AMAZING-6G
Amazing Large-Scale Trials and Pilots for Verticals in 6G

Deliverable 4.1

Health and Public Safety Domain intermediate developments

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Executive Summary

This deliverable (D4.1) presents the intermediate technical progress, design specifications, and integration status of the Health and Public Safety use cases developed within the AMAZING-6G project. The project aims to demonstrate the transformative role of Beyond 5G (B5G) and 6G technologies through large-scale trials that utilizes combined Ultra-Reliable Low-Latency Communications (URLLC), advanced edge computing, Artificial Intelligence (AI), and intelligent network orchestration to support critical and unpredictable operational environments. Work Package 4 (WP4) plays a central role in the project by defining, implementing, integrating, and validating advanced use cases for the Health and Public Protection and Disaster Relief (PPDR) domains. Acting as the operational bridge between the architecture and technology enablers developed in other work packages (WP2 and WP3) and the large-scale demonstrations planned in WP7, WP4 focuses on: (i) the definition and design of specialized use cases, (ii) the implementation and integration of novel 6G technology enablers, and (iii) the collection of empirical evaluation data required for trial execution and performance assessment.

Significant progress has been achieved during the first reporting period. Task 4.1, dedicated to use case definition and design, has been successfully completed, establishing the functional and non-functional requirements for all scenarios and defining a comprehensive framework of Key Performance Indicators (KPIs) and Key Value Indicators (KVIs). The established targets include sub-10 ms end-to-end latency for PPDR services, ultra-high reliability reaching 99.999%–99.9999% for Health and PPDR, and peak data rates exceeding 0.5 Gbps. Beyond technical performance, the project also evaluates societal impact indicators, including reductions in emergency response times and improvements in patient safety and operational resilience.

Tasks 4.2 and 4.3 are currently ongoing and focus on implementation, integration, and testing activities. These tasks support the continuous deployment of platform services and the integration of technology enablers developed in WP3 into operational demonstrators and pilot environments. Current efforts include interface definition, interoperability validation, AI-driven orchestration, and preparation for large-scale field trials across partner testbed facilities such as the TNO testbed, Patras-5G infrastructure,5GTN Finland and ORO lab. The resulting evaluation data contributes both to the preparation of WP7 demonstrations and to ongoing international standardization activities aligned with future 6G ecosystems.

The deliverable highlights several “first-of-its-kind” innovations that push the boundaries of current B5G/6G capabilities. In the health domain, Intelligent Edge-AI enables wearable ultrasound patches and cardiac monitoring systems to offload computationally intensive AI processing to edge infrastructure, overcoming battery and processing limitations while supporting real-time diagnostics. In the public safety domain, the project demonstrates ubiquitous interoperability across terrestrial 5G, Wi-Fi 6, and Non-Terrestrial Networks (NTNs), including satellite connectivity. Additional innovations include rapidly deployable “network-in-a-box” tactical infrastructures, AI-driven network slicing and orchestration, autonomous backhaul selection, and resilient communication mechanisms for infrastructure-less and extreme environments. Innovative AI-enabled services and applications in the PPDR domain that enhance situational awareness and support preparedness have been integrated and tested in the various testbeds.

Seven core use cases are currently progressing through pre-trial integration and validation phases.

Within the Health domain, the H1 use case introduces a wearable adhesive ultrasound patch for continuous cardiac monitoring, utilizing edge-based AI for real-time imaging analysis and enabling improved remote healthcare services. The H2 use case focuses on predictive AI-driven reprogramming of implantable cardiac devices, enabling closed-loop and near real-time pacemaker adjustment through ultra-low-latency 6G communications.

Within the PPDR domain, the P1 use case focuses on AR/VR-assisted control centers and autonomous deployment of digital infrastructure for enhanced situational awareness during emergency operations.

P2 addresses seamless interoperability across heterogeneous communication systems, enabling uninterrupted mission-critical connectivity between terrestrial, Wi-Fi, and satellite networks. P3 introduces emergency communication-on-the-move capabilities through independent private B5G/6G networks deployed in areas where public infrastructure is unavailable or destroyed. P4 targets Arctic search-and-rescue operations in extreme environmental conditions using hybrid satellite-terrestrial communications and sensor-equipped eSled. P5 demonstrates rapidly deployable tactical B5G/6G networks with portable standalone cores and opportunistic satellite backhaul for resilient field operations.

Large-scale trials are therefore essential to validate these technologies under realistic operational conditions. The planned field trials will assess system performance under heavy traffic loads, high mobility, isolated environments, and heterogeneous connectivity conditions. They will also evaluate operational impact and user acceptance through KVIs related to responder safety, operational efficiency, reduced downtime, and improved patient outcomes. These trials constitute the final step toward validating interoperability, robustness, and compliance with evolving global 6G and 3GPP-aligned standards.

Preliminary results already confirm the feasibility of edge-centric healthcare and hybrid terrestrial/satellite connectivity as foundational pillars for future resilient digital services. Early healthcare evaluations demonstrate that AI offloading to the edge can significantly reduce wearable device power consumption while maintaining real-time analytical capabilities. In the public safety domain, initial field tests have successfully validated the integration of Low Earth Orbit (LEO) satellite backhaul with communication latencies as low as 17 ms under pre-trial conditions.

Despite the encouraging results, several technical challenges remain. These include maintaining reliable signalling over high-latency satellite links, ensuring seamless transitions between connected and standalone network modes, achieving automated Quality of Service (QoS) configuration in highly dynamic environments, and managing the complexity introduced by the integration of network slicing, Multi-access Edge Computing (MEC), Open RAN architectures, and AI-driven orchestration mechanisms. Additional challenges arise from operating in harsh and infrastructure-degraded environments where communications must remain resilient under near worst-case radio conditions.

Overall, WP4 has successfully progressed from use case definition and laboratory integration toward advanced field validation activities. The project is now entering a critical phase focused on large-scale experimentation, optimization of AI-enabled orchestration mechanisms, and validation under real-world operational conditions. The final execution of large-scale demonstrations across all use cases is scheduled for the second and third quarters of 2027, marking a major step toward establishing 6G as a key technological foundation for future healthcare and public safety services.

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List of Acronyms and Abbreviations

TERM	DESCRIPTION
5MBS	5G Multicast-Broadcast Services
ABR	Adaptive Bitrate
AF	Application Function
AGV	Autonomous Guided Vehicle
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
ASE	American Society of Echocardiography
AV	Atrioventricular
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
BBU	Baseband Unit
CBE	Cell Broadcast Entity
CBS	Cell Broadcast Service
CBSF	Cell Broadcast Service Function
CCC	Command and Control Center
CMAS	Commercial Mobile Alert System
CMUT	Capacitive Micromachined Ultrasonic Transducer
CPE	Customer Premises Equipment
CPRI	Common Public Radio Interface
DL	Downlink
E2E	End-to-End
EC	European Commission
ED	End-diastolic

ECG	Electro-cardiogram
EF	Ejection Fraction
EGM	Electrogram
EPC	Evolved-Packet Core
ES	End-systolic
ETWS	Earthquake and Tsunami Warning System
EU	European Union
FAC	Fractional Area Change
FET	First Encounter Team
FR	First Responders
GEO	Geostationary Orbit
GNB	Next Generation Node B (gNodeB)
HPC	High-Performance Computer
ICD	Implantable Cardioverter-Defibrillators
IOT	Internet of Things
KPI	Key Performance Indicator
KVI	Key Value Indicator
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LTE	Long-Term Evolution
LV	Left Ventricle
MAC	Medium Access Control
MBS	Multicast and Broadcast Services
MC	Mission Critical
MCX	Mission Critical Services
MCC	Mission Critical Communications
MCPTT	Mission Critical Push-to-Talk

MEC	Multi-Access Edge Computing
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MOCN	Multi Operator Core Network
MQTT	Message Queuing Telemetry Transport
NAS	Non-Access Stratum
NEF	Network Exposure Function
NG-RAN	Next Generation Radio Access Network
NFV	Network Function Virtualisation
NIFTI	Neuroimaging Informatics Technology Initiative
NPN	Non-Public Network
NTN	Non-Terrestrial Networks
NTP	Network Time Protocol
NR	New Radio
NSAAS	Network Slice as a Service
NUC	Next Unit of Computing
O-CU	O-RAN Central Unit
O-DU	O-RAN Distributed Unit
O-RAN	Open Radio Access Network
O-RU	O-RAN Radio Unit
PACCS	The Physical Activity and Fitness in Childhood Cancer Survivors Study
PLMN	Public Land Mobile Network
PM	Pacemakers
PNG	Portable Network Graphics
PNI-NPN	Public Network Integrated Non-Public Network
PPDR	Public Protection and Disaster Relief
PPP	Point-to-Point Protocol

PTP	Precision Time Protocol
PTT	Push-to-Talk
PWS	Public Warning System
QAM	Quadrature Amplitude Modulation
QCI	Quality of Service Class Identifier
QOD	Quality on Demand
QOS	Quality of Service
R&D	Research & Development
RAN	Radio Access Network
RAT	Radio Access Technology
REDCAP	Reduced Capability
RF	Radio Frequency
RFID	Radio Frequency Identification
RIC	RAN Intelligent Controller
RIT	Receive Idle Time
RRC	Radio Resource Control
RRH	Remote Radio Head
RRU	Remote Radio Unit
RSRP	Reference Signal Received Power
RTMP	Real-Time Messaging Protocol
RTSP	Real-Time Streaming Protocol
RTT	Round Trip Time
SA	Standalone
SDR	Software Defined Radio
SHE	Service Hosting Environment
SIGMF	Signal Metadata Format
SMO	Service and Management Orchestration Framework

SMS	Short Message Service
SNPN	Standalone Non-Public Network
SNR	Signal-to-Noise Ratio
SRIT	Short Receive Idle Time
SRT	Secure Reliable Transport
TCN	Temporal Convolutional Network
TDD	Time Division Duplex
TN	Terrestrial Networks
UAV	Unmanned Aerial Vehicle
UC	Use Case
UE	User Equipment
UL	Uplink
UPF	User Packet Function
URLLC	Ultra-reliable Low Latency Communications
USRP	Universal Software Radio Peripheral
VM	Virtual Machine
VPN	Virtual Private Network
VR	Virtual Reality
VSAT	Very Small Aperture Terminal

1 Introduction

Health and Public Safety Domain Intermediate Developments

This deliverable (D4.1) documents the intermediate technical progress and design specifications for the Health and Public Safety use cases within the AMAZING-6G project focusing on fast provisioning of infrastructures and services and autonomous, AI-enabled performance to support unpredictable situations. The project aims to revolutionize these critical sectors by deploying large-scale 6G-enabled trials that leverage Ultra-Reliable Low-Latency Communications (URLLC), advanced edge computing, and AI-driven network orchestration, based on various enablers that have been identified as critical for the specific domains.

Key Technical Innovations

The project introduces several innovative technical enablers designed to push the boundaries of current B5G/6G capabilities:

- Intelligent Edge-AI for Medical Diagnostics (H1/H2): Development of wearable, adhesive ultrasound patches and cardiac monitors that offload heavy AI processing (e.g., fractional area change analysis, cardiac event prediction) to the 6G edge. This enables real-time, continuous monitoring without the battery or processing constraints of traditional wearable devices.
- Ubiquitous Multi-Network Interoperability (P1/P2/P5): Implementation of seamless roaming and intelligent network selection across terrestrial 5G, Wi-Fi 6, and Non-Terrestrial Networks (NTN)/Satellite like Starlink. This ensures mission-critical continuity for first responders in disaster zones where primary infrastructure may be compromised.
- Rapidly Deployable Tactical Networks (P1/P5): A "network-in-a-box" solution featuring a portable gNodeB (gNB) and local Standalone (SA) Core. Innovation lies in its ability to operate in full isolation (SA mode) or with opportunistic satellite backhaul, utilizing End-to-End (E2E) network slicing to prioritize Mission Critical Push-to-Talk (MCPTT) and Mission Critical (MC) Video traffic.
- AI-Driven Slice Management (P2/P3/P4): Automated gNB configuration and real-time slice performance monitoring that dynamically allocates resources based on situational awareness, such as Augmented Reality (AR)/Virtual reality (VR) feeds for control Centers.

Domain-Specific Progress & Trial Status

The deliverable outlines seven (7) core use cases currently in the pre-trial and integration phases. The particular focus of each case is presented in Table 1:

Table 1 : Health & Public Safety Use Case Focus

Domain	ID	Use Case Focus	Key Innovation/Enabler
Health	H1	Wearable Ultrasound Patch	Edge-based AI for cardiac imaging
	H2	Cardiac Device Reprogramming	Predictive AI for closed-loop pacemaker adjustment
Public Safety	P1	AR/VR Assisted Control Centers	Multi-operator slice deployment & backhaul selection
	P2	Multi-System Interoperability	Seamless handover between 5G, Wi-Fi, and Satellite

	P3	Emergency Communication-on-the-Move	Integrated private network slicing for MCX services
	P4	Arctic Search & Rescue	B5G connectivity in extreme environmental conditions
	P5	Tactical B5G/6G Networks	Deployable local core with satellite-connected fallback

KPI and KVI Framework

In the AMAZING-6G project, technical and operational success is measured through a rigorous framework consisting of Key Performance Indicators (KPIs) and Key Value Indicators (KVIs). This dual-metric approach ensures that the project not only meets advanced technical requirements but also delivers tangible benefits to society and specialized professional sectors like healthcare and public safety.

KPIs are used to quantitatively measure the technical performance of the 6G-enabled systems. These metrics focus on the capabilities of the network and its underlying technology enablers. Key targets identified in the project's introduction include:

- End-to-End (E2E) Latency: Achieving targets as low as <10ms for critical services like AR/VR in Public Protection and Disaster Relief (PPDR).
- Reliability: Maintaining service stability of up to 99.999%.
- Data Rates: Reaching peak data rates exceeding 1Gbps.

KVIs shift the focus from pure technical specs to the societal and operational impact of the solutions. They evaluate the "value" provided to end-users and the broader community. Examples of KVI targets include:

- User Experience: A target of 75% for improved user experience in selecting optimal connectivity options.
- Operational Efficiency: Measuring significant reductions in search and rescue times during emergency missions.
- Health Outcomes: In medical use cases, KVIs include targets like a 10% reduction in mortality risk and a 20% increase in patient quality-of-life scores.
- Role in Project Development

The definition and design of these KPIs and KVIs were a primary output of Task 4.1 (Definition and Design), which concluded at Month 12 (M12). These metrics serve as the baseline for empirical data collection during testing and will be the primary criteria for evaluating the success of the large-scale trials and pilots scheduled for execution in WP7.

Relation to WP2, WP3 and WP7

Work Package 4 (WP4) maintains strong interdependencies with Work Packages 2, 3, and 7 within the AMAZING-6G architecture and innovation framework. WP4 acts as a key vertical validation and integration layer for the Health and PPDR domains, ensuring that technological developments are aligned with real operational requirements and are validated through large-scale experimentation.

WP4 provides critical input to WP2 by defining the functional and non-functional requirements derived from the Health and Public Safety use cases. Through the activities performed in Task 4.1 and reported here, WP4 identifies the communication, latency, reliability, interoperability, mobility, and security requirements necessary to support mission-critical healthcare and PPDR services. These requirements directly contribute to the design and refinement of the overall AMAZING-6G system architecture developed in WP2. In addition, WP4 supports WP2 through continuous feedback loops established during implementation and testing activities. Results obtained from prototype integration, pre-trials, and field evaluations are used to validate architectural assumptions and refine system-level design decisions. This iterative interaction ensures that the overall AMAZING-6G architecture remains aligned with realistic deployment conditions and evolving operational needs.

WP4 serves as one of the principal validation environments for the advanced technology enablers developed in WP3. The Health and Public Safety use cases integrate and assess several key WP3 innovations, and are analysed on per Use Case basis. Through Tasks 4.2 and 4.3, WP4 identifies the required interfaces, integration mechanisms, and orchestration procedures necessary to deploy these enablers in operational scenarios. The use cases therefore act as realistic testbeds for evaluating the performance, scalability, robustness, and interoperability of WP3 technologies under demanding conditions, such as high mobility, extreme environments, infrastructure degradation, and life-critical medical operations.

Finally, WP4 constitutes a major contributor to the planning, execution, and validation activities of WP7, which is responsible for large-scale trials and demonstrations within the AMAZING-6G project. The use case definitions, KPI/KVI frameworks, implementation guidelines, and evaluation methodologies developed in WP4 provide the operational foundation for the WP7 demonstrations. As the project transitions from laboratory integration toward real-world deployment, WP4 and WP7 collaborate closely to ensure that the large-scale trials accurately reflect realistic operational conditions, including high traffic loads, heterogeneous connectivity, autonomous orchestration, and mission-critical service continuity. The final demonstrations planned for Q2 and Q3 of 2027 will therefore represent the culmination of the design, integration, testing, and validation activities initiated within WP4.

2 Use Case Definition and Design

This section describes the definition and design of the 2 Health and 5 Public Safety Domain use cases developed in WP4. It covers the goals and scope of each use case but also their implementation schemes, key components, developed enablers and how they interact with the B5G/6G infrastructure through these enablers.

This chapter reports on the work developed in Task 4.1 capturing the definition and design of these use cases in detail as the first step to enable the start of their implementation, that is reported in the next chapter. By clearly outlining the technical application solutions and integration with communication networks and enablers, this section sets the foundation needed to move forward with development and testing activities.

These use cases are directly related to the design initiated in the project deliverable D2.1 [1]. There, the context views and the initial diagrams have been drafted although in some cases the descriptions have been updated.

2.1 H1 Wearable ultrasound patch for cardiac function monitoring

New adhesive-patch-based, ultrasound devices, leveraging CMUT (Capacitive Micromachined Ultrasonic Transducer) and similar transducer technologies, are appearing on the market, enabling totally new ways of exploiting cardiac functional imaging. These patches, which are semi-permanently attached to the patient's body, promise to enable more frequent assessments and monitoring for longer periods of time. This way critical time points before, during, and after hospital interventions (e.g., surgery or catheter interventions) can be covered. Furthermore, patients can be monitored during advanced treatments for heart failure, such as intensive care therapy or while being moved in the ambulance. Finally, patients can be monitored at home, at work, on-the-move, or even during exercise, in order to expand and improve the cardiac assessment toolbox.

Patch-based, cardiac ultrasound assessment can be automated by deploying AI-based, ultrasound image analysis algorithms on the edge (as obviously, the patch itself lacks processing power and battery capacity to do so by itself). These algorithms will extract cardiac function parameters, such as fractional area change. Also, hemodynamic (e.g., blood pressure) and Electro-cardiogram (ECG) data can be integrated into analyses for addressing different clinical situations and enhancing the output of the ultrasound image data.

2.1.1 Description of the Use Case

Figure 1 depicts the cardiac assessment solution comprising a 6G-enabled, ultrasound patch (EGC and blood pressure sensing are optional) on the left-hand side and the 6G Radio Access Network (RAN) and Core hosting AI-based image analysis on the edge on the right-hand side. The AI-based assessments are communicated to the cardiologist via the Clinical backend which is connected to the 6G-System via a Data Network such as the Internet.

