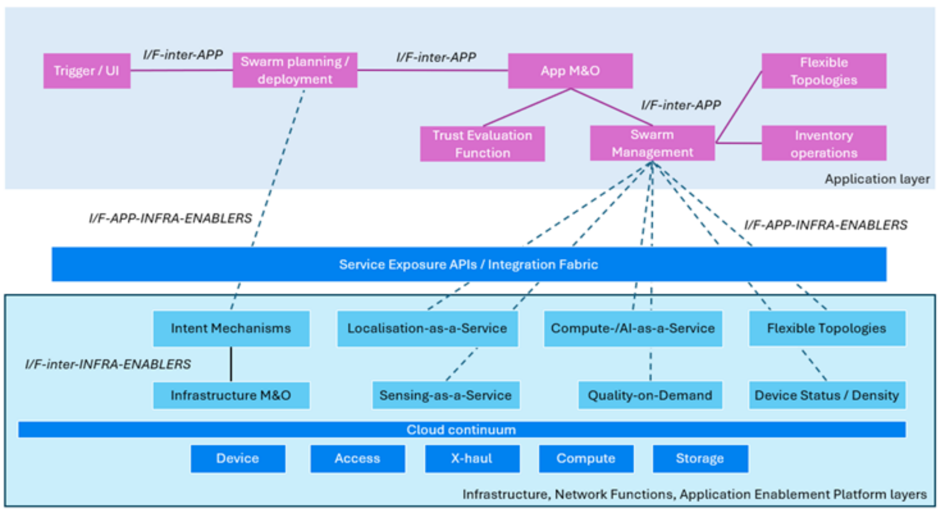


Figure 58: Experimental Platform / Testbed Used: WINGS 5G NPN and compute testbed

Trial deployment including integration with vertical solutions

The trial follows a multi-domain, intent-driven architecture where applications express business intent. Network, compute, and AI resources are dynamically orchestrated across sites, enabling workload placement, migration, and adaptation, supported by observability and closed-loop automation. The system integrates vertical application components through the WINGS **wi.supply**[1] platform, providing inventory management and vision-based surveillance services. Through AEP-exposed APIs, applications access network, compute, localisation, device status, and QoD capabilities, ensuring alignment between application needs and system-level orchestration.

[1] https://www.wings-ict-solutions.eu/introducing-wi-supply-by-wings-revolutionizing-industry-logistics/

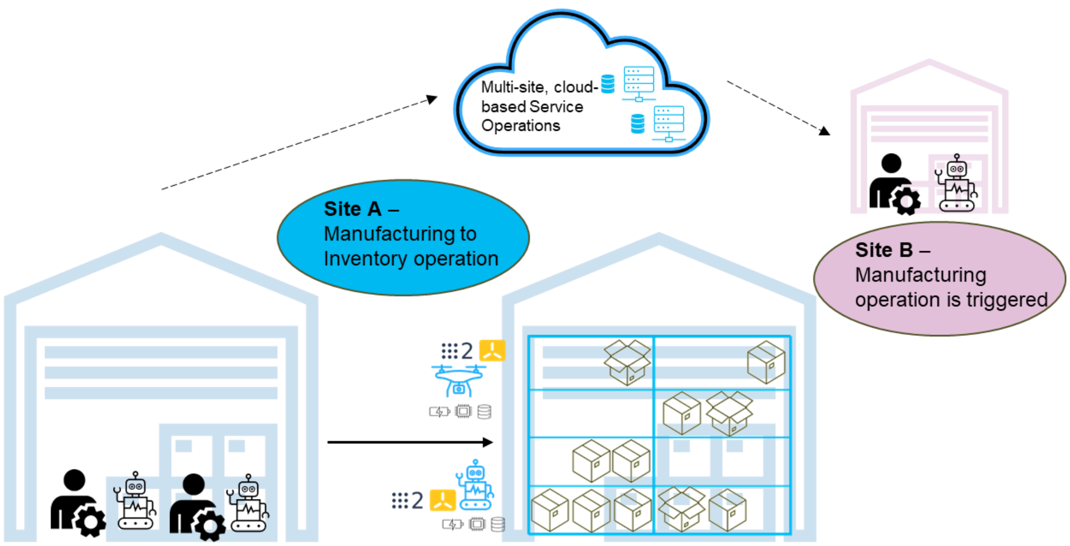


Figure 59: Trial Architecture

Key Technologies Used

- Intent-based networking and orchestration
- Software-Defined Networking (SDN) with transport network emulation
- Flexible topologies and network-of-networks concepts
- Compute-as-a-Service (CaaS) and AI-as-a-Service (AIaaS)
- Edge and cloud computing
- Multi-agent reinforcement learning for orchestration
- Energy-harvesting IoT devices and TinyML
- Application Enablement Platform (AEP) with exposed APIs (e.g. QoD, device status)

KPIs and KVIs

- **Technical KPIs:**
  - Service migration downtime ($t_2 - t_1$) during cross-site workload migration
  - End-to-end latency for video streaming and object detection workflows
  - Throughput and packet loss before and after migration
  - Resource utilisation (compute and network) per site
  - Reliability of intent execution and orchestration actions

- **Vertical KVIs:**
    - Operational continuity during service migration
    - System adaptability to changing resource availability
    - Energy efficiency of workload placement decisions
    - Resilience of monitoring and surveillance services
    - Effectiveness of intent-driven automation in multi-site scenarios

- **Measurement Methodology:**

  KPIs are collected via a distributed observability platform gathering telemetry from applications, network infrastructure, and compute resources across sites. Measurements are compared before, during, and after dynamic events (e.g. bandwidth regulation, service migration). KVIs are assessed through scenario-based evaluation of service continuity, adaptability, and qualitative power consumption considerations.