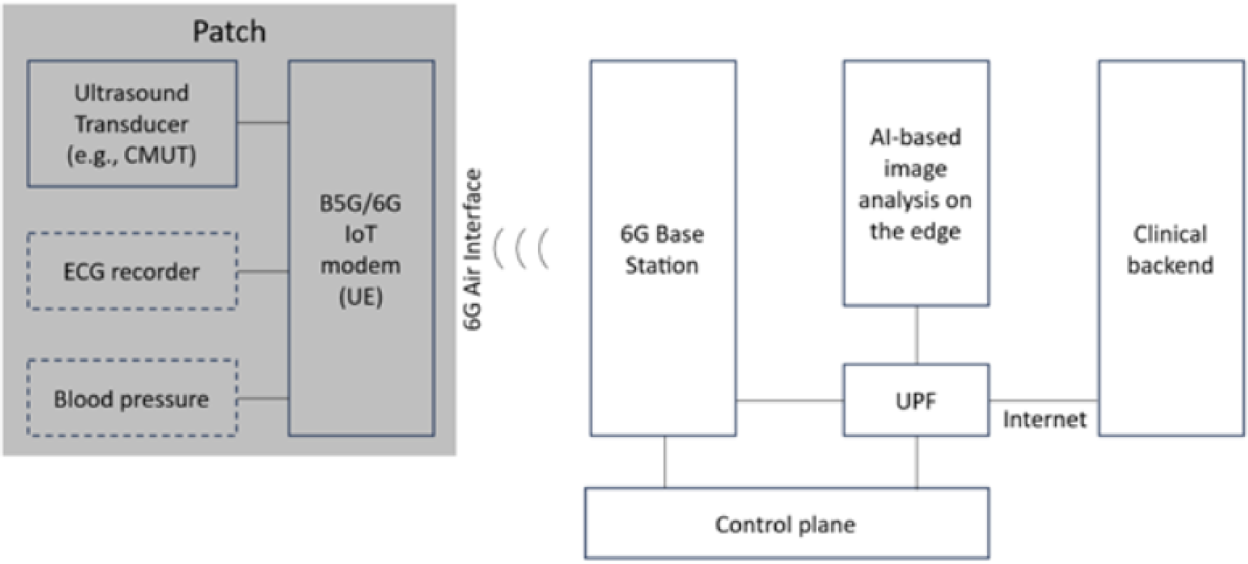


Figure 1 : H1 use case overview

This solution may prove to be a new powerful tool for early detection of critical changes in cardiac function and complications to treatment, such as cardiac effusions, cardiac tamponades, functional consequences of arrhythmias in especially fragile patients and pulmonary hypertensive crises. Similarly, the effects of drug treatment can be monitored more closely by continuous registration of cardiac ultrasound data in the hospital and by providing daily short registration updates after discharge to home or to lower-level care settings. The latter also enables early discharge from the hospital. In short, cardiac ultrasound patches combined with edge-based AI analysis will improve patient outcomes and lower the cost of care, while improving patient and caregiver experience.

2.1.1.1 *Clinical Scenarios*

As described above, an ultrasound patch with cardiac function analysis on the edge could benefit patient treatment during several stages of the patient's journey (e.g., during treatment and after returning home). However, each of these stages sets different requirements for the patch, the AI-based analysis, and their deployment on the 6G System. Specifically, the following three variables can be helpful when defining different clinical scenarios:

- Location: at home (H), during transportation – i.e., in the ambulance – (T), or at the hospital – i.e., during intervention or in the intensive care unit – (I).
- Power source: battery (B) or cable (C).
- Data analysis: offline – i.e., batch – processing (O) or real-time analysis (RT).

It should be noted that these variables are interdependent and may lead to conflicting requirements. For example, in ambulatory settings (H), the patch will need to be battery-powered (B). This severely limits its energy budget and therefore real-time analysis – i.e., continuously sending data to the edge in real-time – (RT) will not be feasible. However, for this situation, offline analysis (O) is sufficient. On the other hand, during interventions and intensive care (I) the patient can be tethered to an external power supply (C) and real-time monitoring (RT) is needed and possible.

The two scenarios chosen for H1 use case are:

- **H1A** (H-B-O): Home-based, battery-operated use with offline analysis, for testing of heart function during ambulatory exercise, such as walking stairs, running, or bicycling (e.g., assessment of contractile reserve (how much extra above baseline work level the heart can work during exercise, i.e. how much the heart can increase its blood volume output per minute when needed) during exercise to further fine-tune medication therapy). Nowadays, exercise echocardiography is an advanced assessment only performed in select specialized Centers.

- **H1B** (I-C-RT): Intensive care monitoring of cardiac output in patients with circulation failure and continuous titration and adjustment of medical treatment that supports heart function and circulation, such as direct infusions into the veins of drugs that increase heart frequency and contraction like epinephrine, levosimendan or milrinone or that dilate the arterial vessels such as nitroprusside or again milrinone. Temporary pacemakers may be adjusted based on input from the patch to optimize heart function and output.

It is imaginable that a single patch product (i.e., multi-use ultrasound patch) and associated AI service on the edge could address both clinical cases. For example, the patch could have a power connection which could be used to charge the battery (H1A), but alternatively also to power the patch continuously while still attached to the patient's body (H1B). In the latter case, the patch could switch to continuous mode, streaming real-time image data to the edge, while the AI service deployment on the edge would switch to a real-time deployment by allocating additional resources (i.e., computational resources on the edge and a low-latency, high-bandwidth slice deployment). Therefore, it should be noted that, even though potentially a single device is involved, the requirements (and in particular the KPIs) for the 6G System are profoundly different.

2.1.1.2 *Benefits*

This use case illustrates the need for edge deployed AI algorithms to analyse medical image data in real time for patients with critical heart disease in order to improve:

1. Safety at home.
2. Safety and diagnostics during transportation in emergencies.
3. Improved cardiac care and management of patient flows.
4. Improved safety and alertness during hospital stays by improved real time heart function monitoring.
5. Earlier discharge from hospital to home by enhanced home monitoring.
6. Automated or semi- automated at home follow-up applications at home after cardiac interventions.

2.1.2 Deployment and implementation details

2.1.2.1 *Application Design*

After sketching the anticipated test setup for the use case, the work on its different components will be discussed: ultrasound transducers (and cabling), AI algorithm development, 5G RedCap connectivity, and edge deployment.

The developed pipeline for live streaming and clinical parameters prediction is based on segmentation of left ventricles using an AI model. The workflow needs to be parallelized with a multi-thread approach to reduce latency and obtain real time predictions. It has the following steps:

1. Prior to establishing real-time, live-stream prediction experiments, an AI model needs to be trained and validated with heterogenous quality data (noisy, race, age, vendors, different skilled sonographers, pathological heart, etc.).
2. If the ultrasound image is acquired from a machine that is from a commercially available vendor, then there are approved software packages for streaming ultrasound images in real-time to another computer. Also, the data can be acquired directly from that software for the AI workflow with anatomical information.
3. On other hand, if a research ultrasound machine such as Verasonics is used, then the streaming data can be captured from a screen and used for the AI prediction.
4. A High-Performance Computer (HPC) with 24 GB video and 64 GB CPU memory were used for AI prediction.

5. In addition to the AI based prediction, a few metrics on AI prediction were computed and saved.
6. Also, the echo image slices and the corresponding AI predictions were stored as Portable Network Graphics (PNG) or Neuroimaging Informatics Technology Initiative (NIfTI) compressed images for further use.
7. The computed metrics were compared with the parameters obtained from the clinically approved software.

2.1.2.1.1 Test setup

The anticipated test set-up is shown in Figure 2. A wearable, patch-based, ultrasound transducer (Xu labs, San Diego, USA- see Section below) is applied to the patient's chest, for continuous ultrasound imaging. It is connected to a Verasonics research ultrasound machine, which produces B-mode, ultrasound data (i.e., grey-scale moving video). A connection is made between Verasonics and the Quectel RC255C (New Radio (NR) Reduced Capability (RedCap)) evaluation board, which functions as the User Equipment (UE) towards the B5G System. It communicates with TNO's Hi5, B5G research facility which comprises a base station (Amarisoft), Core, and Edge. The OUS AI-algorithm will be deployed on this Edge and send its resulting data (i.e., cardiac function parameters such as fractional area change) to some PC mimicking the Clinical backend on the Intranet or Internet.

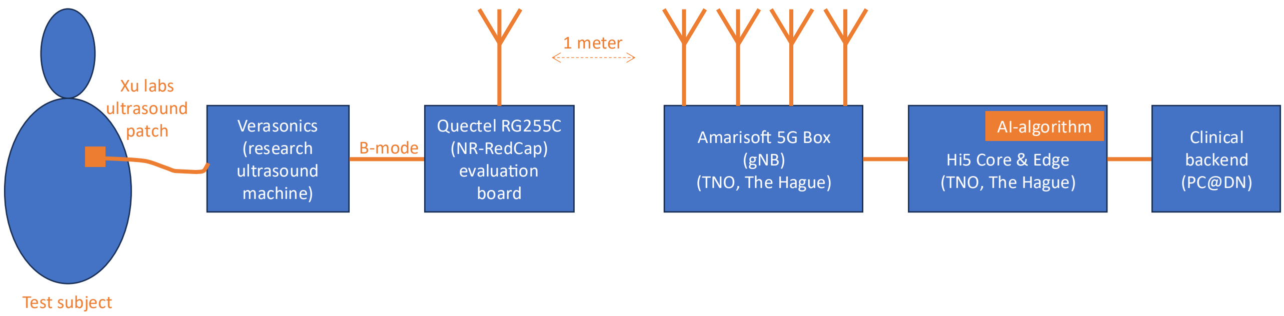


Figure 2 : H1 test setup design

The demonstration will take place at the TNO office in The Hague. However, it is conceivable that a patient's ultrasound (B-mode) data will be captured and recorded at OUS and that this recording will be used for the demonstration instead.

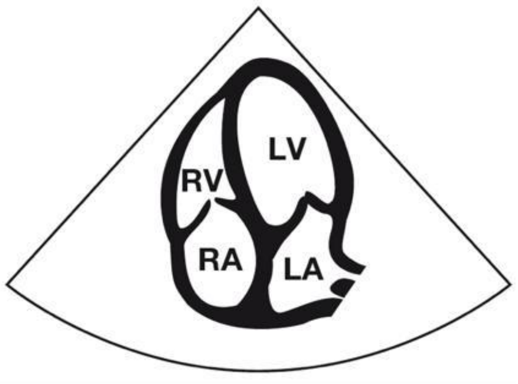
2.1.2.1.2 Ultrasound transducers

The adhesive ultrasound patches to be employed in the planned tests and studies are specified for paediatrics and adult medicine separately. These are provided in collaboration with, and designed and produced at, Xu research labs at the University of San Diego, USA. The transduced type employed is CMUT (see Figure 3). Ultrasound patches from Xu Lab were delivered and conducted first test in February 2026. Two patch models with different specifications for paediatric and adult application respectively, are being produced; the paediatric transducer being smaller and operating on a higher frequency. They will be delivered with connector cables that fit the Verasonics research ultrasound machine at the Institute for Informatics, OUS will collaborate during the setup and tuning of the transducers.

Figure 3 : Ultrasound transducer patches close to final development

2.1.2.1.3 AI algorithm development

This study aims to develop an AI algorithm for segmentation of moving cardiac ultrasound (B-mode) images and utilize the segmented cardiac structures for clinical interpretation. Firstly, it is important to explain the cardiac performance metrics before describing the AI algorithm implementation. These physiological metrics provide insight into cardiac functions and support diagnostic applications.



(b)

RV denotes Righ
Ventricle, RA denote

Figure 4 : Schema
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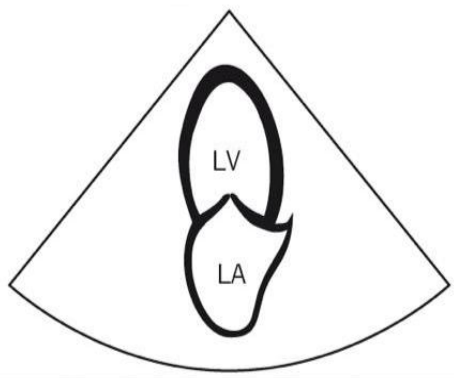

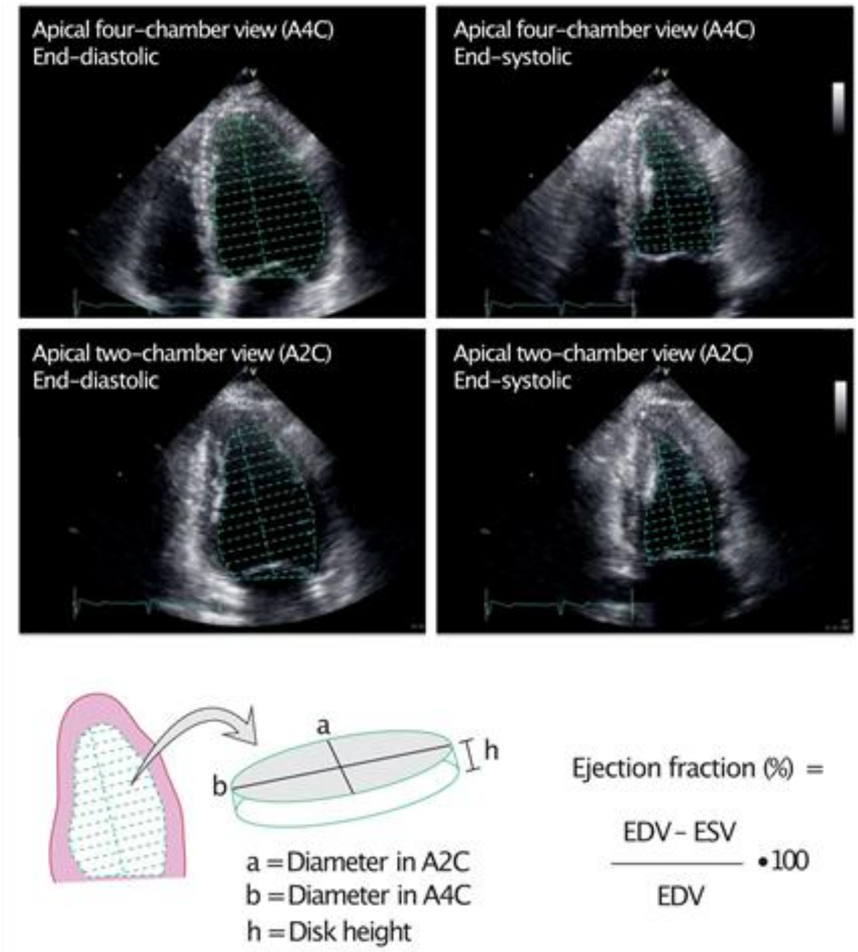

End-diastolic denotes the maximum heart volume, and End-systolic denotes end of the fully contracted heart volume.

Figure 5 : Annotated echocardiography views of apical 4 chamber, apical 2 chamber, and the formula for the ejection fraction

Ejection fraction is one of the key parameters for assessing cardiac function, representing the percentage of blood ejected from a ventricle with each heartbeat, given by

$$\text{EF}=\frac{SV}{EDV}\times 100,$$

where SV = EDV-ESV denotes the stroke volume, EDV denotes the diastole volume, and ESV represents the end systolic volume.

The present study is focused on echocardiography of the LV; the Simpson's bi-planner rule and that is the most accurate mathematical formula to calculate EF. Figure 4 describes the apical 4- chamber and apical 2- chamber views. The left ventricle is divided into segmental discs, calculated in their volumes, and then added together to get the full left ventricular volume, as shown in Figure 5 and Figure 6.

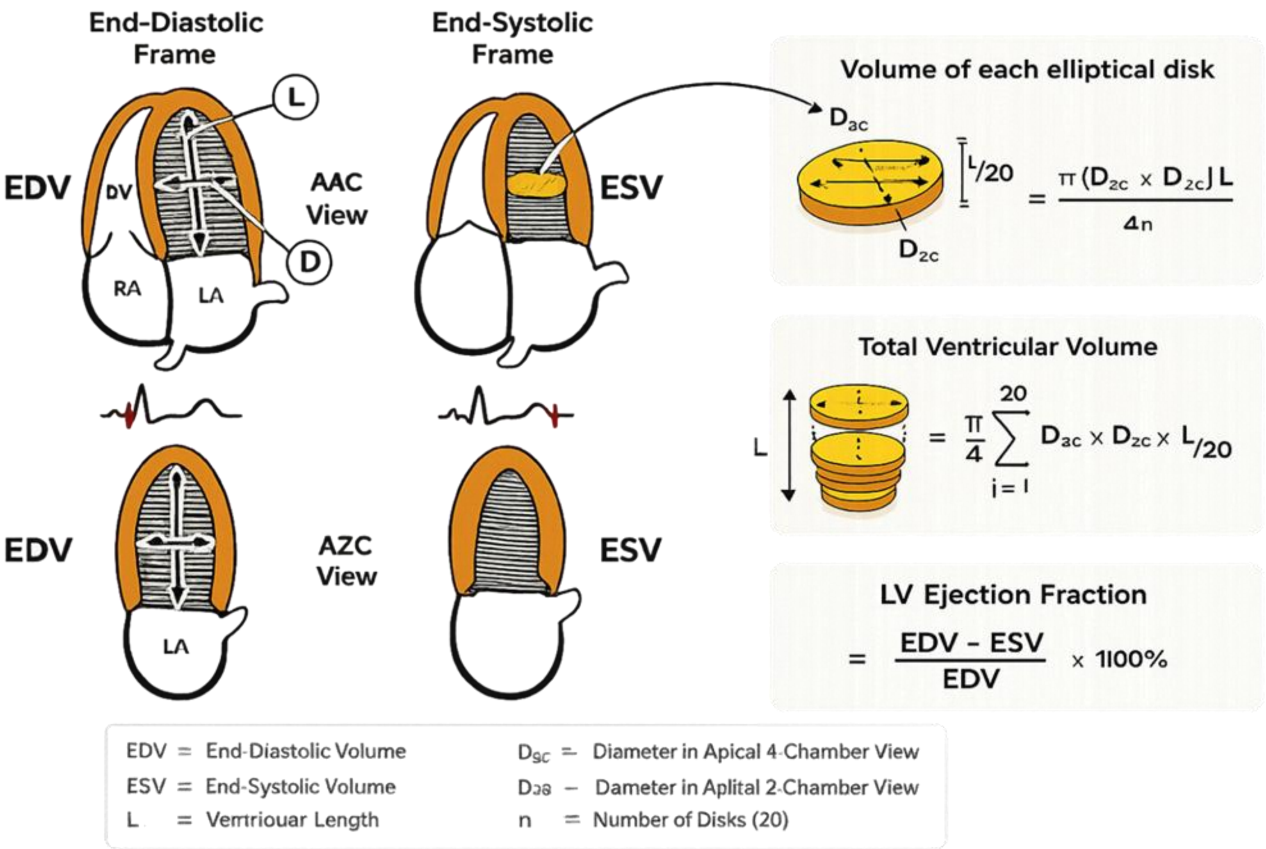

Figure 6 : Pictorial representation of the end diastolic, end systolic frames, and volume calculation using the Simpson's bi-planner formula

However, we utilize one view at a time in this work when we do live stream real time experiments. Thus, the biplane Simpson's bi-plane method of calculating LV volume cannot be utilized.

One of the first methods used was the *single-plane Simpson's method*. The American Society of Echocardiography (ASE) mentioned that this method could be used when two adequate views are not available. It is defined by

$$V = \sum_{i=1}^{N} \left(\frac{d_i}{2}\right)^2 \frac{L}{N} V = \sum_{i=0}^{n} \pi \left(\frac{d_i}{2}\right)^2 \frac{L}{N},$$

where V is the LV volume, N is the number of disks which is 20, d_i is the diameter for each disk, and L is the length/height of the LV from the apex to the middle point of the line created between the two mitral valves.

A deep learning algorithm for real-time analysis of apical 4-chamber transthoracic echocardiography images, which obtains estimates of left ventricular ejection fraction based on single plane area changes, (i.e., a fractional area change of the 4-chamber image), has been developed and tested with a clinical ultrasound platform at OUS.

When we use an area that is (semi) automatically segmented by an AI algorithm, the anatomical information is required to compute the ventricle ED or ES frame area. However, the Xu-labs (Santiago) ultrasound transducer patch (opposed to the ultrasound machine used thus far) does not export an affine matrix. The affine matrix provides the anatomical information and that can be used to calculate the area of the end diastolic and end systolic frames.

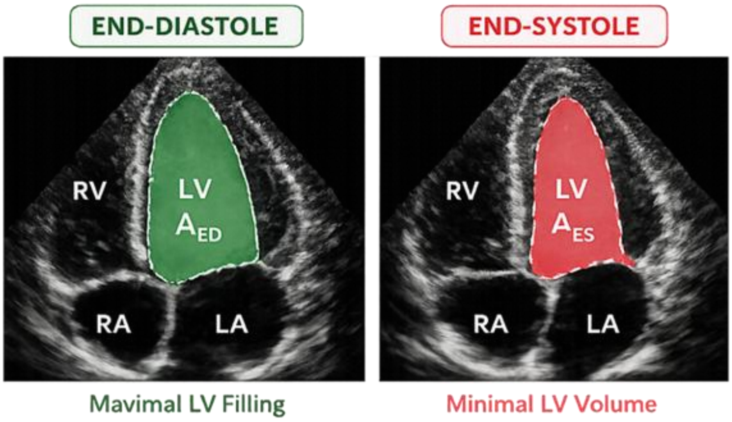

Figure 7 : Presentation of end diastole and end systole area, and the fractional area change

An alternative performance metric (than EF) to observe the function of the heart is *fractional area change* (FAC). It can be used also when the anatomical scaling information is unavailable. It is presented in Figure 7. The *fractional area changes* measures how much the ventricular cavity area decreases from end-diastole (ED) to end-systole (ES), expressed as

$$FAC = \frac{A_{ED} - A_{ES}}{A_{ED}} \times 100$$

where A_{ED} is the end-diastolic area and A_{ES} is the end-systolic area. The higher FAC represents a better systolic contraction, and lower FAC represents an impaired systolic function.

Therefore, the algorithm has been modified to calculate FAC, a metric to calculate the change in area of heart chambers irrespective of the actual anatomical area. Further work is currently underway, focusing on exact cardiac event timing to improve the accuracy and precision of the algorithms when compared to state-of-the-art echocardiographic heart function measurements.

Performance Metric Computation for offline AI Algorithms

Prior to live stream experiments, a UNet deep learning algorithm using PyTorch was developed. The UNet algorithm is a convolutional neural network architecture designed for biomedical image segmentation. It consists of two main parts: a contracting path (encoder) and an expanding path (decoder). The encoder captures contextual information from the input image through repeated convolution and max-pooling operations, progressively extracting deeper feature representations while reducing spatial dimensions.

The decoder reconstructs the segmentation map by up sampling the extracted features and combining them with corresponding high-resolution features from the encoder through skip connections. These skip connections help preserve fine spatial details and improve localization accuracy. Due to its symmetric U-shaped structure and ability to perform precise pixel-wise segmentation. UNet has become one of the most widely used deep learning models in medical image analysis, including applications such as organ, tumour, and cardiac structure segmentation in CT, MRI, and echocardiography images.

The UNet was trained, validated, and evaluated using two publicly available datasets viz., CAMUS and EchoNet Dynamics datasets. We also used an in-house dataset from a study called PACCS, which is a cardiac study on childhood cancer survivors. The pictorial representation of the UNet deep learning algorithm is provided in Figure 8.

The deep learning consists of the following steps while training and inference:

Preprocessing: The incoming grayscale ultrasound frames were resized (256x256) and normalized.

Augmentations: To make AI understand the real-world image variations, we used flipping the echo frames to 90 degrees, rotation of -20 to 20 degrees, and random salt and pepper noise were used. All these variations, each with 40% of the whole input date, and independent of each other were used. It means there is a chance for a frame to get more than one variation.

Inference: The deep learning model predicted binary masks highlighting the LV region.

Postprocessing: The predicted masks were resized back to their original dimensions before being passed to subsequent processing threads.

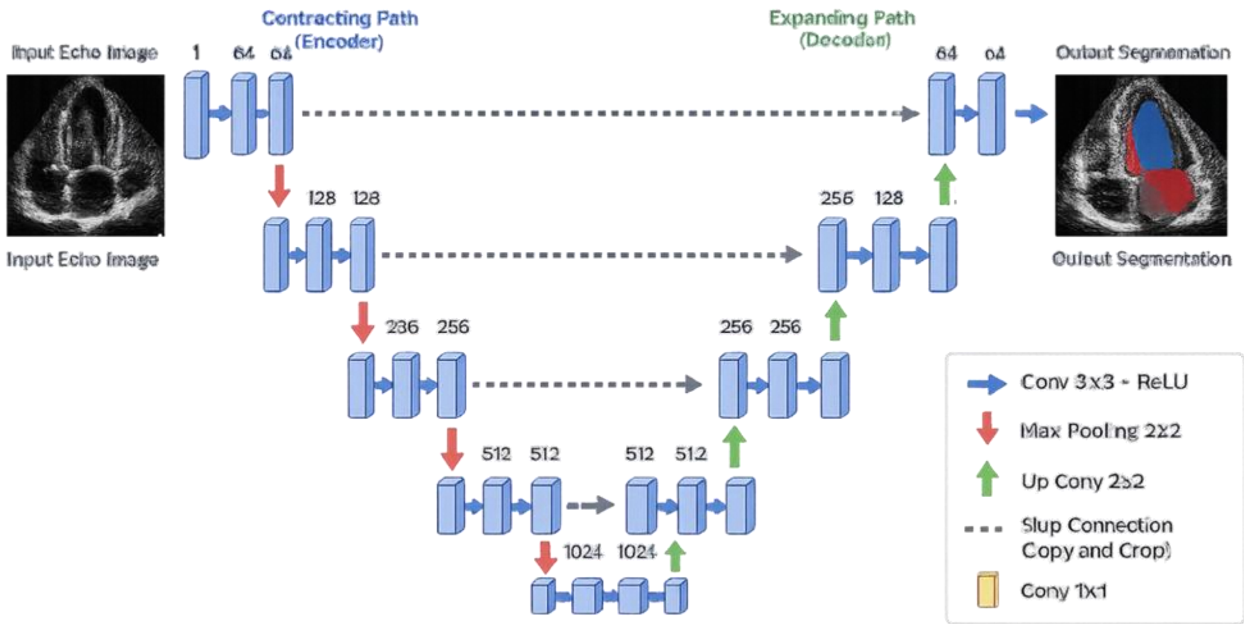

Figure 8 : Presentation of UNet deep learning architecture

We have used the Dice score as performance metrics in this study, as presented in Figure 9. The performance metrics were calculated independent of the overlay visualization.

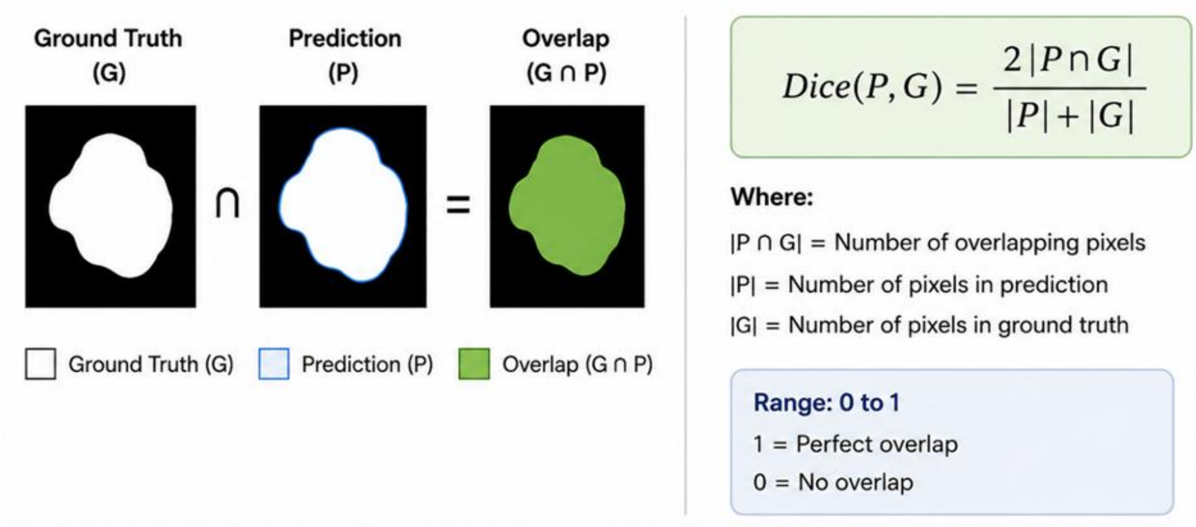

Figure 9 : Presentation of Dice score metric

Finally, a function was called to save all the calculated metrics into a CSV (Comma Separated Values) file.

2.1.2.1.4 5G RedCap connectivity

TNO uses the 5G RedCap test setup as described in Section 5.2.3 of the project deliverable D3.1 [2] for performing energy consumption measurements on the modem, evaluating different scenarios at different levels of coverage. Refer to Section 4.1 for details.

2.1.2.1.5 Edge deployment

Deployment of OUS AI algorithm on the Edge of the TNO location in The Hague is ongoing. This involves containerization on the algorithm on the edge, ingestion of the data feed via NR-RedCap using HTTPS as the (secure) transport protocol, the connection to the "clinical backend", and the instantiation of Edge and slicing via CAMARA APIs as per Figure 10. This figure depicts that the "clinical backend" will be in charge of instantiating the solution for a particular patient by instantiating the algorithm on the edge and instantiating the associated slices for the RedCap feed. As developing a true clinical backend (e.g., integration with the patient record) is well beyond the scope of the project, this will likely be a simple PC program showcasing the essence of the use case on the AMAZING-6G facility at TNO.

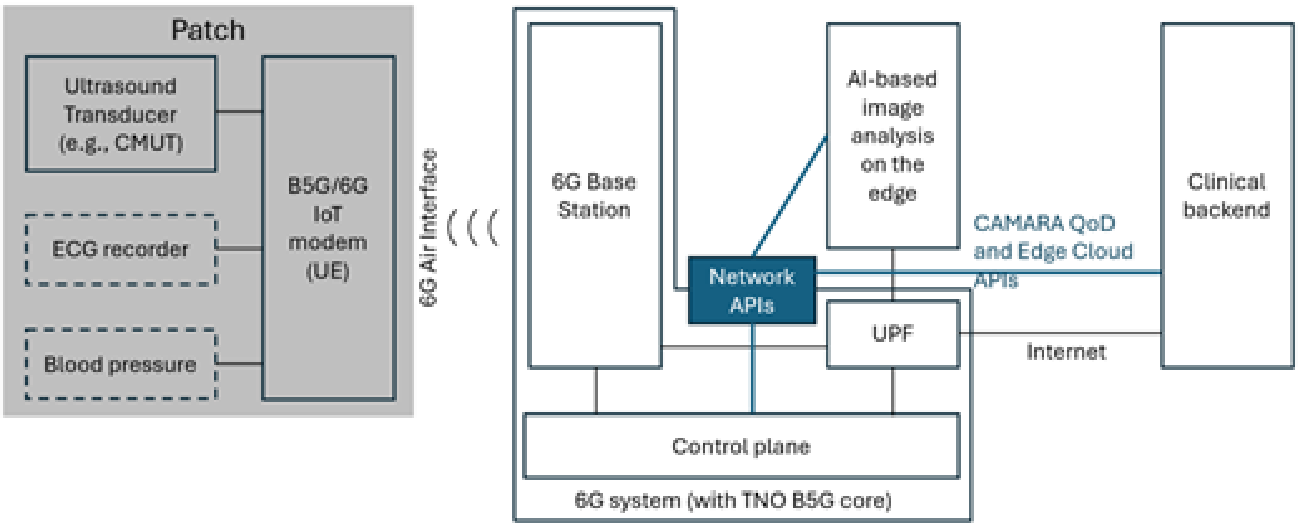

Figure 10 : CAMARA APIs for H1 use case

2.1.2.2 *Devices, sensors and supporting equipment*

Details on the digital infrastructure equipment in Table 2.

Table 2 : Equipment for H1 use case

Category	Component	Technical Details	Units
Sensor	Xu labs ultrasound transducer patch for child (UPatch Ped)	2D b-mode only Center frequency 5.5 MHz Typical frame rate 15-30 FPS 64 transducer elements	1
Sensor	Xu labs ultrasound transducer patch for adult (UPatch Ad)	2D b-mode only Center frequency 3.5 +/- 0.5 MHz (Varies per probe) Typical frame rate 15-30 FPS 64 transducer elements	1

Cable	Cable connector to connect transducer with Verasonics	Custom made connector	2
Medical equipment	Verasonics research ultrasound machine	Verasonics Vantage 256 with standard frequency configuration	1
Modem	Quectel RG255C evaluation board	Quectel RedCap evaluation kit including the RG255C redcap modem. Supports bandwidth up to 223 Mbps up and 123 Mbps down. Supports all major E, NA and global NR bands. Communication via UART or USB with drivers for Windows and Linux. Typical sleep current: 1.8 mA	1
Alternative modem	Fibocom FG132-GL	PCI module using the same chipset as the Quectel RG255C with different firmware, the specs are the same	
PC	Laptop for "clinical backend"	Mimics a real clinical backend. Any PC would suffice.	1

2.1.3 Network infrastructure

A major technical challenge for the H1A clinical case is safeguarding sufficient battery life. Therefore, extensive energy measurements are being conducted on the modem, evaluating various scenarios under various coverage conditions. A dedicated setup has been developed for those experiments, which is presented in Section 2.1.3.1 below. The integrated demonstration setup showcasing the entire chain for either clinical case is subsequently presented in Section 2.1.3.2. The (pre-trial) activities for energy-assessment and stepwise integration will be conducted in parallel, eventually culminating in a final integrated trial.

The RedCap modem is connected to a laptop that is responsible for sending and receiving data through the modem. The RedCap modem communicates via a coax cable with the 6G Radio Box, rather than over the air, as this creates a more controlled environment for the measurements. The 6G Radio Box consists of a Next Unit of Computing (NUC) running Ubuntu 24.04 LTS and a USRP (Universal Software Radio Peripheral) N320 SDR (Software Defined Radio), which together implements the Open-Air Interface–based 5G/6G radio stack. Open5GS is used for the 5G core and runs in our cloud. A variable attenuator is placed between the modem and the 6G box to simulate wireless path losses.

24.04 LTS. This laptop hosts the client and server software (UDP, TCP, HTTP, HTTPS, etc.) and communicates with the RedCap modem over USB. Packets generated by the testbed software are sent over the RedCap modem to the 6G Radio Box and returned to the same laptop, where the corresponding servers run. This loopback setup allows the software to verify whether each packet was successfully received and to log performance metrics such as data rates, data consumption, and packet loss.

A power meter (OTII) measures the modem's power consumption as a function of time (1 kHz sampling frequency) throughout each experiment/measurement. This data is stored by the laptop (allowing detailed analysis of these power profiles). For each experiment/measurement (e.g., a single upload for H1 or a single packet for H2), the aggregate energy consumed by it is extracted. Each experiment/measurement is repeated a certain number of times for statistical significance (1000 packet for H2) and the energy consumptions for the different runs are averaged and standard deviation is computed.

2.1.3.1 *Energy-assessment setup*

The setup is presented in Figure 11.

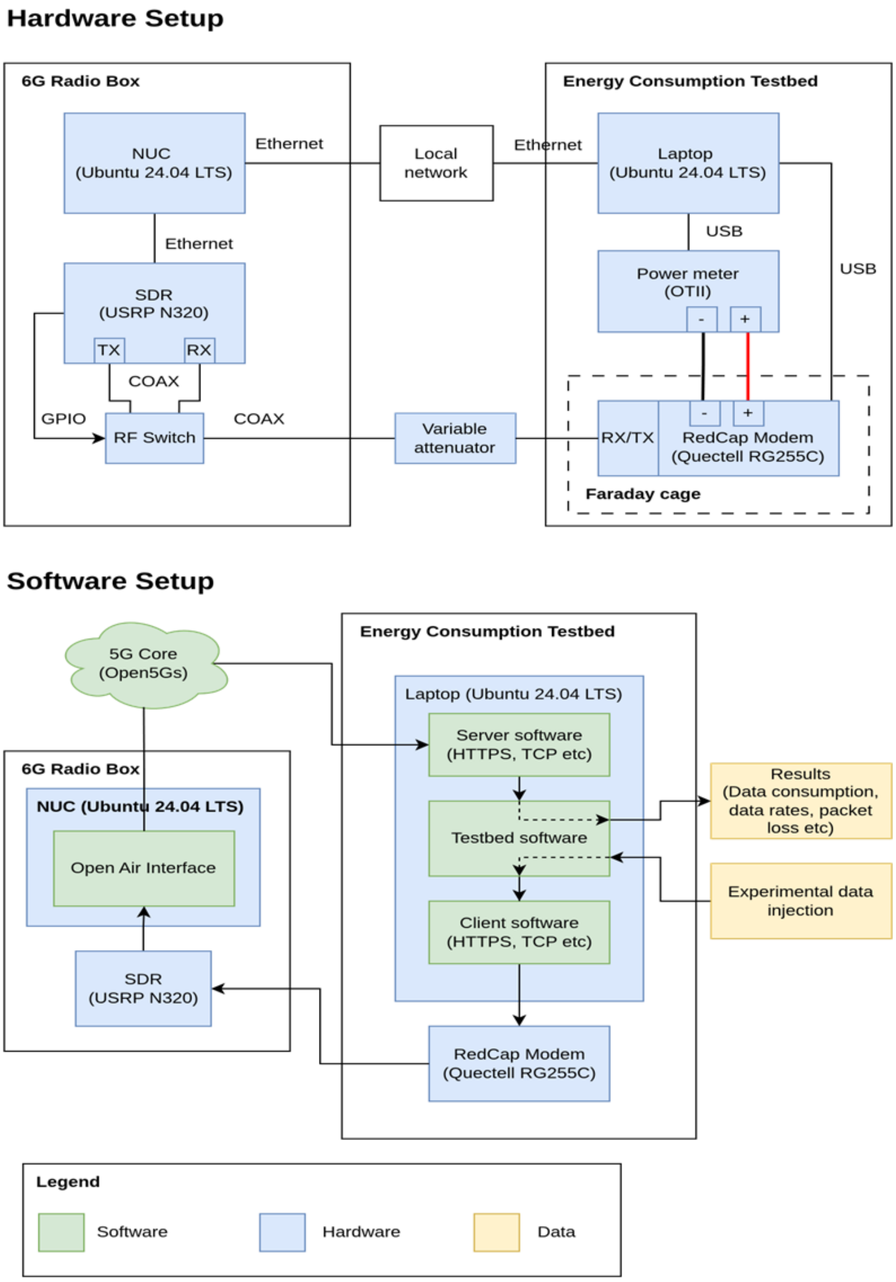

Figure 11 : Energy-assessment setup for H1 (and H2)

Experiments are controlled by a laptop in the Energy Consumption Testbed, which also runs Ubuntu.

2.1.3.2 *Integrated demonstration setup*

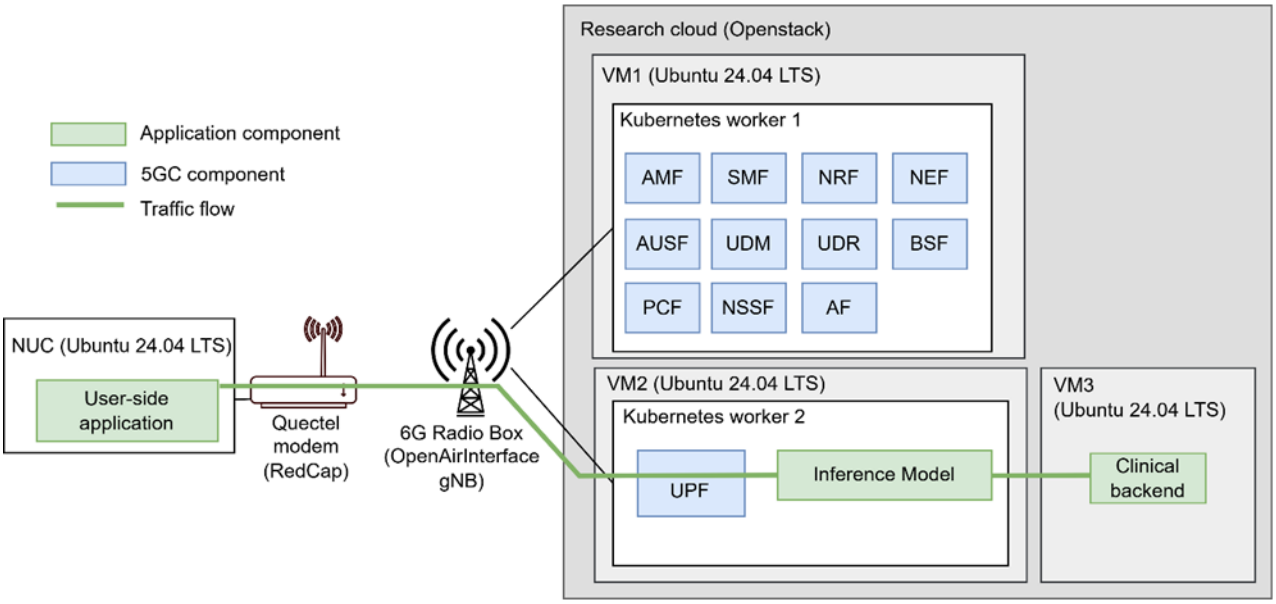

Figure 12 : Integrated demonstration setup for H1

Our integrated demonstration setup (Figure 12) includes a UE, a RAN node, and 3 virtual machines deployed within TNO's on-premises OpenStack Research Cloud. The first two Virtual Machines (VMs) run an extended Open5GS 5G core deployed on a Kubernetes cluster. The Kubernetes cluster features two worker nodes: one serves as the central node (worker 1), and the other acts as the edge node (worker 2). The third VM runs a clinical backend application.