Lessons learned

Technical insights: Intent-based orchestration across multi-domain infrastructure enables dynamic workload migration and adaptive resource management, but requires strong observability and coordination mechanisms across network, compute, and AI resources.
Operational insights: Cobots and distributed sensing enhance warehouse monitoring and automation, while effective orchestration depends on clear intent abstraction and seamless interaction between applications and infrastructure.
Measurement insights: System-level evaluation in multi-domain environments requires coordinated monitoring and synchronized frameworks to capture the impact of dynamic orchestration actions.

References

Related Publications/Deliverables:

- Hexa-X-II D2.5, Hexa-X-II D2.6 (https://hexa-x-ii.eu/category/deliverables/)

Links to Videos / Demos: https://www.youtube.com/watch?v=EiZUSK-e66c

3. Technical Insights and Statistical Analysis

Metric	Value
Total Trials	27
Countries	10
Vertical Domains	6
SNS Projects	9
Testbeds Used	21+
Max Replicability Score	60 / 100 (La Mayora Agriculture – 6G-PATH)

3.1 Statistical Distribution of Trials

This section provides a statistical overview of the 27 Large-Scale Trials conducted under the SNS JU programme across four dimensions: use-case domain, country, hosting project, and 5G feature frequency.

3.1.1 Distribution by Use Case Domain

Public Safety / PPDR is the dominant vertical (8 trials, 30%). The remaining five domains each contribute 4 trials (15%), reflecting a deliberate balance across strategic European verticals.

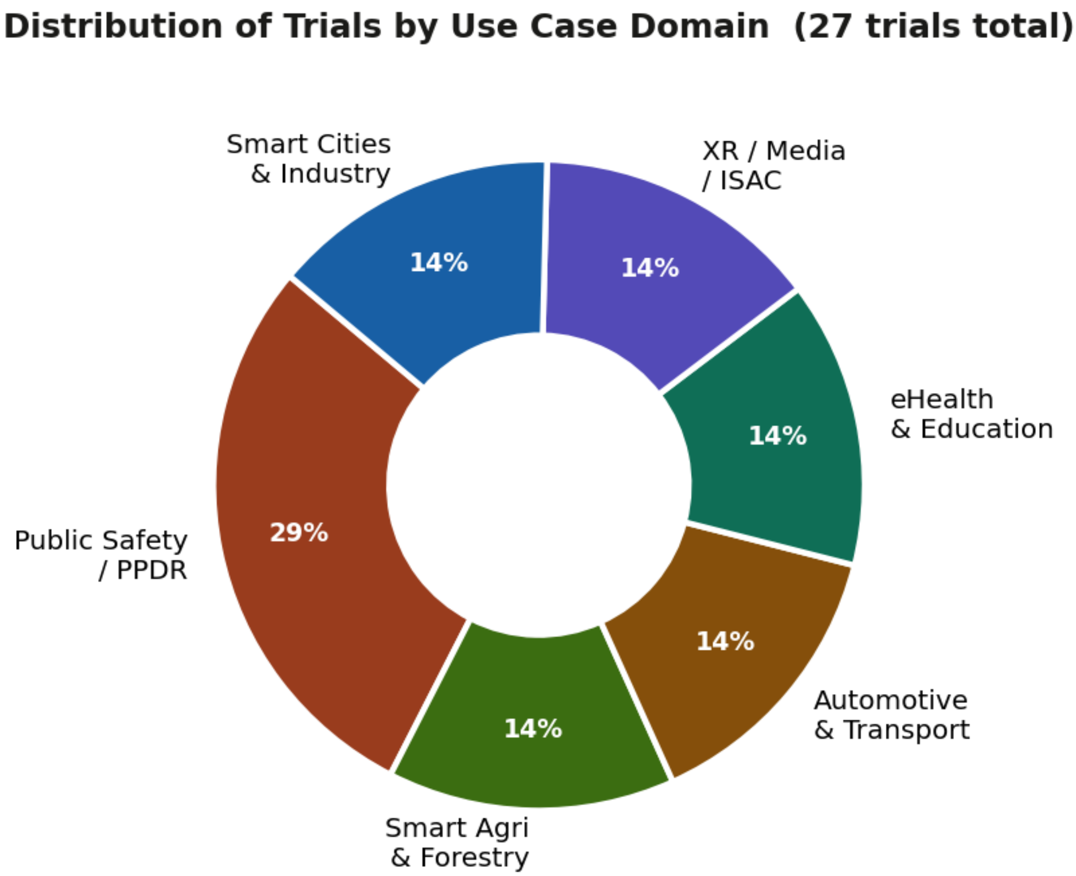


Figure 60: Number of trials by Use Case domain

Key observations, domain distribution

- PPDR dominance reflects Europe's strategic priority to modernise emergency communications infrastructure with 5G MCX capabilities.
- Balance across non-safety domains signals the programme's intent to demonstrate 5G cross-sector value, not only mission-critical use.
- The XR/Media/ISAC domain includes the only pre-6G sensing trial (JCAS/ISAC, EuCNC 2025), marking a technology readiness milestone.

3.1.2 Distribution by Country

Trials span 10 European countries. Spain leads with 7–8 active sites, followed by Greece (6 trials) and Germany (3–4). Infrastructure models range from commercial 5G SA (Spain) and private testbeds (Greece) to 5G campus networks (Germany) and Network-on-Wheels in remote areas (Norway).

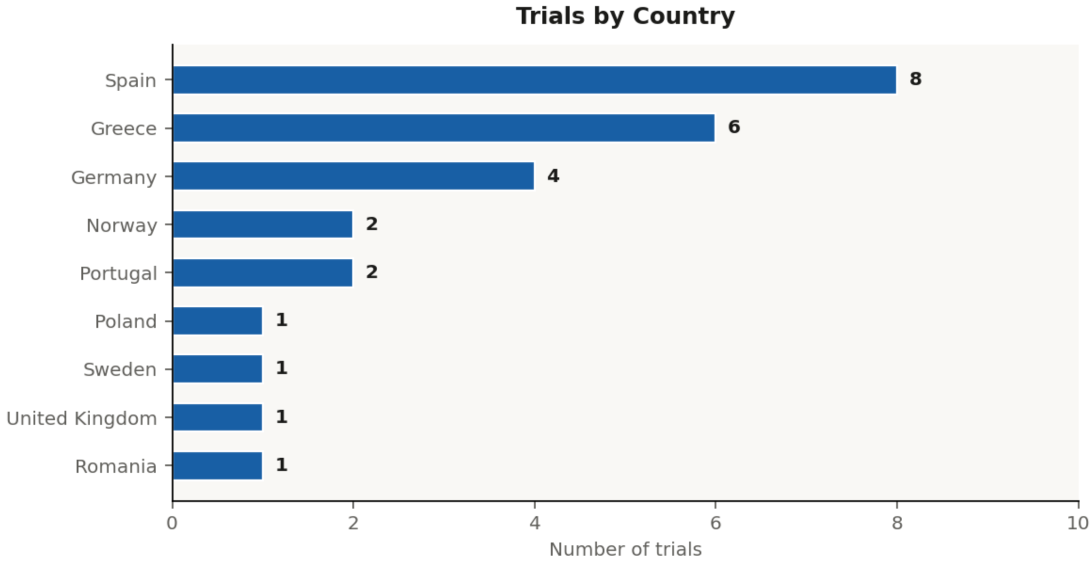


Figure 61: Number of trials per country

Notable testbed concentrations

- Victoria Network (UMA, Málaga, Spain): hosts 4 trials from 3 projects, FIDAL PPDR, FIDAL MC-SEAL, 6G-PATH La Mayora, 6G-SANDBOX JCAS/ISAC.
- Patras5G (UoP/PNET, Greece): hosts 4 trials from FIDAL and AMAZING-6G simultaneously, validating the NSaaS model at scale.
- Fraunhofer FOKUS (Berlin, Germany): hosts 2 healthcare trials from 6G-PATH, both using Open5GCore, enabling deep infrastructure reuse.

3.1.3 Distribution by SNS Project

IMAGINE-B5G and 6G-PATH lead in trial volume with 7 trials each, reflecting their role as open-call platforms. FIDAL contributes 6 trials exclusively in Public Safety. Smaller projects deliver focused experiments in specific technology niches.

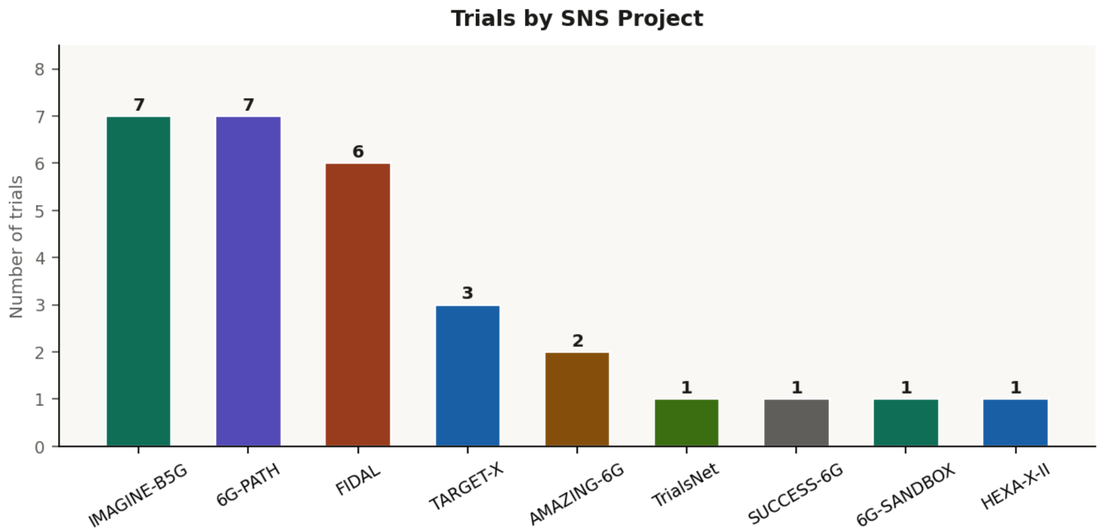


Figure 62: Number of trials per SNS project

3.1.4 Most Repeated 5G Features Across All Trials

Analysis of explicit 5G feature deployments reveals a clear hierarchy. 5G Standalone and Edge Computing are near-universal. Network Slicing is present in 19 trials as the primary vertical differentiation mechanism. AI/ML at the Edge (16 trials) confirms its role as a core service component, not an add-on. Kubernetes is the de facto orchestration platform (13 trials). ISAC/JCAS appears in only 2 trials, the emerging pre-6G frontier.