For the UE, we have deployed a Quectel modem, which is connected to a NUC, running Ubuntu 24.04. The 5G core consists of our extended version of the Open5GS core, which includes additional components such as the Network Exposure Function (NEF) and Application Function (AF), which are not typically included in the open-source version. These extensions expose the 5G core to external vertical applications via CAMARA APIs. Additional enablers, such as Wi-Fi integration and multi-party cloud may be added to this setup at a later stage.

Additionally, in the Kubernetes cluster, we have deployed the inference models required for H1, respectively H2. The 5G UE connects to the 5G Core through the RAN, with user traffic (indicated in green) being carried over the HTTPS protocol. This traffic is exchanged between the user-side application running on the NUC and the inference model hosted on one of the Kubernetes worker nodes.

2.1.4 Use case enablers

Table 3 lists the enablers which could (potentially) be applied to use case H1 and is obtained from Section 1.3 of the project deliverable D3.1 [2].

Table 3 : Enablers for H1 use case

Domain & Enablers Reference Task3.x	Enabler	Sub enabler/ UC Related Functionalities
T3.1	Network slicing	Enables high-availability communication to the Edge.
T3.1	Sidelink	Alternate Radio Access Technology (RAT) offering potential optimization by reducing energy consumption and improving

		coverage for patches (especially, indoors and at home). Will not be realized due to lack of UE supporting Sidelink.
T3.1	Wi-Fi integration	Alternate RAT offering potential optimization by reducing energy consumption and improving coverage for patches (especially, indoors and at home).
T3.2	Distributed user-edge-cloud compute continuum	Enables reliable and short latency execution of the AI algorithm.
T3.2	Multi-party cloud	Cloud environment enabling multiple independent parties to securely share data and computing resources while preserving data ownership and access control.
T3.3	CAMARA APIs for Quality on Demand	Enables the clinical backend to set a Quality of Service (QoS) profile for a UE traffic flow.
T3.3	CAMARA APIs for Edge/Cloud	Enables the clinical backend to instantiate an AI algorithm instance on the Edge to process the images uploaded by the cardiac ultrasound patch via 5G RedCap IoT.
T3.4	5G RedCap IoT	Enables connectivity from the cardiac ultrasound patch to the B5G network with minimal energy consumption to maximize battery life.

2.1.5 KPIs definition

Each clinical case (i.e., H1A and H1B) has its own (critical) combination of KPIs, which are discussed in the subsections below.

2.1.5.1 *H1A clinical case: home-based, battery-operated use with offline analysis*

Table 4 shows the target KPIs for this clinical case, the critical combination of KPIs being highlighted in blue, most notably to emphasize that a large amount of data shall be uploaded, while having a very limited energy budget, even under adverse coverage conditions (i.e., indoor). This combination of KPIs (highlighted in blue) is so challenging that it pushes the boundaries for novel 6G technologies. Therefore, this clinical scenario and the associated KPIs have been contributed to the 3GPP 6G Study as documented in [3] (see Clauses 11.28 and 14.2.6.5; Table 13.2.6.5-3 in particular).

Table 4 : KPIs for H1A clinical case

KPI name	Description/KPI definition	Scenario/profile	KPI target
Network service latency	Time between the source node sends a data packet to when the destination node receives it		< 100 s
Network availability	Percentage of time the service can be delivered		> 99.99 %
Network reliability	Period of time for which the service satisfies the required performance		> 1 month

	constraints (DL/UL capacity, E2E latency)		
Connection density	Number of connected devices per area		10/km^2 to 100/km^2
User Experienced data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time		< 86 Mbit/s
Mobility	Maximum speed, at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/multi-RAT) can be achieved	Patient can be at home (stationary) or on the move (<250 km/h)	< 250 km/h (or stationary)
Coverage	Geographic area where a network signal can be received and used by a device	For patient at home, indoor coverage is needed as well	Urban and rural areas (+ indoor for stationary)
Device Energy efficiency	The capability of the RIT/SRIT to minimise the power consumed by the device modem in relation to traffic characteristics		Energy-efficient transmissions using a device powered with a 3.6V battery of capacity < 1000 mAh that can last at least several hours without recharging

2.1.5.2 *H1B clinical case: critical patient monitoring for patient under direct medical supervision*

Table 5 shows the target KPIs for this clinical case, the critical combination of KPIs being highlighted in blue, most notably to emphasize that high bandwidth connectivity is needed with very high availability/reliability.

Table 5 : KPIs for H1B clinical case

KPI name	Description/KPI definition	Scenario/profile	KPI target
Network service latency	Time between the source node sends a data packet to when the destination node receives it		< 100 ms
Network availability	Percentage of time the service can be delivered		> 99.9999 %
Network reliability	Period of time for which the service satisfies the required performance constraints (DL/UL capacity, E2E latency)		> 1 year

Connection density	Number of connected devices per area	Patient can be in hospital, CathLab/ICU (NPN) or transported (PLMN) in (air) ambulance	NPN: 20-30 per hospital PLMN ambulance: < 10/km^2 PLMN air ambulance: < 1/km^2
User Experienced data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time		< 86 Mbit/s
Mobility	Maximum speed, at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/multi-RAT) can be achieved	Patient can be in hospital, CathLab/ICU (NPN) or transported (PLMN) in (air) ambulance	NPN: stationary PLMN ambulance: < 140 km/h PLMN air ambulance: < 250 km/h
Coverage	Geographic area where a network signal can be received and used by a device	Patient can be in hospital, CathLab/ICU (NPN) or transported (PLMN) in (air) ambulance	NPN: 100 m^2 PLMN: Urban and rural areas
Run time	The execution time of the algorithm, including overhead of the container (e.g., TLS session termination)	The algorithm shall run in real time, i.e. one second worth of ultrasound data shall be processed at the edge-hosted environment within one second.	< 1 s

2.1.6 KVIs definition

Table 6 includes the list of KVIs for the H1 use case.

Table 6 : KVIs for H1 use case

KVI name	Description/KVI definition	KVI target
Mortality risk reduction	The percentage decrease in the probability of patient death within a specified period due to improved monitoring and treatment optimization including preinterventional surveillance, optimisation of interventional timing, critical transportation monitoring, intrahospital monitoring and postinterventional at home monitoring.	Mortality risk reduction 10% (Annual deaths among patients waiting for and having performed cardiac surgery and interventions. Open heart surgeries are around 5000 per year in Norway and structural heart interventions around 1500. Overall procedural mortality is around 2 %. This means that a 10 % reduction in mortality could save the lives of at least 13 patients per year)

Clinic visits reduction	The percentage decrease in routine hospital or clinic visits required for patient follow-up through remote monitoring and automated decision support, both pre and post-surgery interventions.	Clinic visits reduction 20% (For example, with around 250.000 cardiac patients in Norway and about 2 visits per year, remote monitoring could lead to approximately 100,000 avoided visits annually)
Carbon emission reduction	The decrease in CO_2 emissions associated with reduced patient travel and healthcare service utilization.	Carbon emission reduction 1000 tons per year (Assuming about 10 kg CO_2 per visit, reducing 100,000 visits per year would result in approximately this level of emission reduction in Norway)
Quality-of-life score increase	The improvement in standardized patient-reported quality-of-life metrics reflecting better physical, psychological, and social well-being, especially due to at home monitoring at waiting list.	Quality-of-life score increase for the patients >20% (This would be due to increased safety before and after surgery/intervention of around 20% and a reduced expenditure of time and effort for hospital visits by 50%)

2.1.7 Description of the pre-trial and trial setup

Table 7 below describes the (pre-)trial activities for the use case in detail. It should be noted that the general methodology – and the network infrastructure used – for conducting these activities, are identical between H1 and H2. The difference between both use cases lies in (1) the clinical case explored (which affects the pre-trial activities performed at OUS) and (2) the (critical) combination of KPIs explored (which, actually, are vastly different). Therefore, there is significant overlap (duplication) between the text in this table and the corresponding text in the one in Section 2.2.7 to the extent that the reader might have a déjà vu experience.

Table 7 : H1 pre-trial and trial setup

H1 Pre-trial and trial	Wearable ultrasound patch for cardiac function monitoring
Infrastructure / Venue	TNO Hi5 facility in the Hague (NL) and OUS Lab in Oslo (Norway)

<table>
<tr>
<td>Trial Description</td>
<td>
Incremental feasibility assessment and optimization for wearable ultrasound clinical cases (i.e., H1A and H1B), through co-design considering clinical, algorithmic, networking, and computational perspectives.
Three types of pre-trial activities will be conducted in parallel. At OUS, an ultrasound capture and processing pre-trial (H1A and H1B) will take place to obtain ultrasound (i.e., B-mode) video of sufficient quality from the patch and to validate an AI algorithm capable of extracting cardiac performance data from it. As explained in Section 2.1.3, at TNO an energy-assessment pre-trial (H1A only) to maximize patch battery life and an integrated demonstration pre-trial (H1A and H1B) to incrementally work towards a fully integrated demonstration will take place. These three types of pre-trials will be discussed separately for the aspects described below. In the trial phase, this will evolve into a fully integrated demonstration.
</td>
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<tr>
<td rowspan="2">Technical Setup</td>
<td>
System Components
Ultrasound capture and processing pre-trial:

Xu labs ultrasound transducer patch (paediatric or adult)
Custom-made cable connector
Verasonics Vantage 256 research ultrasound machine
Laptop with Windows or Linux OS
Node/server
Automated ultrasound b-mode image analysis AI algorithm
Graphical Processing Unit with Windows or Linux OS

Energy-assessment pre-trial:

6G Radio Box (NUC + USRP N320 SDR + RF Switch) + Open Air Interface software
Energy Consumption Testbed (Laptop + OTII Power meter + Quectel RG255C 5G Redcap modem) + Server/Testbed/Client software
Variable Attenuator
Hi5 Research Cloud + Open5GS software

Integrated demonstration pre-trial + trial:

NUC running application software, inputting pre-recorded ultrasound video and transmitting through 5G modem
Quectel RG255C 5G Redcap modem
6G Radio Box + Open Air Interface software (see above).
Three VMs in the Hi5 Research Cloud:

VM1: Kubernetes worker node running Open5GS control plane software
VM2: Kubernetes worker node running Open5GS User Packet Function (UPF) + Inference Model
VM3: “Clinical back end” (receiving and printing the obtained cardiac output parameters)

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<td>
System Configuration
Ultrasound capture and processing pre-trial:
The patch transducer is attached to the volunteer chest above the heart and positioned to provide an apical 4 chamber or parasternal short axis b mode image.
The patch is cabled to the Verasonics ultrasound scanner which is connected to a laptop. The video stream can be transferred wirelessly from the laptop to a nearby node/server for AI
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analysis and results are fed back to the laptop or copied to another station that responds to changes in condition of a future patient.
Energy-assessment pre-trail:
6G Radio Box and Energy Consumption Testbed communicate via coax (representing the air interface) and over local network (representing a data network). The Core Network runs in the Hi5 Research Cloud.
Integrated demonstration pre-trail + trial:

The UE side (mimicking the patch) is realized by NUC + 5G Redcap modem, the NUC controlling the modem through its AT-command interface.
The B5G network comprises 6G Radio Box + Open Air Interface as RAN and VM1/VM2 as Core Network (Control Part and User Part, respectively). The Smart Healthcare Engine (SHE) is running the Inference Model and deployed on VM2 as well. VM1 and VM2 embody separate Kubernetes workers.
The “clinical backend” is reachable from the SHE via the Data Network (Intranet), which enables transmission of the inference results (i.e., cardiac performance parameters) to said “clinical backend”. The “clinical backend” simply outputs those parameters (e.g., to standard output).
VM1, VM2, and VM3 are deployed on the Hi5 research cloud (doubling as cloud and edge).
Eventually, the “clinical backend” will initialize the service instance by setting up the inference model running in the edge and by modifying the QoS of the PDU session through the respective CAMARA APIs.

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<tr>
<td>Pre-Trial execution (initial phase, included in this deliverable, Section 4.1)</td>
<td>
Pre-conditions
Ultrasound capture and processing pre-trial:

Ethical approval for healthy volunteer testing.
Data officer at hospital approval for healthy volunteer testing.
Inclusion of healthy volunteers (6-26 years of age).

Energy-assessment pre-trial:

6G Radio Box / Open5GS and Energy Consumption Testbed set up and connected via local network / coax (+ variable attenuator).
Data transmission scenario pre-programmed on Energy Consumption Testbed’s laptop (e.g., enabling data transmission of pre-determined amount of data – as determined / agreed, based on ultrasound experiments at OUS – over pre-determined transport protocol e.g., HTTPS).

Integrated demonstration pre-trail:

The inference model (provided by OUS) is deployed in the edge node and setup to be able to receive data via the predetermined transport protocol (e.g., HTTPS).
A UE (NUC + 5G Redcap modem) is connected to the 5GS and a PDU session is established in a default network slice. The UE is able to transmit data to the inference model running in the edge.
Data transmission setup is preprogrammed on the NUC based on the test data provided by OUS (i.e., compressed or uncompressed video stream of B-mode ultrasound recording) using predetermined transport protocol (e.g., HTTPS).
The clinical backend is running on VM3 and reachable from the Inference Model running on VM2.

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Trial Steps

Ultrasound capture and processing pre-trial:

1. Echocardiographer performs cardiac ultrasound exams with a standard ultrasound machine and probe as used in clinical practice and extracts the cardiac function parameters manually and automatically (i.e., gold standard measurements).
2. Ultrasound B-mode video is captured with the patch and recorded in a file. The file is analysed by the AI algorithm. The results are compared with the gold standard.
3. Ultrasound B-mode video is captured with the patch, fed as a life stream to the AI algorithm. The results are compared to the gold standard. Also, the time lag is measured.

Energy-assessment pre-trail:

1. Energy Consumption Testbed runs pre-programmed data transmission scenario a predetermined number of times (i.e., for statistical significance), collects results (i.e., energy measurements, transmission success rate, etc.) and generates statistical results automatically.
2. Experiment is repeated for different attenuator settings to assess the impact of coverage conditions (i.e., wireless path losses).
3. Instrumentation may be added to measure KPIs like algorithm execution time, communication latency, and end-to-end system delay.

Integrated demonstration pre-trail:

1. Integrated Demonstration Testbed reads pre-recorded ultrasound video stream from a file and sends it via the 5G network to the inference model running in the edge. The edge computes the cardiac function parameters and outputs them to the “clinical backend”.
2. The output of the clinical backend is checked to verify correctness.

Methodology

Iterative development comprises determining a baseline (M12) and three subsequent optimization/integration cycles (M17, M25, M33).

Ultrasound capture and processing pre-trial:

Iterative testing starts with setups that are fully cabled and manually analysed, moving in a stepwise fashion towards a fully automated real time image stream that is automatically analysed.

Also, exploring possibilities to reduce the demands on the network (e.g., data compression and/or reduced spatial resolution to reduce bitrate/data volume), while maintaining clinical accuracy. This requires close cooperation with the energy-assessment of pre-trail activities to jointly optimize battery life / performance without affecting clinical accuracy (iterative improvement, see above).

Energy-assessment pre-trial:

- Ultrasound capture and processing pre-trial activities determine the amount of data to transmit and how often to transmit that data.
- Dummy data matching these requirements will be used to conduct automated energy measurements at different coverage levels (see Trial steps).
- The results will be analysed and discussed between OUS and TNO to identify and prioritize potential optimization steps to be conducted in the next iteration (iterative improvement, see above).

	Integrated demonstration pre-trail: • The end-to-end chain as sketched in Section 2.1.2.1.1 (Figure 2) will be realized stepwise. The first step is the containerization and deployment of the AI algorithm developed by OUS on the Hi5 Edge (Research Cloud). Gradually, the right choice of protocol (i.e., HTTPS), data ingestion with 5G (RedCap), connection to the clinical backend, and the use of the CAMARA APIs will be realized. • At least during pre-trail, recorded ultrasound data by OUS will be used as input to the edge-based setup.
	Technology Enablers *Ultrasound capture and processing pre-trial:* Not applicable *Energy-assessment pre-trail:* • 5G Redcap IoT • Network slicing • Wi-Fi integration (in later iterations, Wi-Fi to replace 5G Redcap IoT) *Integrated demonstration pre-trail:* • Compute continuum (distributed user-edge-cloud continuum + multi-party cloud) • CAMARA APIs (Quality on Demand + Edge/Cloud) • 5G Redcap IoT (not initially)
	Expected Outcome *Ultrasound capture and processing pre-trial:* • Bias and variability of patch-based heart function measurements such as fractional area change – compared to gold standards. • Bias and variability of AI analysed heart function offline compared to gold standard measurement. • Time lag and bias, and variability of real-time AI based analysis of heart function measurements compared to gold standards. • Minimum KPIs (e.g., resolution, bitrate, data volume) are required to achieve the results (i.e., sufficient clinical quality). *Energy-assessment pre-trail:* • Initial feasibility assessment of the concept (battery-life perspective). • Understanding the minimum data traffic (i.e., volume, frequency) requirements enabling the use case, based on clinical and algorithmic requirements (OUS/TNO co-design). • Initial assessment of coverage (i.e., permissible wireless path loss) constraints. *Integrated demonstration pre-trail:* • Initial feasibility assessment of the concept (whole chain by piecewise demonstration). • Initial demonstrator(s).
Trial Execution (final phase)	**Pre-conditions** As for “integrated demonstration pre-trial” above plus: • Healthy volunteer recruitment and present (OUS). • Clinical trial approved by ethical board (OUS).

- Xu Labs patch, cabling and Verasonics available and setup, connected to UE (NUC + 5G RedCap modem) enabling live streaming of ultrasound through the modem.
- Optionally, we might want a display in the chain to visualize the ultrasound live stream for demonstration and validation purposes.

Disclaimer: Getting the whole setup in one location might be challenging due to heavy and costly equipment involved. Fallback is recording ultrasound data from the volunteer at OUS and playback at TNO (as in the pre-trial phase).

Trial Steps

For KPI measurements, this is identical to the integrated demonstration pre-trial. For demonstration the following steps will be followed:

- Ultrasound patch is applied to healthy volunteers.
- Ultrasound is visualized on optional display.
- The output of the clinical backend is also visualized.
- Possibly, the healthy volunteer is asked to perform certain exercises to see the impact on the measurements.

Methodology

The final trial essentially equals the last iteration of the integrated demonstration pre-trial as discussed above. The focus is two-fold: (1) provide table-top demonstration of the concept, preferably fully integrated, (2) provide final measurements of the KPIs showcasing feasibility of the concept (and/or a gap analysis targeting new requirements for 6G).

As for the final KPI measurements, the critical KPIs will be assessed as follows:

- H1A: The critical combination of the KPIs user experienced data rate, coverage, and device energy efficiency. The final assessment will equal the final iteration of the energy-assessment pre-trial.
- H1B: The critical combination of the KPIs network availability / reliability and user experienced data rate

Observe that the initial KPIs as stated in Section 2.1.5 are subject to change, as the clinical/algorithmic side of things (i.e., OUS) will attempt to lower the demands on the system as much of possible, whereas the network side of things (i.e., TNO) will attempt to meet challenging KPIs as much as possible.