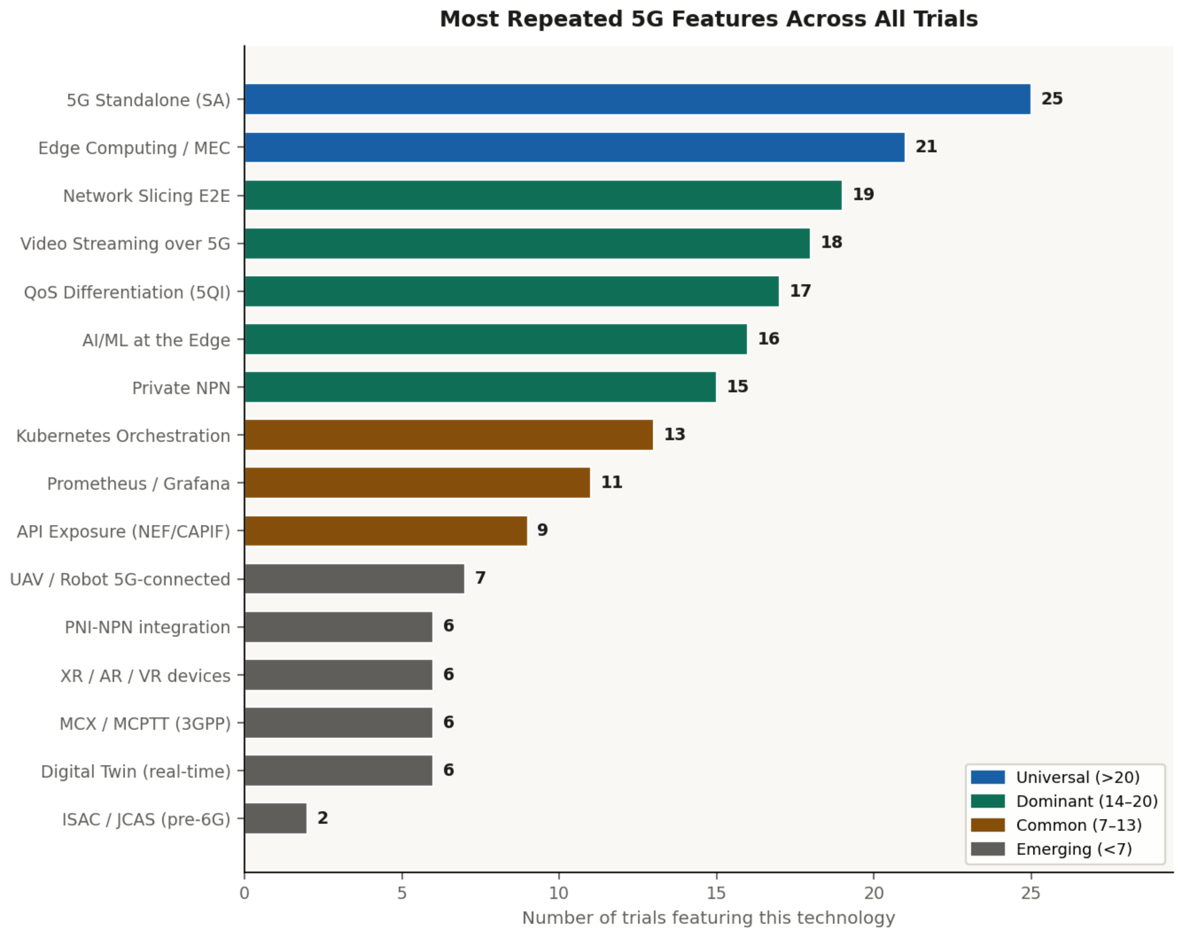


Figure 63: Most repeated 5G features, number of trials featuring each technology

The universal 5G vertical stack (80%+ of all trials)

- 5G Standalone (SA), 25+ trials. The non-negotiable baseline. NSA was used only as a fallback in hybrid setups.
- Edge Computing / MEC, 21 trials. Co-location of compute with the 5G core or gNB is the universal architectural answer to latency requirements.
- Network Slicing E2E, 19 trials. The primary QoS differentiation mechanism enables PPDR, XR and IoT to coexist on the same physical infrastructure.
- AI/ML at the Edge, 16 trials. No longer optional: fire detection, vehicle anomaly monitoring, maritime threat detection, crop maturity classification.

3.1.5 Trial Replicability Scores

Replicability scores, assessing how readily a trial can be reproduced in a different location or by a different team, were reported for 11 of the 27 trials, ranging from 35 to 60. The highest scores correlate with well-documented private 5G deployments, standardised measurement tools (NEMO Handy, iPerf3), and reproducible open-call hardware configurations.

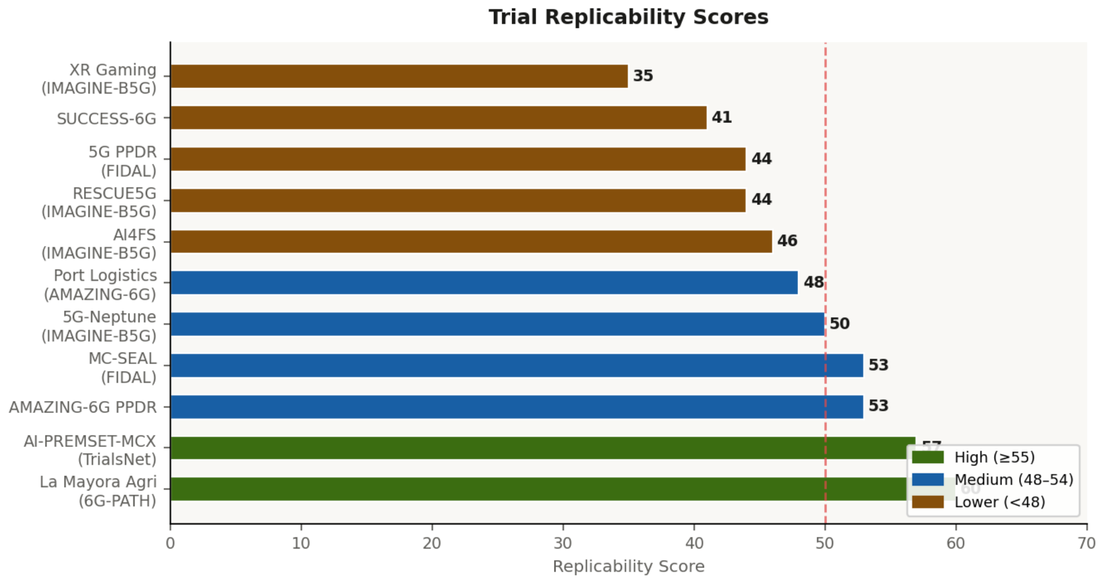


Figure 64: Replicability scores for trials where values were reported

3.1.6 KPI and KVI Coverage by Domain

All trials defined both technical KPIs and value-oriented KVIs across economic, societal and environmental dimensions. Safety/PPDR trials show the most complete KVI coverage. Agriculture trials lead on environmental KVIs (CO_2, water). Transport trials lead on economic KVIs through logistics optimisation.

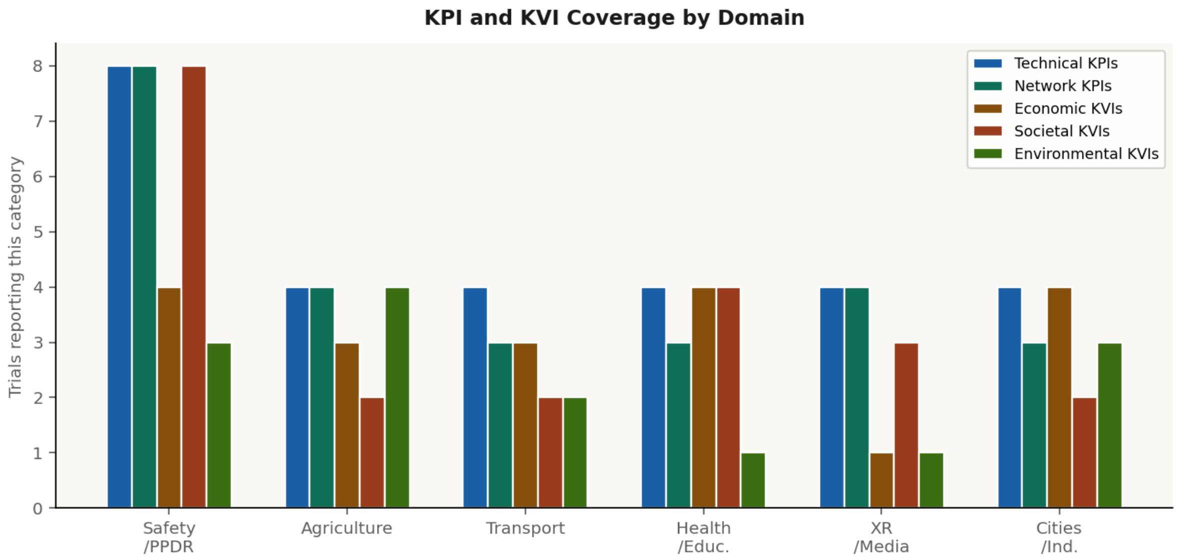


Figure 65: KPI and KVI category coverage by use case domain

4. Lessons Learned from Large-Scale Trials

This section analysed technical, operational and measurement insights from all 27 trials. Lessons are grouped thematically to highlight cross-cutting patterns that transcend individual projects or vertical domains. Specific trials are cited when the evidence is particularly strong.

4.1 Technical Insights

4.1.1 5G SA and Network Slicing: Essential, Not Optional

5G Standalone and end-to-end network slicing are the non-negotiable technical foundation for differentiated service quality. Trials relying on 5G NSA or unmanaged shared slices consistently reported higher latency variance and reduced reliability under congestion. Three trials demonstrated simultaneous multi-slice operation under real load.

- FIDAL PPDR (Málaga): Dedicated PPDR slice on Telefónica's commercial 5G SA maintained MCPTT access times during congested stadium events while default-slice users experienced degraded throughput, direct empirical validation of slice isolation.
- La Mayora Agriculture (6G-PATH): Three simultaneous slices, eMBB for 4K UAV video, URLLC-like for drone control, mMTC-like for soil sensors, demonstrated measurable resource isolation with no cross-service interference under real field conditions.
- XR Gaming (IMAGINE-B5G / UPV Valencia): Dedicated 5QI priority for HMDs was necessary to maintain stable latency and jitter during a 19-participant competition. Without the slice, XR quality degraded significantly under campus network load.

4.1.2 Edge Computing Is the Architectural Answer to Latency

Every trial with a sub-50 ms latency requirement independently reached the same conclusion: compute must be co-located with the 5G core or gNB, and never routed to a regional or central cloud. The quantified evidence across trials is unambiguous and consistent.

- RTwin-CAV (TARGET-X, IDIADA Barcelona): 24 ms end-to-end latency from AI hazard detection to digital twin update in Unity over 5G+edge, versus ~106 ms over 4G+cloud (AWS). A 4–5× improvement critical for proactive safety intervention in connected automated vehicles.
- AR Public Safety (FIDAL, Patras5G): Edge-based AI video processing maintained ~30 FPS at 30–40 ms E2E latency across multiple simultaneous AR devices. Cloud routing would have exceeded the 50 ms perceptual threshold for AR usability.

- 5G-Neptune (IMAGINE-B5G, Jaren Norway): Co-locating the gNB and UPF inside the Network-on-Wheels enabled local data path for MCX traffic, reducing backhaul bottlenecks and improving communication privacy without fixed infrastructure.

4.1.3 AI/ML Has Become a Core Service Component

AI/ML at the edge appeared in at least 15 of the 27 trials. In every case, the AI component was critical to delivering the vertical service value, not an optional enhancement. Independent convergence on YOLO-family models across safety, maritime and automotive trials is particularly notable.