Additional KPI measurements include run time (which will be measured internally in inference model implementation and/or the container), network service latency (which may involve instrumentation of the TCP layer to collect timestamps to measure round-trip delay).

Based on the last iteration of the use case, a demo video will be made and demonstrated to highly experienced clinical personnel (anaesthesiologists, intensivists, cardiologists, cardiac surgeons, for a Likert scale rating of its utility and added value on top of today's existing cardiac monitoring solutions.

Complementary Measurements

From a clinical perspective, this could be bias and variability analysis (SD) based on Bland-Altman plots comparing the AI analysis to manual clinical expert measurements on standard bedside echocardiography.

Calculation Process

	From a clinical perspective, this could e.g. describe Bland-Altman statistics. The energy-assessment setup automatically repeats each measurement a number of times and reports average and standard deviation (the number of times will be determined based on the spread observed and on practical considerations).	
Technology Enablers	**Communication Enablers**	• Network slicing • Wi-Fi integration (in later iterations, Wi-Fi to replace 5G Redcap IoT) • Note that Sidelink will not be addressed due to practical limitations.
	Compute-as-a-Service (CaaS) Enablers	• Compute continuum (distributed user-edge-cloud continuum + multi-party cloud)
	Application enablers and AI	• CAMARA APIs (Quality on Demand + Edge/Cloud)
	IoT and localization enablers	• 5G Redcap IoT
Expected Outcome	Overall feasibility assessment of the use case, including battery life estimations and coverage assessments.	

2.2 H2 Predictive remote reprogramming of implantable cardiac devices

On-body and implantable devices are fundamental in the management of cardiac conduction and rhythm disorders. Permanent pacemakers (PMs) are designed to maintain adequate heart rates in patients with bradyarrhythmia, while implantable cardioverter-defibrillators (ICDs) are intended to terminate life-threatening ventricular tachycardia. These systems deliver low-energy electrical pulses to stimulate myocardial depolarization or combine pacing with high-energy shock therapy to terminate cardiac arrest, thereby ensuring both acute protection and long-term prevention of sudden cardiac death.

Reprogramming of PMs/ICDs is essential to ensure that device performance remains aligned with the patient's evolving clinical needs. While these devices are initially configured according to the patient's condition, physiological changes, disease progression, and lifestyle factors often necessitate subsequent adjustments. Current technologies largely lack real-time, predictive reprogramming capabilities, which would enable timely modification of detection or therapy algorithms before adverse outcomes occur.

Such predictive adaptability has the potential to reduce inappropriate shocks, extend battery life, and enhance patient safety, comfort, and therapeutic efficacy, especially during transitions in human activity. Event-aware, real-time predictive reprogramming of PM/ICD is proposed to adapt device performance to a patient's daily activities in a closed-loop, remote, and automated setup. This requires continuous communication between the implanted device and the edge, currently a power-hungry limitation. To mitigate communication constraints, a wearable patch is proposed as a gateway between the PM/ICD and mobile networks. For event-aware reprogramming, an AI-based algorithm is deployed at the edge, enabling semantic pacing and sensing adjustment of the device, leveraging greater computational resources compared to the more limited capabilities of the patch device. The edge infrastructure also supports sensor fusion from devices like accelerometers to recognize patient activity contexts.

As a practical case, Figure 13 illustrates a scenario for atrioventricular (AV) synchronization in a dual-chamber leadless pacemaker system. Current technologies rely on intracardiac communication between two leadless pacemakers, enabling the ventricular device to sense or pace at the appropriate time. However, this communication link can significantly drain the atrial device battery and is highly dependent on device clock accuracy, which may be insufficient. Moreover, the AV delay is typically determined using a simple model embedded in the ventricular pacemaker that does not adequately account for patient-specific physiological variations. The proposed solution replaces the intracardiac link with a patch-mediated communication framework. This approach improves energy efficiency by leveraging a backscatter link for device-to-patch communication, thereby extending battery life. In addition, the patch-to-edge connection enables the use of external computational resources and AI-based models to predict AV delay dynamically on a beat-by-beat basis. Similarly, in single-chamber leadless pacemakers, the system can benefit from Edge-AI assistance to estimate atrial contraction, instead of relying solely on embedded accelerometer-based mechanical detection of the P-wave, which tends to be less accurate at higher heart rates.

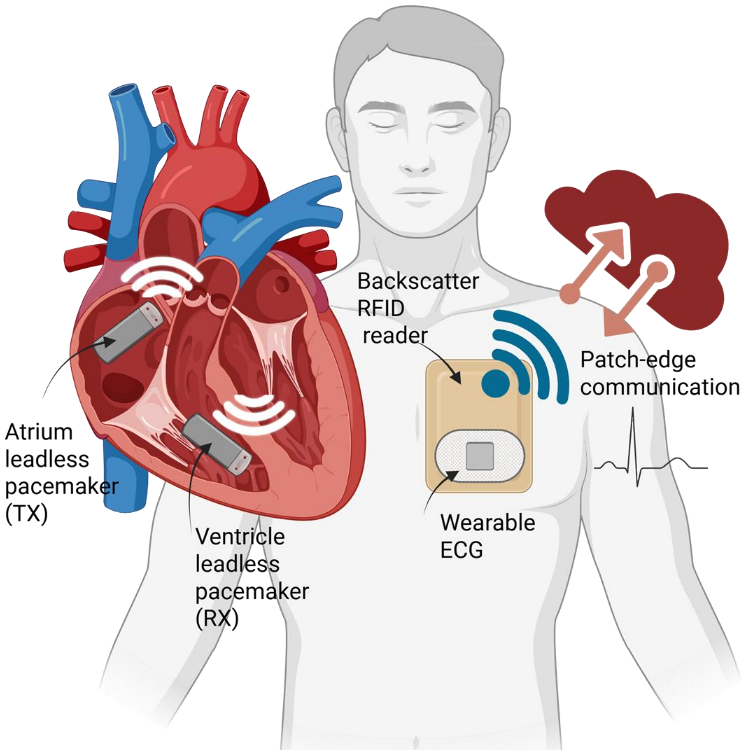


Figure 13 : Synchronization in dual-chamber leadless pacemaker through the edge-based communication and prediction

2.2.1 Description of the Use Case

Figure 14 depicts the cardiac assessment solution comprising a 6G-enabled patch on the left-hand side and the 6G RAN and Core hosting AI-based signal analysis on the edge on the right-hand side. The patch obtains Electrogram (EGM) data from the PM/ICD via Radio Frequency Identification (RFID) and subsequently transmits it via the B5G/6G Network (5G NR-RedCap will be used in the project) to the edge. The edge may send back reprogramming instructions via the same path. All of this has the occur – literally – within a heartbeat. The use of RFID (backscatter) communication allows all reading and writing from/to the PM/ICD to be powered by the patch, rather than by the battery of the pacemaker, safeguarding its lifetime. The AI-based assessments are communicated to the cardiologist via the Clinical backend which is connected to the 6G-System via a Data Network such as the Internet.

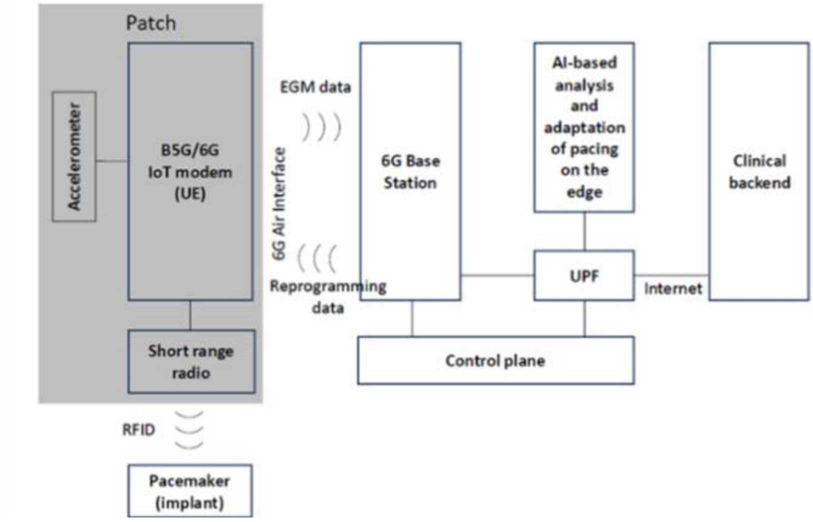


Figure 14 : Predictive remote reprogramming of implantable cardiac devices use case concept

2.2.2 Deployment and implementation details

2.2.2.1 *Application Design*

After sketching the anticipated test setup for the use case, the work on its different components will be discussed: AI algorithm development, 5G RedCap connectivity, and edge deployment.

2.2.2.1.1 Anticipated test setup

The anticipated integrated demo setup for this use case is shown in Figure 15. We expect an incremental build-up of the full chain. The AI algorithm will be developed on a PC using a public dataset (ECG/EGM) at OUS. Subsequently, this ECG/EGM signal will be fed through the tag and recorded by the reader at OUS. Also, the algorithm will be containerized and deployed at the Edge by TNO using the ECG/EGM signal from the public dataset as input. Later this signal will be fed to the Edge via NR-RedCap. Several of these steps may proceed in parallel. Finally, the elements of the chain developed at OUS and TNO can be put together to obtain an integrated demo.

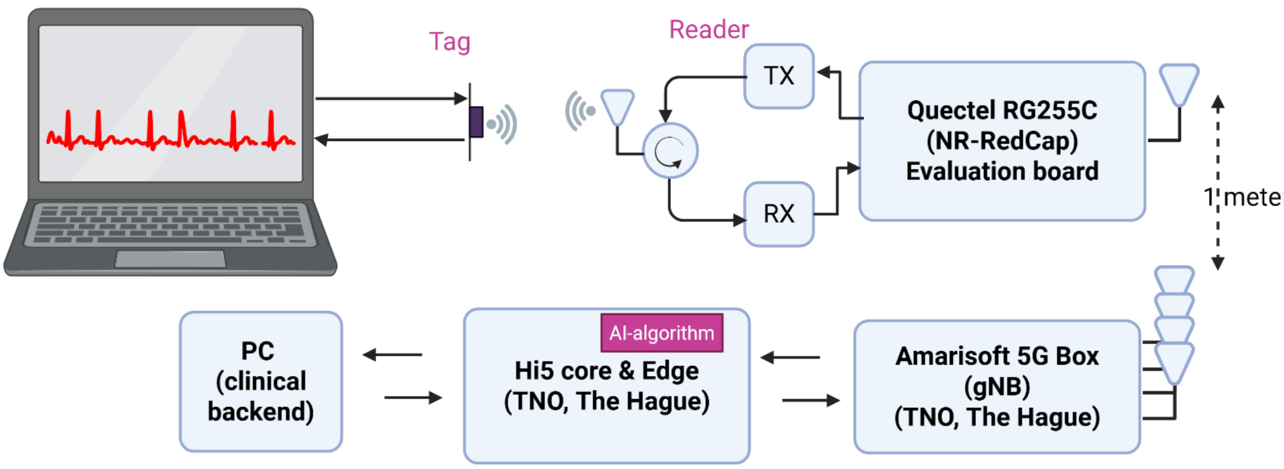


Figure 15 : Anticipated integrated demo setup

2.2.2.1.2 AI algorithm development

The algorithm should be designed to reflect the patient-specific conditions and clinical scenarios in terms of input/output as well as the processing steps. The data processing and prediction algorithms are deployed partly on the patch and partly on the edge, as shown in Figure 16. On the patch, beat segments between successive R-waves are detected, as transmission will be done on a segment-by-segment basis (i.e., one packet per segment). Subsequently, the ECG/EGM data is subsequently filtered and denoised. The processed beats are then encapsulated into packets and transmitted to the edge. On the edge, the transmitted beat segments are normalized and resampled. Subsequently, the P-wave, QRS (a naming sequence of waveform deflections on the ECG) complex, and T-wave are segmented, and their features i.e., amplitude and temporal features (latency, duration, intervals) are extracted and concatenated to subsequently predict the PM/ICD parameters. Finally, key parameters for PM/ICD adjustment – such as AV delay and P-wave timing – are forecasted within a single beat, and the updated parameters are sent back to the PM/ICD for real-time reprogramming.

The runtime and accuracy of the model at each processing stage are evaluated on both a local system (laptop) and the edge device. End-to-end latency is measured, including both communication and computation delays.

We balance the trade-off between the accuracy of predicted PM/ICD timing parameters and system latency. Higher parameter accuracy can be achieved with very low packet loss, but this typically requires retransmissions, which increases latency. The added latency may disrupt pacing timing and ultimately reduce overall pacing accuracy. Therefore, a compromise is needed between estimation accuracy and latency, as latency can limit device actuation accuracy.

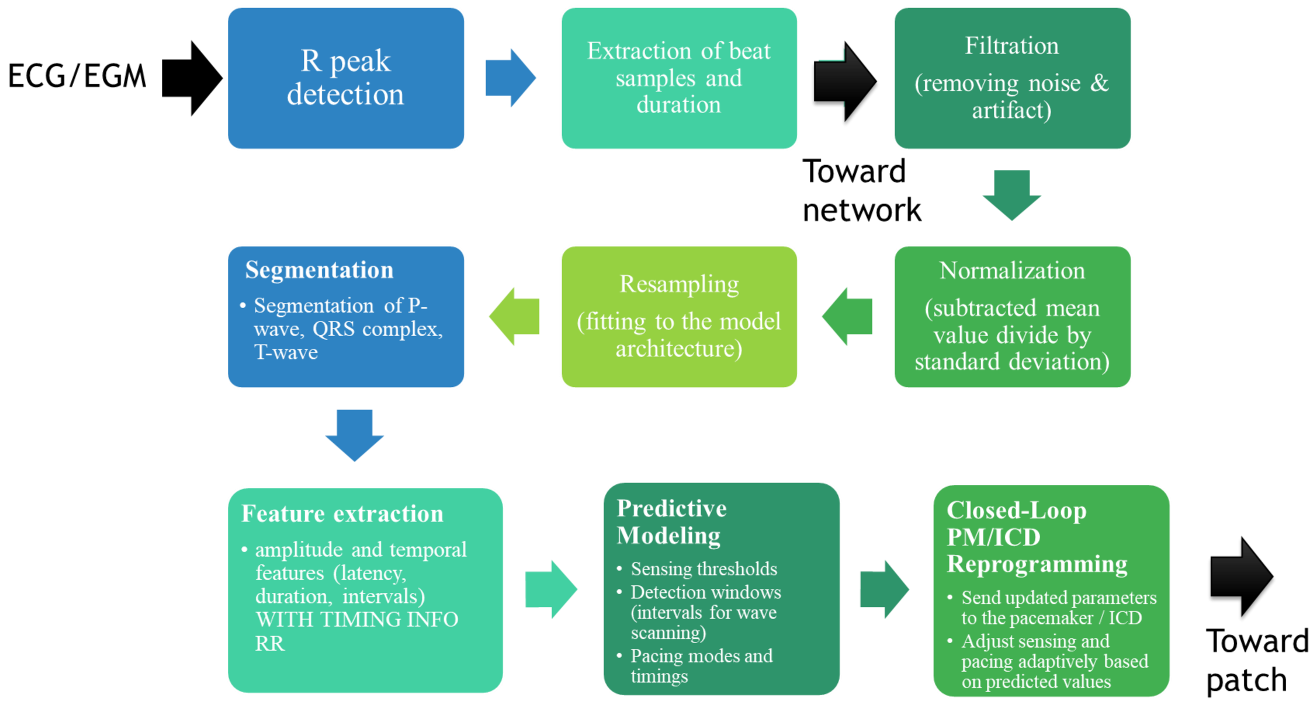


Figure 16 : Project pipeline deployed on the patch and edge

EGM streams measured from the atrium and/or ventricle can be utilized at the patch level to accurately determine beat onset and offset timings. These intracardiac signals, acquired by atrial and/or ventricular leads (or by leadless pacemakers), provide highly accurate near-field information about the P-wave and/or QRS complex onset, which can be used for reliable beat extraction at the patch level.

2.2.2.1.3 5G RedCap connectivity

TNO uses the 5G RedCap test setup as described in Section 5.2.3 of the project deliverable D3.1 [2] for performing energy consumption measurements on the modem, evaluating different scenarios at different levels of coverage. Refer to Section 0 for details.

2.2.2.1.4 Edge deployment

Deployment of OUS' AI algorithm on the Edge of the TNO location in The Hague is ongoing. This involves containerization on the algorithm on the edge, ingestion of the data feed via NR-RedCap using HTTPS as the (secure) transport protocol, the connection to the "clinical backend", and the instantiation of Edge and slicing via CAMARA APIs as per Figure 17. This figure depicts that the "clinical backend" will be in charge of instantiating the solution for a particular patient by instantiating the algorithm on the edge and instantiating the associated slices for the RedCap feed. As developing a true clinical backend (e.g., integration with the patient record) is well beyond the scope of the project, this will likely be a simple PC program showcasing the essence of the use case on the AMAZING-6G facility at TNO.

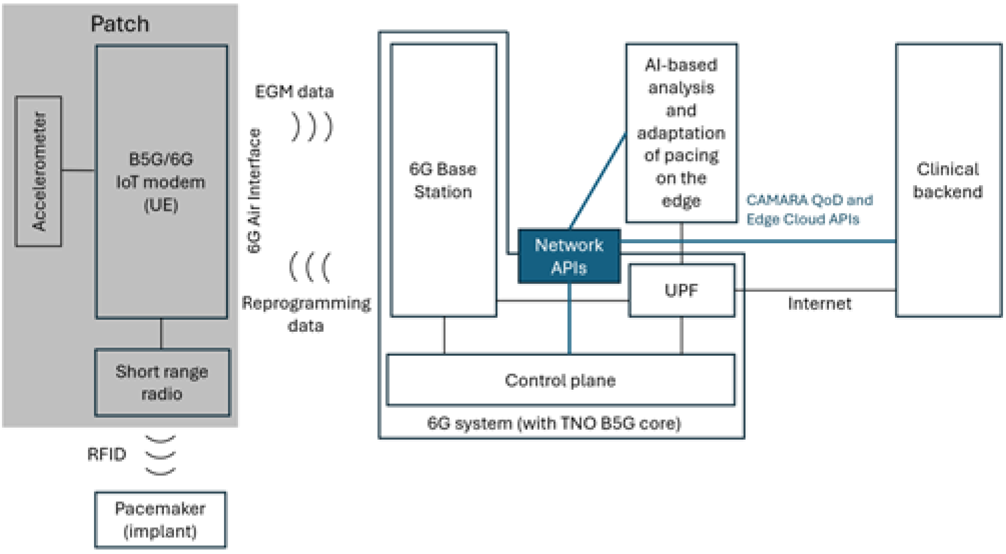


Figure 17 : CAMARA APIs for H2 use case

2.2.2.2 *Devices, sensors and supporting equipment*

Details on the digital infrastructure equipment in Table 8.

Table 8 : Equipment for H2 use case

Category	Component	Technical Details	Units
PC	Laptop to provide EGM data feed for testing	Initial setup would be demonstrated with a test signal from a public dataset.	1
RFID link	Tag & Tag reader	A lab-based backscatter link implemented using a previously developed tag and tag reader.	1
Modem	Quectel RG255C evaluation board	Quectel RedCap evaluation kit including the RG255C redcap modem. Supports bandwidth up to 223 Mbps up and 123 Mbps down. Supports all major E, NA and global NR bands. Communication via UART or USB with drivers for Windows and Linux. Typical sleep current: 1.8 mA	1
Alternative modem	Fibocom FG132-GL	PCI module using the same chipset as the Quectel RG255C with different firmware, the specs are the same	

2.2.3 Network infrastructure

The network infrastructure setup for H2 is identical to the one for H1 (i.e., the same setups are used for both energy assessment and integrated demonstration). Refer to Section 2.1.3 for details.

2.2.4 Use case enablers

Table 9 lists the enablers which could (potentially) be applied to use case H2 and is obtained from Table 1-2 in Section 1.3 of the project deliverable D3.1 [2].