- RESCUE5G (IMAGINE-B5G, Port of Valencia): YOLO, Faster-RCNN, Detectron2 and EfficientDet ran at the edge for real-time threat detection from USV cameras. A CI/CD pipeline enabled model updates within one week (≤30 min for urgent changes), essential for adapting to variable sea conditions and lighting.
- AI-PREMSET-MCX (TrialsNet, Romania): TensorFlow/scikit-learn models were trained on real collected MCX service metrics to optimise 5G network configuration, the first use of AI/ML trained directly on live MCX data from a real 5G SA deployment.
- SUCCESS-6G (Castelloli, Cellnex): KServe inference provided scalable real-time vehicular anomaly detection from C-V2X measurement streams, with precision/recall/F1 measured across multiple handover events at the Cellnex Mobility Lab circuit.

4.1.4 Uplink Bandwidth Is the Persistent UAV and Video Bottleneck

Every trial deploying UAVs, body cameras or multi-stream live video identified uplink bandwidth as the primary network constraint. 5G SA's uplink advantage over LTE was consistently demonstrated, but the absence of native 5G airframes and growing multi-stream demand make this an ongoing concern.

- Digital Twin for First Responders (FIDAL, Patras): 5G SA sustained 120 Mbps aggregate uplink supporting two drones and four surveillance cameras simultaneously. The trial explicitly noted that 5G SA and network slicing are essential to eliminate latency and jitter in real-time UAV video analytics.
- La Mayora Agriculture (6G-PATH): The eMBB slice for 4K UAV video required dedicated uplink allocation. Without slice isolation, mMTC sensor traffic would compete for uplink resources, degrading video quality below usable thresholds.

4.1.5 Native 5G Devices for Drones and XR Remain Unavailable

The absence of commercially available drones, XR headsets and industrial equipment with native 5G SA connectivity was the single most frequently cited technical limitation across all domains. Workarounds, USB adapters, WiFi tethering, and 5G router attachments introduce jitter, corrupting the validity of the latency KPI.

- XR-assisted PPDR (FIDAL, Patras): HoloLens 2 required USB-C adapters or WiFi tethering via 5G smartphones. The WiFi path introduced significant jitter, skewing latency measurements and degrading the XR streaming quality of experience for first responders.
- 5G XR Gaming (IMAGINE-B5G): Multiple USB dongles tested for HoloLens 2 were found unsupported, requiring Ethernet conversion adapters and workarounds that added infrastructure complexity and measurement uncertainty.
- FIDAL Digital Twin: 'Not all devices are fully compatible, and some 5G-enabled devices perform inconsistently across networks or require complex configurations', the lack of fully 5G-native drone airframes required iterative configuration work across all outdoor sessions.

4.2 Operational Insights

4.2.1 Real End Users Must Be Co-Designers, Not Just Evaluators

Trials with the highest replicability scores and strongest adoption outcomes consistently involved real operational users in scenario design, not just execution. In every documented case, early user involvement produced scenario changes and interface refinements that desk-based design had not anticipated.

- AI-PREMSET-MCX (TrialsNet, Romania): Collaboration with STS (Romanian Special Telecommunications Service) first responders in scenario design (urban fire, building collapse, mass casualty) directly improved execution quality and refined system behaviour to match real PPDR protocol requirements.
- 5G-Neptune (IMAGINE-B5G, Norway): Involvement of NDMA (Norwegian Defence Material Agency) and Police IT Dept. validated the PNI-NoW architecture and contributed to advancing the solution's TRL from 6 to 7, the level required for commercial potential demonstration.
- MC-SEAL (FIDAL, San Sebastián): 25 actors, including Municipal Guard agents and crisis room commanders, participated in a simulated major football event scenario. Third-party stakeholders explicitly reported operational value and expressed interest in continued collaboration beyond the project.

4.2.2 Technology Adoption Is the Real Barrier, Not Performance

Across all PPDR and healthcare trials, users consistently rated reliability and interface simplicity above feature completeness. The path from 'technically validated' to 'operationally adopted' was identified in every domain as the primary deployment barrier, driven by training requirements, interface design and institutional processes, not network performance gaps.

- 5G for PPDR (FIDAL, Málaga): Police officers appreciated communication reliability but emphasised that field deployment requires simple, intuitive interfaces. Training and familiarisation were identified as essential prerequisites; technology that performs well in demonstrations fails in the field without adequate user preparation.
- Elderly Monitoring (6G-PATH, Berlin / Charité): Nursing home staff highlighted the need for intuitive daily-use interfaces. On-site support during initial sessions was identified as a critical trust-building mechanism that cannot be skipped, regardless of how well the system performs technically.

4.2.3 Logistics Planning Cannot Be Compressed Below 6 Months

Coordinating permits, safety protocols and availability windows in real operational environments, seaports, stadiums, road circuits, and hospitals cannot be compressed. Every trial in such environments reported that logistics was the critical path, not technology integration.

- RESCUE5G (IMAGINE-B5G, Port of Valencia): Port permits, harbour authority approval, safety procedures and vessel traffic management required months of coordination. Weather and sea conditions required contingency playbooks with adaptive bitrate thresholds and safety cut-off protocols that had to be pre-approved.
- AI-PREMSET-MCX (TrialsNet): Reaching 100 simultaneous MCX smartphones required SIM procurement and operator API agreements initiated at project start. Trials that deferred device planning consistently missed their scale targets by significant margins.

4.2.4 Environmental KVIs Can Be Quantified, and Should Be

Trials that consciously tracked measurable environmental impacts produced concrete KVI evidence that strengthens the overall value proposition and can be independently audited against ISO 14001 or equivalent standards.