Table 9 : Enablers for H2 use case

Domain & Enablers Reference Task3.x	**Enabler**	**Sub enabler/ UC Related Functionalities**
T3.1	Network slicing	Enables high-availability, short latency communication to the Edge.
T3.1	Sidelink	Alternate RAT offering potential optimization by reducing energy consumption and improving coverage for patches (especially, indoor and at home). Will not be realized due to lack of UE supporting Sidelink.
T3.1	Wi-Fi integration	Alternate RAT offering potential optimization by reducing energy consumption and improve coverage for patches (especially, indoor and at home).
T3.2	Distributed user-edge-cloud compute continuum	Enables reliable and short latency execution of the AI algorithm.
T3.2	Multi-party cloud	Cloud environment enabling multiple independent parties to securely share data and computing resources while preserving data ownership and access control.
T3.3	CAMARA APIs for Quality on Demand	Enables the clinical backend to set a QoS profile for a UEs traffic flow.
T3.3	CAMARA APIs for Edge/Cloud	Enables the clinical backend to instantiate an AI algorithm instance on the Edge to process the EGM/ECG feed uploaded by the patch via 5G RedCap IoT.
T3.4	5G RedCap IoT	Enables connectivity from the patch to the B5G network with minimal energy consumption to maximize battery life.

2.2.5 KPIs definition

Table 10 shows the target KPIs for the use case, the critical combination of KPIs being highlighted in blue. ECG/EGM data is sampled at 512 Hz, 1 byte per sample, leading to an uplink payload feed of 512 bytes per second (4 kbps). These samples are gathered into packets and transmitted to the edge. Further research will determine whether one packet will be sent per second (i.e., containing 512 bytes of payload) or whether beat detection on the patch will enable sending one packet per heartbeat. The latter may imply sending up to 4 packets per second in case of tachycardia and down to 0.5 packets per second in case of bradycardia. Beat-by-beat transmission may truly enable the algorithm on the Edge to predict the proper settings for the next heartbeat.

Table 10 : KPIs for H2 use case

KPI name	Description/KPI definition	Scenario/profile	KPI target
Network service latency	Time between the source node sends a data packet to when the destination node receives it		< 10 ms
Network availability	Percentage of time the service can be delivered		> 99.9999 %
Network reliability	Period of time for which the service satisfies the required performance constraints (DL/UL capacity, E2E latency)		> 1 year
Connection density	Number of connected devices per area		5 / km^2
User Experienced data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time	UL traffic. One packet per heartbeat. DL traffic will be minimal	4 kbps
Mobility	Max. speed, at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/multi-RAT) can be achieved	When travelling in high-speed train	< 300 km/h
Coverage	Geographic area where a network signal can be received and used by a device	Patch will be worn by patients anywhere, especially at home.	Country wide including rural areas and indoor
Device Energy efficiency	The capability of the Receive Idle Time / Short Receive Idle Time (RIT/SRIT) to minimise the power consumed by the device modem in relation to traffic characteristics	Battery powered device	Energy-efficient transmissions using a device powered with a 3.6V battery of capacity < 1000 mAh that can last at least several hours without recharging
Run time	The execution time of the algorithm, including overhead of the container (e.g., TLS session termination)		< 10 ms

Prediction error (application KPI)	PM/ICD pacing time error integrating the network latency and algorithm inference error regarding the inference accuracy		<10 ms

Even though the uplink speed is not very challenging at all, both very high availability (99.9999%) and short latency (10 ms) are required, as the application is life critical and prediction should be available before the next heartbeat. Also, the application requires ubiquitous coverage, including indoors. Figure 18 illustrates the need for 10 ms latency. The total round-trip time from capturing a beat (or second) to reprogramming the PM/ICD in time is only 50 ms. Initially, an equal distribution of the latency budget over RFID read, 6G uplink, Edge processing, 6G downlink, and RFID write is assumed but this distribution may be finetuned during the course of the project.

Figure 18 : Breakdown of system-level latency budget

2.2.6 KVIs definition

Table 11 includes the list of KVIs for the H2 use case.

Table 11 : KVIs for H2 use case

KVI name	Description/KVI definition	KVI target
Mortality risk reduction	The percentage decrease in the probability of patient death within a specified period due to improved monitoring and treatment optimization.	>10% (Annual deaths among pacemaker/defibrillator patients are around 2,500 in Norway. This means that a 10% reduction in mortality could save the lives of at least 250 patients per year)
Clinic visits reduction	The percentage decrease in routine hospital or clinic visits required for patient follow-up through remote monitoring and automated decision support.	>40% (For example, with around 50,000 PM/ICD patients in Norway and about 3 visits per year, remote monitoring could lead to approximately 60,000 avoided visits annually.)
Carbon emission reduction	The decrease in CO_2 emissions associated with reduced patient travel and healthcare service utilization.	>600 tons/year (Assuming about 10 kg CO_2 per visit, reducing 60,000 visits per year would result in approximately this level of emission reduction in Norway)
Quality-of-life score increase	The improvement in standardized patient-reported quality-of-life metrics	>20%

	reflecting better physical, psychological, and social well-being.	(This would be due to increased physical activity levels by around 20% and a reduced number of hospital visits by 40%)

2.2.7 Description of the trial setup

Table 12 describes the (pre-)trial activities for the use case in detail. It should be noted that the general methodology – and the network infrastructure used – for conducting these activities, are identical between H1 and H2. The difference between both use cases lies in (1) the clinical case explored (which affects the pre-trial activities performed at OUS) and (2) the (critical) combination of KPIs explored (which, actually, are vastly different). Therefore, there is significant overlap (duplication) between the text in this table and the corresponding text in the one in Section 2.1.7 to the extent that the reader might have a déjà vu experience.

Table 12 : H2 pre-trial and trial setup

H2 Pre-trial and trial	**Predictive remote reprogramming of implantable cardiac devices**
Infrastructure / Venue	TNO Hi5 facility in the Hague (NL) and OUS Lab in Oslo (Norway)
Trial Description	Incremental feasibility assessment and optimization for the predictive remote reprogramming of implantable cardiac devices use case, through co-design taking into account clinical, algorithmic, networking, and computational perspectives. Three types of pre-trial activities will be conducted in parallel. At OUS an *EGM/ECG capture and processing pre-trial* will take place to obtain EGM/ECG data via an RFID interface and to validate an AI algorithm capable of predicting cardiac events from it. As explained in Section 2.2.3 (2.1.3), at TNO an *energy-assessment pre-trial* to maximize patch battery life and an *integrated demonstration pre-trial* to incrementally work towards a fully integrated demonstration will take place. These three types of pre-trials will be discussed separately for the aspects described below. In the trial phase, this will evolve into a fully integrated demonstration.

Technical Setup	**System Components** *EGM/ECG capture and processing pre-trial:* • Laptop (to feed prerecorded EGM/ECG) • PC/Edge (to run AI algorithm) • RFID link (tag & tag reader) • AI algorithm for PM/ICD parameter prediction *Energy-assessment pre-trail:* • 6G Radio Box (NUC + USRP N320 SDR + RF Switch) + Open Air Interface software • Energy Consumption Testbed (Laptop + OTII Power meter + Quectel RG255C 5G Redcap modem) + Server/Testbed/Client software • Variable Attenuator • Hi5 Research Cloud + Open5GS software *Integrated demonstration pre-trail + trial:* • NUC running application software, inputting pre-recorded EGM/ECG and transmitting through 5G modem • Quectel RG255C 5G Redcap modem • 6G Radio Box + Open Air Interface software (see above). • Three VMs in the Hi5 Research Cloud: o VM1: Kubernetes worker node running Open5GS control plane software o VM2: Kubernetes worker node running Open5GS UPF + Inference Model o VM3: "Clinical back end" (receiving and printing the PM/ICD parameter predictions as well as the ECG/EGM after event-aware device adjustment)
	System Configuration *EGM/ECG capture and processing pre-trial:* The laptop feeding EGM/ECG data is connected to the tag and the tag reader is connected to the PC / Edge consuming this data and running the AI algorithm. *Energy-assessment pre-trial:* 6G Radio Box and Energy Consumption Testbed communicate via COAX (representing the air interface) and over local network (representing a data network). The Core Network runs in the Hi5 Research Cloud. *Integrated demonstration pre-trail + trial:* • The UE side (mimicking the patch) is realized by NUC + 5G Redcap modem, the NUC controlling the modem through its AT-command interface. • The B5G network comprises 6G Radio Box + Open Air Interface as RAN and VM1/VM2 as Core Network (Control Part and User Part, respectively). The Service Hosting Environment (SHE) is running the Inference Model and deployed on VM2 as well. VM1 and VM2 embody separate Kubernetes workers. • The "clinical backend" is reachable from the SHE via the Data Network (Intranet), which enables transmission of the inference results (i.e., cardiac event predictions) to said "clinical backend". The "clinical backend" simply outputs those parameters (e.g., to standard output). • VM1, VM2, and VM3 are deployed on the Hi5 research cloud (doubling as cloud and edge).

	Eventually, the "clinical backend" will initialize the service instance by setting up the inference model running in the edge and by modifying the QoS of the PDU session through the respective CAMARA APIs.
Pre-Trial execution (initial phase, included in this deliverable, Section 0)	**Pre-conditions** *EGM/ECG capture and processing pre-trial:* • Selected relevant public datasets for model training and validation. • Secured sufficient computational resources on a local system (PC / Edge) to support model training and performance evaluation. *Energy-assessment pre-trial:* • 6G Radio Box / Open5GS and Energy Consumption Testbed set up and connected via local network / coax (+ variable attenuator). • Data transmission scenario pre-programmed on Energy Consumption Testbed's laptop (e.g., enabling data transmission of pre-determined amount of data – as determined / agreed, based on cardiac event detection experiments at OUS – over pre-determined transport protocol e.g., HTTPS). *Integrated demonstration pre-trial:* • The inference model (provided by OUS) is deployed in the edge node and setup to be able to receive data via the predetermined transport protocol (e.g., HTTPS). • A UE (NUC + 5G Redcap modem) is connected to the 5GS and a PDU session is established in a default network slice. The UE is able to transmit data to the inference model running in the edge. • Data transmission setup is preprogrammed on the NUC based on the test data provided by OUS (i.e., EGM/ECG data) using predetermined transport protocol (e.g., HTTPS). The clinical backend is running on VM3 and reachable from the Inference Model running on VM2.
	Trial Steps *EGM/ECG capture and processing pre-trial:* 1. Feed public data set to the laptop mimicking the patch. 2. Feed the output of this processing to the PC / Edge running the AI algorithm. 3. Record the prediction as (to be) sent back to the patch and/or clinical back end. 4. Compare the results to the baseline to assess the application KPIs (i.e., accuracy of prediction). Keep track of (developments) in algorithm run-time on patch (laptop) and on edge (PC). *Energy-assessment pre-trial:* 1. Energy Consumption Testbed runs pre-programmed data transmission scenario a predetermined number of times (i.e., for statistical significance), collects results (i.e., energy measurements, transmission success rate, ...) and generates statistical results automatically. 2. Experiment is repeated for different attenuator settings to assess impact of coverage conditions (i.e., wireless path losses). 3. Instrumentation may be added to measure KPIs like algorithm execution time, communication latency, and end-to-end system delay.

	Integrated demonstration pre-trial: 1. Integrated Demonstration Testbed reads EGM/ECG data from a file and sends it via the 5G network to the inference model running in the edge and the predicted control parameters are sent back to the patch in a closed-loop manner. 2. The updated cardiac events are sent to the "clinical backend" and checked to verify correctness.
	Methodology Iterative development comprising determining a baseline (M12) and three subsequent optimization/integration cycles (M17, M25, M33). *EGM/ECG capture and processing pre-trial:* • The assignment of processing tasks between patch and edge is designed considering energy consumption, overall latency, and AI-edge input and deployment requirements. • The AI model at the edge is evaluated in terms of accuracy and computational complexity. • Patch and edge processing are integrated and evaluated using streams of ECG/EGM data, focusing on energy consumption, accuracy, and latency, along with robustness to input perturbations. • System optimization is achieved through beat transmission strategies, model complexity adjustment, and exploration of accuracy–latency trade-offs. • The performance of the closed-loop system is assessed by integrating patch- and edge-level operations, with predicted parameters fed back to the local system. Control aspects are analysed using an open-loop system as a baseline, and device-level energy savings enabled by backscatter communication are also evaluated. *Energy-assessment pre-trial:* • OUS' clinical and algorithmic requirements and experiments determine the amount of data to transmit and how often to transmit that data. • Dummy data matching these requirements will be used to conduct automated energy measurements at different coverage levels (see Trial steps). • The results will be analysed and discussed between OUS and TNO to identify and prioritize potential optimization steps to be conducted in the next iteration. *Integrated demonstration pre-trail:* • The end-to-end chain as sketched in Section 2.2.2.1.1 (Figure 15) will be realized stepwise. First step is the containerization and deployment of the AI algorithm developed by OUS on the Hi5 Edge (Research Cloud). Gradually, the right choice of protocol (i.e., HTTPS), data ingestion with 5G (RedCap), connection to the clinical backend and the use of the CAMARA APIs will be realized. • EGM/ECG data from a public dataset (provided by OUS) will be used as input to the edge-based setup. No human testing is foreseen.
	Technical Enablers *EGM/ECG capture and processing pre-trial:* Not applicable *Energy-assessment pre-trail:* • 5G Redcap IoT • Network slicing

	• Wi-Fi integration (in later iterations, Wi-Fi to replace 5G Redcap IoT) *Integrated demonstration pre-trail:* • Compute continuum (distributed user-edge-cloud continuum + multi-party cloud) • CAMARA APIs (Quality on Demand + Edge/Cloud) 5G Redcap IoT (not initially)
	Expected Outcome *EGM/ECG capture and processing pre-trial:* • The required computational resources on the edge device to support real-time model execution. • The model architecture and complexity based on the trade-off between accuracy and latency. • The optimal data transmission scheme from the patch to the edge, considering energy consumption, system latency, and model accuracy (this involves iterative cooperation with TNO, see “Energy-assessment pre-trail below). • The percentage of device performance improvement through adaptive real-time adjustments. • Feasibility assessment of using combined EGM-ECG for device parameters adjustment. *Energy-assessment pre-trail:* • Initial feasibility assessment of the concept (battery-life perspective). • Understanding of the minimum data traffic (i.e., volume, frequency) requirements enabling the use case, based on clinical and algorithmic requirements (OUS/TNO co-design). • Initial assessment of coverage (i.e., permissible wireless path loss) constraints. *Integrated demonstration pre-trail:* • Initial feasibility assessment of the concept (whole chain by piecewise demonstration). • Initial demonstrator(s).
Trial Executio	**Pre-conditions** As for “integrated demonstration pre-trial” above.
	Trial Steps As for “integrated demonstration pre-trial” above.
	Methodology The final trial essentially equals the last iteration of the integrated demonstration pre-trial as discussed above. The focus is two-fold: (1) provide table-top demonstration of the concept, preferably fully integrated, (2) provide final measurements of the KPIs showcasing feasibility of the concept (and/or a gap analysis targeting new requirements for 6G). As for the final KPI measurements, the critical KPIs will be assessed as follows: • The critical combination of the KPIs network service latency, coverage, and device energy efficiency. The final assessment will equal the final iteration of the energy-assessment

	pre-trial. Network service latency may involve instrumentation of the TCP layer to collect timestamps to measure round-trip delay. • The critical combination of the KPIs network availability / reliability Observe that the initial KPIs as stated in Section 2.2.5 are subject to change, as the clinical/algorithmic side of things (i.e., OUS) will attempt to lower the demands on the system as much of possible, whereas the network side of things (i.e., TNO) will attempt to meet challenging KPIs as much as possible. Additional KPI measurements relate to AI algorithm run time (which will be measured internally in inference model implementation and/or the container). We evaluate system performance using signals captured during daily activities such as walking, running, and driving to quantify improvements in the patient's quality of life. ECG data acquired from a wearable device or smartwatch is transmitted to a laptop (emulating the patch) and used as input to the system. The predicted parameters are then compared with clinician-measured values for the recorded samples.
	Complementary Measurements • Application KPI measurements in final trial setup. • Quality-of-life score related to the daily activities.
	Calculation Process The energy-assessment setup, automatically repeats each measurement a number of times and reports average and standard deviation (the number of times will be determined based on the spread observed and on practical considerations).
Expected Outcome	Overall feasibility assessment of the use case, including battery life estimations and coverage assessments.

2.3 P1 Ubiquitous B5G/6G communication and slice deployment across operators for PPDR AR/VR assisted control Centers

P1 is designed in way that proves the concept of all network and application related functionalities that ensure fast and reliable digital infrastructures provisioning during a PPDR campaign are there.

During a disaster recovery and while the rescuers are trying to understand the situation and the take actions the requirements from the digital infrastructure are simple: **autonomous deployment and ubiquity.**

The P1 design meets this two-fold objective innovations both at the network and the application integration layer. In order to ensure that the actors can focus on the PPDR aspects of the campaign and the important tasks of saving lives and ecosystems, P1 is designed in a way that automation of the digital infrastructure and ubiquity of the network coverage will assist all applications that will enhance situation awareness and prioritize communication among actors.

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 QoS 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 setup, addressing areas where B5G/6G coverage is poor or non-existent.

At the application layer, PPDR campaigns rely on various applications. In order to demonstrate an autonomous operation of the whole infrastructure at the edge of the network, this use case will showcase situation monitoring, including the ground assets, through Unmanned Vehicles (UMVs), closed loop control and collaboration among robots, it will execute prediction models for the situation propagation, while AR/VR will enhance the PPDR awareness.

A real case scenario we assume that although we have 3 technologically different scenarios (A, B and C) the sequence of the events or a possible story line would start with a deployed Scenario B. We assume the case of a wildfire. As it will be discussed this B5G/6G private/public network connected with central Control Center will be used for predicting the fire and deploying various services (UMVs etc) that can enhance awareness. Rescuers are informed and come along to the affected area with their own autonomous private network (IN A BOX). They initiate communication and services. In order to enhance awareness and receive input from local control centre, Scenario C is developed where backhaul connectivity is sought.

2.3.1 Description of the Use Case

The specific PPDR use case is deployed with the following steps, as shown in Figure 19.

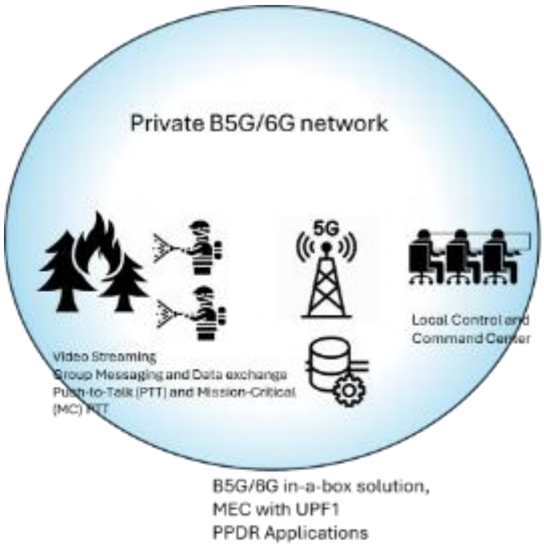


Figure 19 : Scenario A - Private 5G/6G network with PPDR services/applications (IN-A-BOX)

Scenario A: Private 5G/6G network with PPDR services/applications (IN-A-BOX)

A private standalone 5G/6G network provides dedicated, secure, and resilient communications for PPDR operations, ensuring all required mission-critical voice, video, and data services are autonomously set up even when public networks are congested or unavailable. In P1 this scenario A, aims at establishing local connectivity within minutes and maintain operational continuity under dynamic and harsh conditions in order to enable real-time situational awareness through high-speed connectivity for drones, body cameras, IoT sensors, and command-and-control systems across emergency response teams and digital infrastructures. Such a private 5G network aims at establishing local connectivity within minutes and maintain operational continuity under dynamic and harsh conditions improving coordination, response times, and overall effectiveness during disaster management and public safety incidents.