- FI-VEG (IMAGINE-B5G, Soria): Remote 5G-enabled vineyard operations reduced CO_2 emissions by 656 kg compared to equivalent conventional operations, a quantified baseline for precision agriculture sustainability claims auditable by third parties.

- AI-PREMSET-MCX (TrialsNet): A 2:1 device reuse ratio was formally assessed against ISO 14001 environmental compliance, establishing a reusable methodology for circular economy KVI reporting that other trials could adopt.
- 5CADE (TARGET-X, Aachen): Automated 5G-monitored irrigation maintained substrate moisture at 65–85% with automatic override during rain events, demonstrating that sensor-driven precision reduces water waste with zero manual intervention and measurable water savings.

4.3 Measurement and Methodology Insights

4.3.1 Synchronised Timestamps Are Mandatory for KPI Correlation

Correlating network metrics with application performance requires synchronised timestamps across all data sources: sensors/cameras, vehicles/USVs, the 5G network, edge services, and visualisation. Without time synchronisation, E2E latency measurements are unreliable and cross-layer analysis is invalid.

- RESCUE5G (IMAGINE-B5G): The KPI toolchain synchronised timestamps across the USV camera, 5G SA network counters, AMQP/Redpanda event bus and edge backend. Radio metrics (RSRP/RSRQ/SINR, DL/UL throughput) were geo-referenced via GPS to generate coverage heatmaps correlated with real-time USV position.
- JCAS/ISAC (6G-SANDBOX, Poznań): PTP time synchronisation via a Falcon RX Grandmaster was identified as mandatory for the O-RAN sensing chain. Without it, SRS channel estimation data cannot be accurately correlated with physical presence/absence ground truth from the LiDAR/camera validation system.

4.3.2 Prometheus/InfluxDB/Grafana Has Converged as the de facto standard

Without formal coordination across projects, the Prometheus (metric collection) + Grafana (dashboarding) + InfluxDB/Telegraf (time-series storage) monitoring stack converged independently across 8+ projects. This spontaneous convergence creates an opportunity: mandating this stack in future programmes would unlock cross-project KPI comparison at the programme level.

- TrialsNet / AI-PREMSET-MCX: Prometheus, PostgreSQL, InfluxDB, Kafka and Parquet formed the complete MCX metrics and infrastructure data pipeline, reused from pre-trial validation through final execution.
- 6G-PATH / Elderly Monitoring: InfluxDB was used for isolated debugging of the smartwatch analytics integration before full-system deployment on the Open5GCore testbed at Fraunhofer FOKUS, identical to the automotive and safety trials.

4.3.3 Separate Technical KPI and User Study Sessions

Collecting network KPIs and user-experience KPIs simultaneously creates logistical overload and risks technical incidents that could contaminate survey responses. The most effective trials planned distinct sessions with independent success criteria for each measurement type.

- Enhanced Healthcare Education (6G-PATH, Karlstad): Technical KPI collection (ICMP ping for manikin control latency, VSFA deep-learning video quality scoring on a 1–5 MOS scale) was formally separated from KVI collection via questionnaires and a focus group with student nurses after the session ended.
- AI-PREMSET-MCX (TrialsNet): Structured questionnaires were completed by all participants after the trial, cleanly decoupled from the real-time network metric ingestion pipeline running during execution.

4.3.4 Drive-Test Tools Are Required for Slicing KPIs on Commercial Networks

Measuring the effect of network slicing on a public 5G SA network cannot be done solely through passive monitoring. Drive-test tools that force 5G SA attachment and per-cell binding are required to control the measurement environment and isolate the slice under test from ambient traffic variability.

- FIDAL PPDR (Málaga / Victoria Network): NEMO Handy was used to force UE connectivity to specific 5G SA cells and to collect slice ID, 5QI configuration, SS-RSRP/RSRQ/SINR and MAC/RLC/PDCP layer metrics simultaneously, measurements not accessible through standard passive monitoring tools.

4.4 Open Challenges and Limitations

4.4.1 PPDR Adoption Faces Regulatory and Institutional Barriers

Technical validation is necessary but not sufficient. Replacing TETRA/PMR with 5G MCX requires regulatory approval, interoperability certification, procurement processes and operational change management that are entirely outside any project's scope and timeline.

- All five PPDR trials involved real first-responder agencies. In each case, agencies reported that the path from trial participation to operational deployment requires years of institutional processes, not driven by technical performance gaps, but by procurement rules, TETRA interoperability requirements and safety certification mandates.

4.4.2 Full B5G/6G Disaggregation Adds Measurable Latency Overhead

As architectures move towards fully disaggregated O-RAN with distributed MEC and cloud-native functions, each additional interface hop adds latency. For XR and PPDR services with strict sub-50 ms requirements, this overhead must be characterised and budgeted at design time.

- AMAZING-6G PPDR explicitly identified this as an open research challenge: 'Investigate the effect that a fully disaggregated B5G/6G architecture and the relative placement of B5G/6G functions, MEC, and backhaul/fronthaul solutions may have on the overall delay for XR-assisted PPDR campaigns.'

4.4.3 Industrial Tool Interoperability Needs Further Standardisation

Trials combining digital construction, warehouse management and port logistics found that BIM tools, parametric design software, robotics interfaces and MR devices lack standardised APIs, forcing bespoke integration work in every project and making results difficult to generalise.

- TRAP (TARGET-X, Aachen): 'Further standardisation of interfaces between BIM, parametric design, robotics, and MR systems is required to fully exploit the potential of the workflow.' Current integration is project-specific and fragile.

4.4.4 Some KVIs Require Longer Timeframes Than Any Single Trial Provides

Indicators such as 'reduction in casualties', 'long-term societal sustainability' and 'workforce upskilling outcomes' cannot be meaningfully validated within a trial's operational window. This structural limitation must be acknowledged explicitly in the KVI framework.