In order to demonstrate autonomous operation at the edge of the network, this first scenario of PPDR use case is setting up a **Local Control Center** with an autonomous private network (in-a-box) that showcases the following indicative services that require low latency, network slicing, and enhanced reliability:

- Video Streaming: live video streaming from cameras, drones or vehicles to Local 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
- Push-to-Talk (PTT) and Mission-Critical (MC) PTT: 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.)
- Detailed monitoring dashboard for visualization of camera feed, alerts, other relevant environmental parameters.

The Autonomous Edge 6G network creates an outdoor network that allows PPDR rescuers to assume connectivity and coverage over the affected area. It comprises a re-configurable gNodeB and SA Core Network and edge computing servers. It also has the possibility for various backhaul connectivity options if and when available (see Scenario C).

Scenario B: Private network connected with central Control Center

In the scenario shown in Figure 20, a private (or even public) B5G/6G network is surveilling and serving a specific region and being PPDR-ready for various prediction and demanding PPDR related applications. The high performance B5G/6G network allows the following service to be deployed:

- Incident detection platform, wi.breathe [4]
- Closed loop control and autonomous resource allocation for collaborative robots
- Video Streaming: live video streaming from cameras, drones or vehicles to Local Control Centers; critical for situational awareness, with optional stream selection
- Detailed monitoring dashboard for visualization of camera feed, alerts, other relevant environmental parameters.
- AR/VR optimized service
- Orchestration: on demand 5G/6G network set up to provide guaranteed resources depending on requirements and reconfiguration needs for network slices

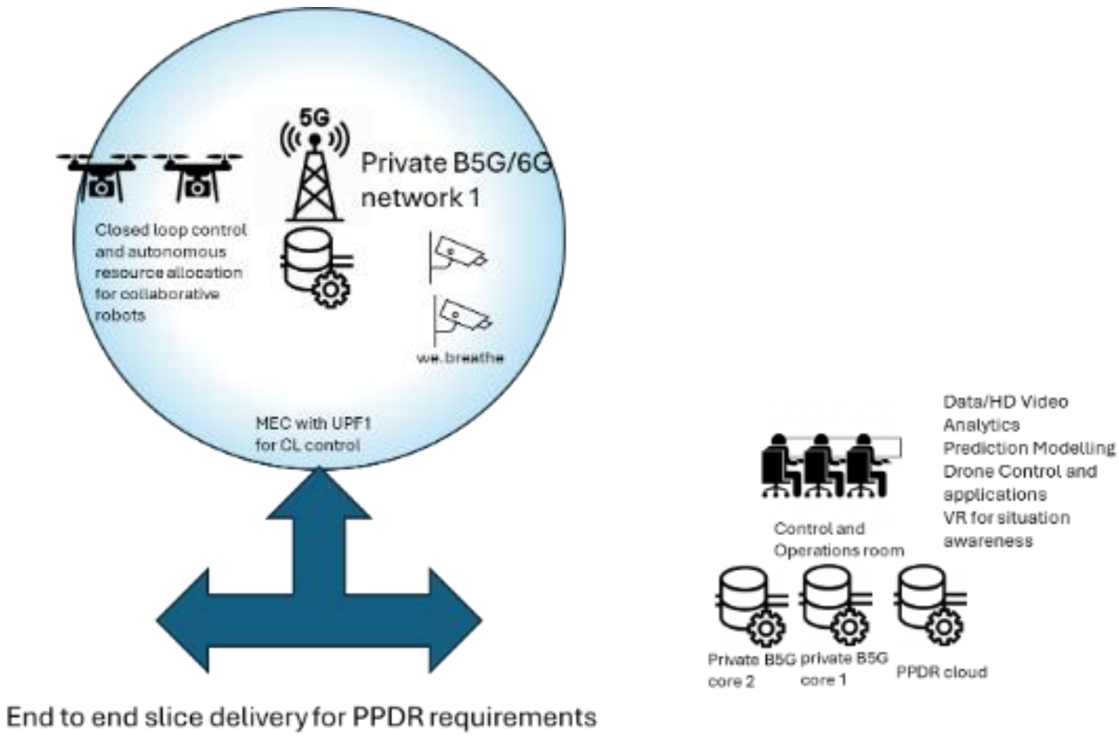


Figure 20 : Scenario B - Ubiquitous B5G/6G communication and slice deployment for PPDR

Scenario C: Slice deployment over multiple private, public B5G/6G and autonomous private networks

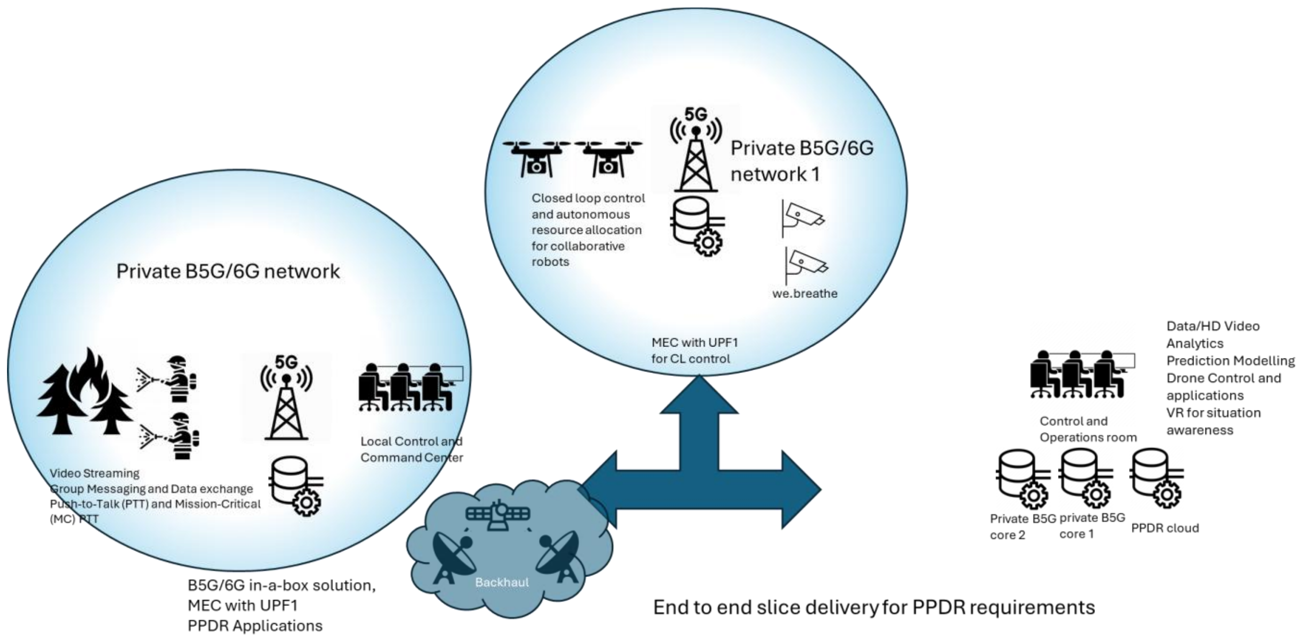


Figure 21 : Scenario C - Slice deployment over multiple private and public B5G/6G networks for PPDR

Scenario C, shown in Figure 21, assumes that two above scenarios are up and running. Scenario B is set up and detects/predicts the incident, while Scenario A is set up to support the PPDR workers. In order to support and further enhance the experience and situation awareness of the separate teams involved, a unified high-performance slice over multiple networks is deployed. This Scenario is a convergence of Scenario C and D, as mentioned in the project deliverable D2.1 [1].

The Autonomous Edge 6G (IN-A-BOX) is equipped with suitable AMAZING-6G enabler to request connectivity if available. Any available backhaul may provide connectivity to the Internet and to UPAT/PNET Core Network and UPF. Evidently, if no backhaul is available, the gNB connects only to the local B5G SA Core Network and edge computing resources, ensuring service continuity and local control of all services. This aims to serve connectivity of the (remote) Local Control Center with the Central Control Center, that may be set up at a Ministry in a remote location. Mechanism for surveying backhaul availability is developed and deployed. This is a dynamic discovery mechanism that continuously scans for available backhaul networks (fibre, microwave, satellite, or cellular) to support the private 5G PPDR deployment. The mechanism is using the Enhanced Network Performance Monitoring and Control enabler that evaluates each backhaul option based on latency, bandwidth, reliability, security, and availability to ensure mission-critical service continuity. It will then rely on the enablers developed within AMAZING-6G that will automatically select and switch to the optimal backhaul link, enabling resilient and uninterrupted connectivity for emergency response operations. The role of the NTN network in the scenario is two-fold: it provides a reliable and ubiquitous backhaul network but will also be used for testing feasibility of broadcasting emergency messages to the affected area.

Furthermore, for the specific scenario the use case implements B5G end-to-end network slicing across RAN, transport, and core domains. Depending on the service and application requirements some slices are pre-configured for the main categories of PPDR users. Specific QoS enabled resource allocation for high-priority services is deployed and conveyed through the Backhaul identifying enabler.

An important challenge for this scenario is that configuration of gNodeB should be automatic in order to ensure that QoS is delivered according to the situation (i.e. for example if drones and or other vehicles should be involved etc). Furthermore, all these should be automatically transferred the edge and the cloud if needed. The scenario assumes that low-latency and reliable services are maintained over backhaul links and under unpredictable conditions.

Simultaneously, PPDR network slice deployment with high priority and increased quality may be required over multiple networks. Main challenges will be the orchestration of the network resources on-demand, and the interconnection of B5G/6G core networks, as well as the interconnection of the private Autonomous Edge B5G/6G with the operating public or private network in the region. The latter may act as a backhaul to the first or as an “extension”.

After both 5G and Internet connectivity are secured, the deployed gNodeBs will employ Multi Operator Core Network (MOCN) configurations to create a RAN that is accessible by the subscribers of all the local operators.

MOCN (Multi-Operator Core Network) is a 3GPP network sharing architecture that allows multiple mobile operators to share the same 5G Radio Access Network (RAN) infrastructure, including gNBs, while maintaining independent core networks and subscriber management. In this scenario, one operator can extend its coverage area by allowing its users to connect through the gNB(s) of another operator without deploying additional radio infrastructure. The shared gNB may broadcast multiple PLMN identities and route user traffic to the appropriate operator core network, enabling efficient coverage expansion, reduced deployment costs, and improved resource utilization while preserving operator independence.

There are many challenges with ensuring that the Push-to-Talk (PTT) and Mission-Critical (MC) PTT: 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.)

2.3.2 Deployment and implementation details

2.3.2.1 *Application Design*

In the section applications that will be tested in the various scenarios are provided.

2.3.2.1.1 Incident detection platform for PPDR (Scenario B)

The incident detection platform for PPDR, with the concept presented in Figure 22, is based on wi.breathe product of WINGS [4] and it includes high-resolution cameras (e.g. optical) that monitor the area of interest automatically, periodically and can be rotated and independently of the operator to focus on case of an event (e.g. fire, etc.). The system uses advanced machine learning algorithms to support high detection accuracy and has a wide range of monitoring capabilities. In addition, it supports people/vehicle detection, as well as fire, smoke and combined smoke and fire detection. Images and videos from the cameras are transmitted in real time to the wi.breathe management platform in the Cloud with the help of a full web-based electronic monitoring and management application (Dashboard), where they are further analysed through advanced smoke and flame detection algorithms.

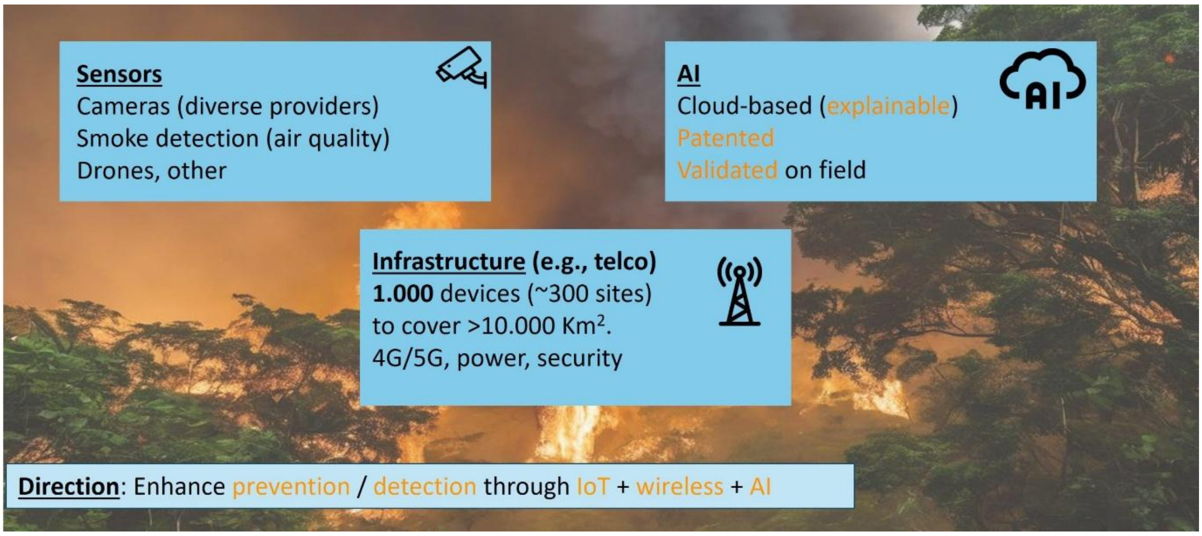


Figure 22 : Incident detection platform for PPDR

The data collected and transmitted by the cameras/sensors are visualized and recorded on the wi.breathe platform for further processing, utilizing the capabilities offered by the Internet of Things and Artificial Intelligence. The capabilities offered by this system are very diverse and range from simple monitoring to more complex tasks (sensor data analysis, report and forecasting, etc.) while always maintaining user-friendliness. The management platform presents the data from the cameras/sensors in a friendly way, predicts the measurement levels and sends notifications to selected users in cases of measurement fluctuations outside the desired limits or in cases of events (e.g. fire detection). The platform allows remote management of the installed equipment, supporting functions such as adjusting the data transmission rate, restarting the devices and upgrading the embedded software. In general, the management platform includes (i) Remote monitoring in real time and at the desired data measurement/transmission frequency, as presented in Figure 23, (ii) Early warning based on modern means and sensors, multiple data sources and computational intelligence technologies, (iii) Management of large volumes of data, (iv) Detection of incidents in areas of interest, (v) Sending notifications in case of fluctuations in measurements outside the limit, (vi) Statistical analysis and comparative data.

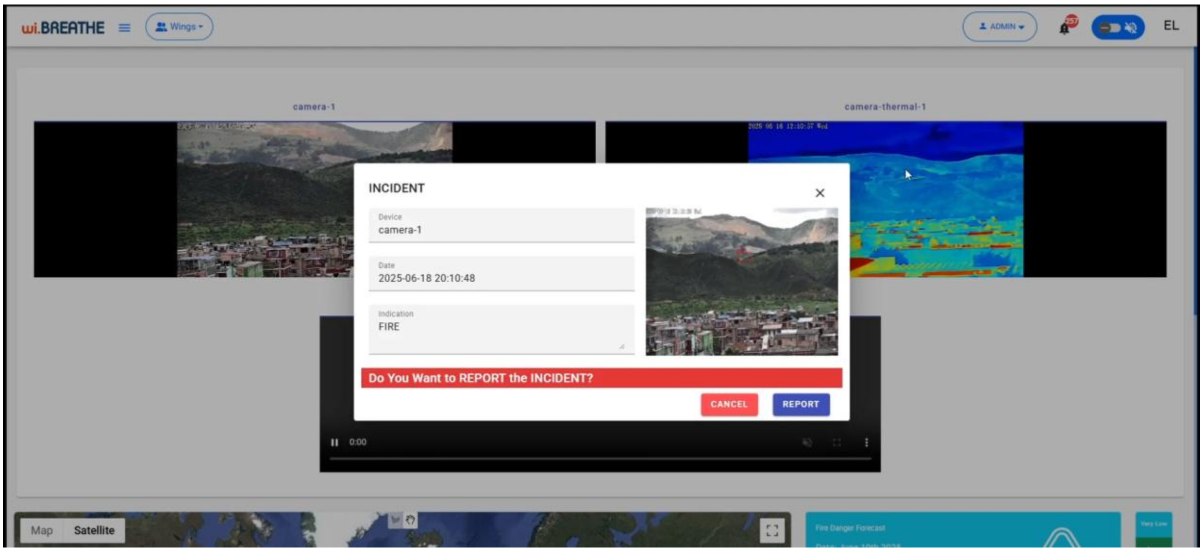


Figure 23 : wi.breathe monitoring platform

2.3.2.1.2 Mission Critical Communications (MCC) for Scenario A and C

Mission Critical Communications (MCC) refer to communication systems that provide highly reliable, secure, and performant information exchange in situations where failure could lead to serious consequences. These systems are essential for public safety, emergency response, transportation, utilities, healthcare, etc. They should support:

- High Reliability & Availability – Continuous connectivity through redundancy, failover mechanisms, and robust coverage (including remote/hard-to-reach areas).
- Low Latency – Critical for real-time coordination; achieved via traffic prioritization, network slicing, and Multi-Access Edge Computing (MEC).
- Security – Encryption, authentication, access control, integrity checks, and isolation techniques to counter threats like jamming, eavesdropping, or cyberattacks.
- Prioritization & QoS – Mechanisms to ensure critical traffic is delivered first (e.g., IEEE 802.1P, network slicing in 5G).
- Interoperability – Ability for different agencies/devices/networks to communicate seamlessly.
- Resilience & Redundancy – Quick recovery from faults (physical, cyber, or technical) via backup systems and alternative paths.

Early MCC relied on dedicated narrowband systems using PTT for half-duplex group communication. 3GPP shifted MCC to cellular broadband starting with Long-Term Evolution (LTE). 5G (Release 15+) added URLLC, with network slicing, MEC (edge computing for reduced latency) and 5G Multicast-Broadcast Services (5MBS). In AMAZING-6G, QoS mechanisms ensure prioritization of mission-critical traffic, enabling congestion control, traffic isolation, and guaranteed bandwidth for emergency communications.

The MCC application supports group communications, real-time video streaming, situational awareness data exchange, and emergency alerting with minimal latency. Operational resilience is achieved through geo-redundant core networks, multi-access connectivity, and seamless roaming across heterogeneous radio access networks. Continuous communication sessions are maintained during mobility events, ensuring uninterrupted coordination between field units and command centers. Reliability is further enhanced through multipath connectivity, redundant devices, and fallback communication paths.

Overall, the MCC application enables secure, highly available, and low-latency mission-critical services tailored to PPDR agencies, supporting coordinated response during emergencies, disasters, and large-scale public safety operations using advanced 5G capabilities.

2.3.2.1.3 Video Streaming: live video streaming from cameras, drones or vehicles to Local Control Center (Scenario A and C)

The proposed system consists of a secure video communication platform designed for a PPDR control room environment. Multiple video sources, including body cameras and mobile phones, connect wirelessly through a dedicated private 5G network that operates independently from the public internet. The system architecture comprises of IP-based video devices, connected via a standalone (in-a-box) private 5G network infrastructure. Each device transmits compressed video streams through the deployed 5G network (5G RAN and Core). Depending on the operational requirements, the Video Streams can be directly consumed by other UEs either through dedicated applications in case of tablets (as in a portable Command Center) or custom-made web applications for laptop based on-field command Centers. If needed, video streams can be routed to an edge-based media gateway or streaming server, which performs stream ingestion, session management, transcoding (if required), and distribution to further control room clients, either on the field or on remote locations, depending upon backhaul connectivity. The control room subsystem includes operator workstations running the developed application capable of displaying multiple simultaneous streams in a grid layout, supporting low-latency viewing, recording, and optional archival storage on local edge . The entire system operates within an isolated private network environment without reliance on external internet connectivity, ensuring security, low latency, and operational resilience suitable for mission-critical PPDR deployments, while allowing for external consumers to receive this feed for even better situational awareness.