- SAFERFLOW (IMAGINE-B5G, Aveiro): 'Minimisation of Casualties' was flagged as hard to validate in non-disaster conditions, and 'Societal Sustainability' as hard to validate in limited pilot conditions. The team recommended large-scale simulations or real-event longitudinal data as the only viable evidence path.

4.5 Consolidated Summary of Lessons Learned

The table below details the 20 key lessons from all 27 trials, mapped to categories and primary evidence sources, and presented as actionable findings.

Category	Lesson	Primary Evidence
Technical	Edge co-location delivers 4–5× latency vs. cloud	RTwin-CAV: 24 ms vs 106 ms (IDIADA)
Technical	Network slicing isolation holds under real congestion	FIDAL PPDR · La Mayora · XR Gaming
Technical	AI/ML is now a core vertical service component	RESCUE5G · AI-PREMSET · SUCCESS-6G
Technical	Uplink BW is the UAV/multi-camera bottleneck	FIDAL Digital Twin · La Mayora 4K
Technical	Native 5G devices for drones/XR are unavailable	FIDAL XR · IMAGINE-B5G XR Gaming
Technical	Kubernetes microservices enable live adaptation	AI-PREMSET-MCX · SUCCESS-6G
Technical	ISAC/JCAS in FR1 is limited by 100 MHz BW resolution	6G-SANDBOX (EuCNC 2025, Poznań)
Operational	Real users as co-designers improve realism & TRL	AI-PREMSET (STS) · 5G-Neptune (NDMA)
Operational	Interface simplicity beats feature richness in the field	FIDAL PPDR · Elderly Monitoring
Operational	Logistics planning needs ≥6 months lead time	RESCUE5G · AI-PREMSET-MCX (100 UEs)
Operational	Device reuse (2:1) provides ISO 14001 evidence	AI-PREMSET-MCX (TrialsNet)
Operational	CO_2/water KVIs are quantifiable with telemetry	FI-VEG (−656 kg) · 5CADE (irrigation)
Measurement	Sync'd timestamps mandatory for E2E KPI correlation	RESCUE5G (AMQP) · JCAS (PTP Falcon RX)
Measurement	Prometheus/InfluxDB/Grafana = de facto standard	8+ independent projects
Measurement	Separate technical and user-study sessions	Healthcare Education · AI-PREMSET
Measurement	Commercial network slicing needs drive-test tools	FIDAL PPDR (NEMO Handy)
Challenge	PPDR adoption blocked by regulatory/procurement	All 5 PPDR trials
Challenge	B5G disaggregation adds latency, must be budgeted	AMAZING-6G PPDR
Challenge	BIM/robotics/MR interop needs standardisation	TRAP (TARGET-X, Aachen)
Challenge	Casualty-reduction KVIs need events or a simulation	SAFERFLOW · AMAZING-6G

5. Recommendations for Future 6G Trials

Eight actionable recommendations for the SNS JU community and designers of future 6G Large-Scale Trial programmes, derived directly from the cross-trial evidence above.

1. Standardise the reference architecture

The stack 5G SA, dedicated slice, distributed edge UPF, Kubernetes, AI/ML inference, REST API-exposed QoS controls and Prometheus/InfluxDB/Grafana monitoring has converged independently across 8+ projects. Future trials should adopt it as a pre-validated starting point, directing innovation efforts toward vertical applications and the 6G-specific technology layers above it.

2. Standardise observability instruments across the programme

Requiring Prometheus/InfluxDB/Grafana as the programme-wide baseline monitoring stack would enable meaningful cross-trial KPI comparison, currently impossible due to heterogeneous tool choices. This single coordination measure would unlock programme-level analytics at negligible per-project cost.

3. Begin device and SIM procurement at project month 1

Reaching 50-100 simultaneous 5G UEs requires SIM provisioning, device acquisition and operator API access agreements to be initiated at project launch. A four to six month lead time is the minimum observed across trials that successfully reached their scale targets.

4. Make end-user co-design a programme requirement, not a recommendation

Trials co-designed with real emergency services, medical staff or industrial operators from the design phase consistently produce higher replicability scores, faster TRL progression and stronger stakeholder adoption outcomes. The evidence is strong enough to justify making this a formal programme condition.

5. Formally separate technical KPI and user-study KVI sessions

Allocate distinct trial windows for network KPI measurement under controlled load (drive-test tools, dedicated slices, iPerf3) and user experience KVI collection (questionnaires, focus groups). Mixing the two produces contaminated results in both dimensions.

6. Design for privacy from the architecture stage

Transmitting structured metadata (object class, bounding box, GPS, timestamp) rather than raw video eliminates GDPR consent overhead, reduces uplink bandwidth requirements, and does not reduce digital twin utility. RTwin-CAV proved this at IDIADA, achieving ≥95% mAP without transmitting a single raw video frame.

7. Coordinate device ecosystem development with 3GPP and ETSI

The absence of native 5G SA commercial drones, XR headsets and industrial equipment is the most frequently cited trial limitation. This cannot be solved within the boundaries of an individual project. We need to coordinate engagement with device manufacturers and standardisation bodies at the programme level.

8. Build systematically toward 6G: ISAC, AI-native control, intent-based networking

The JCAS/ISAC trial at EuCNC 2025 (6G-SANDBOX) and intent-based orchestration in HEXA-X-II are the first concrete 6G proof points in this portfolio. Future programmes should extend validated 5G architectures with integrated sensing, AI-native network control loops, semantic communication and energy-harvesting IoT, individual building blocks already demonstrated across this trial set and ready to be combined.

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