2.3.2.1.4 Closed control loop procedures for extended-duration observation UAVs (Scenario C)

Closed control loop procedures for extended-duration observation Unmanned Aerial Vehicles (UAVs) are very important during crises in order to optimally adjust the drone's path through approved (Human In the Loop) waypoints, sent to the flight-controller through processing nodes located in the deployed edge compute. The nodes ingest video from the drone(s) and reconstruct the crise's terrain and environment while also detecting objects of interest (firefighters, rescuers, vehicles, citizens etc.). The combined information can flow to monitoring environments to better assist operations. To optimally and continuously reconstruct the updated environment the UAVs must adjust their courses according to the movements of personnel and objects of interest and terrain morphology. The processing nodes assess these criteria and provide the optimal waypoints continuously as the situation unfolds. In AMAZING-6G the second and third scenario of P1 showcases the MEC enabled closed loop control of unmanned vehicles that may assist PPDR campaigns and situation awareness at the Central Control Center.

2.3.2.1.5 AR/VR optimized service (Scenario C)

In order to support high performance end to end link deployment in unpredicted environments that can support AR and VR services between the affected area and the Local or Central Control Center, the private network should provide the stakeholders with AR/VR optimized service. In P1, Scenario B and C, this corresponds to supporting L4S, meaning Low Latency, Low Loss, Scalable throughput, is a network architecture that protects network nodes from congestion by informing senders about the cumulative congestion along the route so that they adjust their rates accordingly to avoid congested buffers and packet loss (meaning fewer retransmissions, lower queuing times and better throughput utilization). To support it, both sender and receiver as well as a subset of the network nodes must be L4S capable. In AR/VR environments, heavy traffic due to 3D (and sometimes 2D) content delivery, can create congestion in "bottleneck" nodes increasing latency and packet loss for the content delivery itself but also other streams that might be even more sensitive (voice, information messages, geo-positioning and other types of telemetry). L4S solves this problem by adjusting the sending rate to better utilise the network increasing the content delivery speed but also protecting the network from packet loss and high latency, benefitting other streams as well. In AMAZING-6G optimized AR/VR service provisioning will be supported by L4S ready network infrastructure.

2.3.2.1.6 NTN-Enabled Resilient Backhaul and Emergency Connectivity Service (Scenario C)

The proposed NTN-enabled service provides resilient and ubiquitous connectivity for PPDR operations by integrating satellite-based NTN into the autonomous B5G/6G infrastructure. The service ensures uninterrupted communication between the deployed Private network "IN-A-Box" platform, Local Control Centers, and Central Control Centers, especially in disaster areas where terrestrial infrastructure is unavailable, damaged, or congested. By dynamically complementing terrestrial backhaul links with NTN connectivity, the service guarantees continuity for mission-critical applications such as MCPTT, live video streaming, emergency alerts, and situational awareness services. In addition, intelligent Terrestrial Networks (TN)/NTN handover mechanisms continuously monitor network conditions and autonomously switch between terrestrial and satellite connectivity to maintain service continuity, QoS, and reliable low-latency communications for first responders, drones, and autonomous systems operating under highly dynamic and harsh conditions.

The pre-trial testbed for the P1 use case illustrated in Figure 24 validates the end-to-end capability of a satellite-based NTN to deliver emergency broadcast messages and Short Message Service (SMS)/cell broadcast services to unmodified commercial smartphones (direct-to-device, D2D) in scenarios where terrestrial infrastructure is unavailable or destroyed, directly supporting the resilient backhaul and emergency connectivity service described for PPDR operations.

Testbed Architecture and Components:

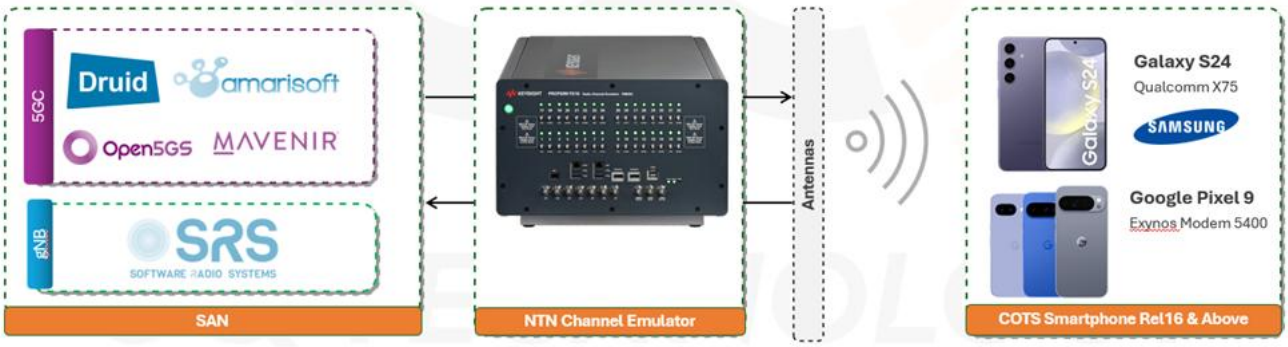


Figure 24 : NTN Testbed for P1 pre-trial

1. gNodeB — srsRAN The open-source srsRAN stack is configured to operate as a 5G NR gNodeB adapted for NTN conditions. Key adaptations include extended timing advance handling to compensate for the large propagation delays inherent in satellite links (GEO/LEO), Doppler pre-compensation for non-geostationary orbits if applicable, and NTN-specific Radio Resource Control (RRC)/ Medium Access Control (MAC) parameter tuning per 3GPP Release 17 NTN specifications. The gNodeB is configured to broadcast System Information Blocks (SIBs) carrying NTN assistance information and to support PWS (Public Warning System) messages for emergency broadcast delivery, such as Earthquake and Tsunami Warning System (ETWS) or Commercial Mobile Alert System (CMAS). SMS over Non-Access Stratum (NAS) is also enabled to validate cell broadcast and mobile-terminated SMS flows toward unmodified UEs.

2. Core Network — Amarisoft EPC/5GC or Druid/Gatehouse SMS-C The 5G Core, or the Evolved Packet Core (EPC) in fallback mode, is instantiated using Amarisoft's all-in-one software suite or the Druid/Gatehouse platform, which provides native support for CBS (Cell Broadcast Service) and SMS-C functionality critical for PPDR alerting. The core network handles AMF, SMF, UPF, and CBSF (Cell Broadcast Service Function) roles. The CBSF interfaces with the gNodeB via the PWS interface to inject geo-targeted Cell Broadcast Entity (CBE) messages, simulating national or regional emergency alert payloads. The SMS-C component enables delivery of emergency SMS messages through the SGs or N20 interface. Both platforms are assessed for their ability to handle NTN-adapted session management with relaxed timer configurations to tolerate round-trip delays.

3. Channel Emulator A hardware or software channel emulator (e.g., Spirent GSS7000, Keysight PXT, or an equivalent RF channel emulation platform) is inserted between the srsRAN gNodeB RF front-end and the UE to reproduce realistic NTN propagation impairments. Emulated conditions include one-way propagation delays representative of LEO (~20–40 ms) and GEO (~270 ms) satellite orbits, Doppler shift profiles corresponding to LEO satellite pass geometries, path loss consistent with the satellite link budget, and fading models appropriate for the satellite-to-ground channel. This allows controlled and repeatable stress-testing of the NTN link without requiring an actual satellite payload.

4. UE — Unmodified Commercial Smartphone (Direct-to-Device) A standard off-the-shelf smartphone supporting 5G NR NTN bands (e.g., n255 or relevant licensed NTN spectrum) is used as the target UE without any software or SIM modification beyond standard provisioning. The test specifically validates that the device can: (a) detect and attach to the NTN cell broadcast by srsRAN under emulated satellite channel conditions; (b) receive ETWS/CMAS emergency alert notifications through the PWS path; and (c) receive mobile-terminated SMS messages via the Druid/Gatehouse SMS-C, all without requiring custom firmware or dedicated NTN chipset configuration beyond what is commercially available. This directly validates the D2D paradigm central to PPDR reach in infrastructure-denied environments.

2.3.2.2 *Devices, sensors and supporting equipment /software*

Details on the digital infrastructure equipment in Table 13.

Table 13 : Equipment for P1 use case

Category	Component	Technical Details	Units
High resolution camera [Scenario B]	Camera	The camera is capable of capturing and live streaming images from an area of interest and transmit to the management platform for further processing and alerts in case of an incident.	At least 1 in a predefined spot of the trials site (Scenario B)
UEs [Scenario A, B, C]	Smartphone https://wiki.patras5g.eu/radio-equipment/u-es	State-of-the-art smartphones	At least 4 (Scenario A and B)
UMV/Drone	Drone equipped with monitoring camera	To be acquired	At least 1
Environment monitoring IoT platform, with cameras, environmental and other sensors, for incident detection	Software platform	As described in subsection 2.3.2.1.1	1 (Scenario B)
VR Headsets Meta Quest 3	VR Headsets for Scenario B		At least 1 (Scenario B)

MC UEs body cameras	For Scenario A		At least 2 (Scenario A and C)

2.3.3 Network infrastructure

The Patras5G 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, it offers customized network slices tailored to the needs of PPDR use cases. The architecture for the P1 pre-trial is presented in Figure 25, while the pre-commercial 5G private network and its outdoor coverage are shown in Figure 26.

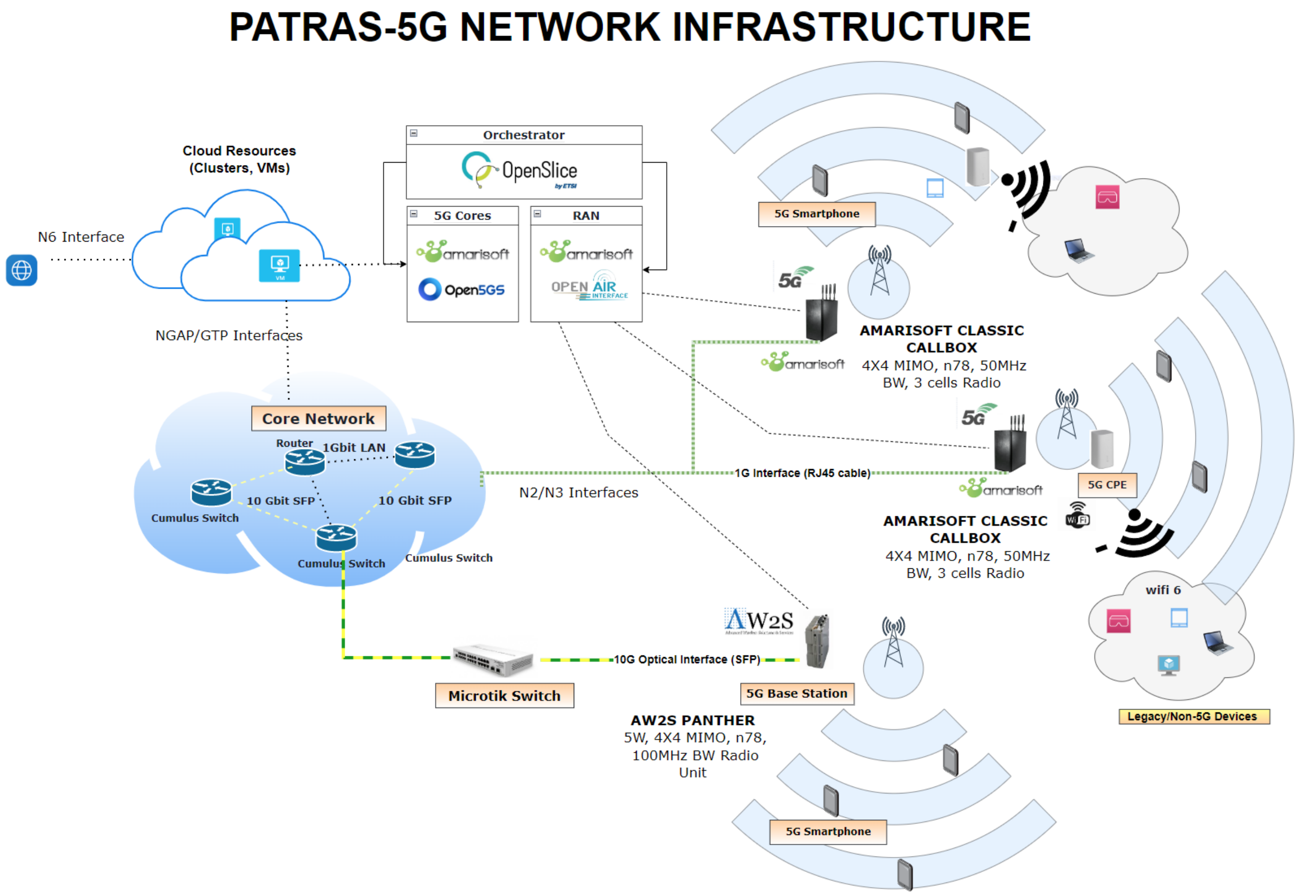
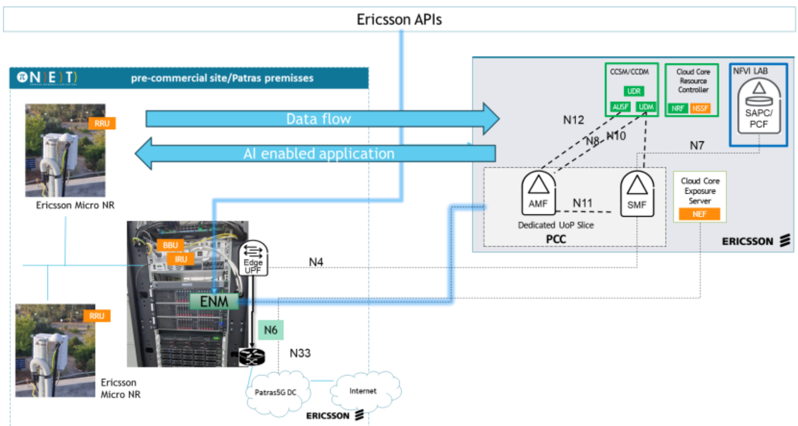


Figure 25 : Patras5G tested architecture diagram for P1 pre-trial



(a)

(b)

Figure 26 : (a) Patras5G pre-commercial private network for pre-trial and trial and (b) Patras5G 5G coverage in Patras University Campus

The network infrastructure components listed in Table 14, are configured and deployed specifically for the AMAZING-6G P1 use case.

Table 14 : Network infrastructure components for P1 use case

Category	Component	Technical Details	Units
Mobile box for private 5G/6G network deployments	Autonomous Edge	XEON D2146NT @ 2.3GHz 8 64 512GB NVMe 6x1Gb + 2 x10Gb XEON D2146NT @ 2.3GHz 8 64 512GB NVMe 6x1Gb + 2 x10Gb	1
Customer Premises Equipment (CPE)	RUTX50	Wi-Fi/Ethernet DL/UL: 2300/150 Mbps - DL/UL: 300/40 Mbps (tested) DL/UL: 3600/250 Mbps - DL/UL: 250/40 Mbps (tested)	2
UPAT/PNET cloud server	Patras 5G facility is equipped with a cloud platform, able to host core network components, as well as Network Functions Virtualisation (NFV) and MEC deployments	The cloud platform offers a total computing power of 1082 CPUs and 4,5 TB of RAM and 100 TB of storage. In AMAZING 6G pre-trial, an AI-enabled server will be used, specifically dedicated for the use case, equipped with 2xGPUs of NVIDIA PNY QUADRO A6000 48GB GDDR6 GPU NVIDIA RTX interconnected via NVIDIA NVLINK Bridge	1
AMARI Callbox Classic	Base station and Core for indoor testing in Scenario A	Allows for multiple cells configuration. Supports 5G NR SA mode 3 x 2x2 Multiple Input Multiple Output (MIMO) SDRs UL/DL : 600/150 Mbps LTE and NB-IoT capable	1
AW2S (indoor)	Base station and Core for indoor	Configuration: Remote Radio Head (RRH) 4x4 Frequency Band N78 3400-3800MHz	1

Category	Component	Technical Details	Units
	testing in Scenario A	Mode: Time Division Duplex (TDD) operating bandwidth up to 100MHz Power per antenna: >=2W Common Public Radio Interface (CPRI) Remote Radio Unit (RRU) unit is connected through fibre (CPRI) to 1 gNodeB composed of : x86 server, AW2S PCIe to CPRI interface board, drivers for RRU Control and management, Amarisoft 5G stack software	
AW2S (outdoor)	Scenario B and C	Configuration: RRH 4x4 Frequency Band N78 3400-3800MHz Mode: TDD operating bandwidth up to 100MHz Power per antenna: >=2W Interface CPRI	1
Edge Server	NUC130Xi5	Intel® Core™ i5-13500H Processor Intel® Iris® Xe Graphics 2 x DDR5-5200 SO-DIMM Sockets 1 x M.2 22x80 M-key supporting PCIe x4 Gen4 NVMe 1 x 2.5” drive bay supporting SATA SSDs	1
SDRs	USRP B-200	RF coverage from 70 MHz – 6 GHz Full duplex operation with up to 56 MHz of real time bandwidth (61.44MS/s quadrature) GNU Radio and OpenBTS support through the open-source USRP Hardware Driver™	2
Ericsson Dots NR (indoor) and Micro NR (outdoor)	Radio Dots are for 5G connectivity, built and optimized for deployments pre-trial and trial.	Output Power 23 - 26 dBm per Dot (approx. 250 - 500 mW, Maximum Data Speeds Up to 3.7 Gbps, NR MIMO Support, MIMO & Carrier Aggregation, Frequency Band Support, Mid-bands (3GPP bands like B78K, n77), enabling multi-operator support	5
NTN Channel Emulator	CELEOS Channel Emulator	Supports real-time NTN channel emulation for Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) satellite scenarios with propagation delay from 2 ms to 1000 ms, and Doppler shifts from −2 MHz to +2 MHz. Provides bandwidth emulation up to 150 MHz using USRP SDRs and up to 400 MHz over DIFI interfaces.	1

Category	Component	Technical Details	Units
		Enables multi-channel satellite emulation with up to 4 independent channels, each supporting different satellites, terminals, or propagation conditions. Implements realistic RF impairments including dynamic path loss, Additive White Gaussian Noise (AWGN) noise injection, weather attenuation (ITU-R based), interference generation, and additional digitally simulated phase noise. Features a hardware-agnostic SDR architecture with support for Digital Intermediate Frequency Interoperability (DIFI), Signal Metadata Format (SigMF) recording/replay, and real-time testing of hybrid TN/NTN and 5G/6G NTN communication systems.	
SDR	USRP SDR	Programmable radio that will be used for 5G NR communication	1
AMARI Dongle		The Amarisoft dongle is a USB hardware license key used to activate and manage Amarisoft wireless network software. It supports advanced telecom technologies including 5G NR for modern standalone and non-standalone 5G network deployments. The dongle can be used in systems supporting emergency broadcast communication, enabling testing and deployment of public warning and alert messaging features.	1
Satellite Hosted Payload	Jetson ORIN NX	The NVIDIA Jetson Orin NX is used as a hosted payload computer for NTN applications. It provides compact, low-power AI and edge computing for onboard satellite and airborne processing. The platform supports real-time data handling, autonomous operations, and integration with 5G NR communication systems.	1

Moreover, pre-trials are running also in Athens in the WINGS 5G/6G Private testbed for intelligent vertical applications. WINGS delivers solutions for verticals, leveraging, among others, on advanced networks, 5G and eventually beyond, which can be public or private. An owned infrastructure has been set up, in order to conduct Research & Development (R&D), internal and collaborative, presales, and testing activities, prior to the deployment to the customers. WINGS' testbed is shown in Figure 27. It provides end-to-end 5G/B5G functionality, along with extensive cloud and edge computing capabilities, leveraging the 3GPP (Rel.16 and beyond) Public Network Integrated Non-Public Network (PNI-NPN) with shared Control Plane (at a first phase) and isolated, Standalone Non-Public Network (SNPN), with all network functions (User Plane and Control Plane) inside WINGS premises, isolated from the public network in the final phase. The site offers a range of B5G/6G-oriented services and supports various vertical domains, with WINGS providing the necessary hardware, software, and configurations to enable the testbed to handle these use cases. WINGS testbed serves as a testing ground for services, equipment, and new features before they are commercially released and used as well as pre-trials of AMAZING-6G.

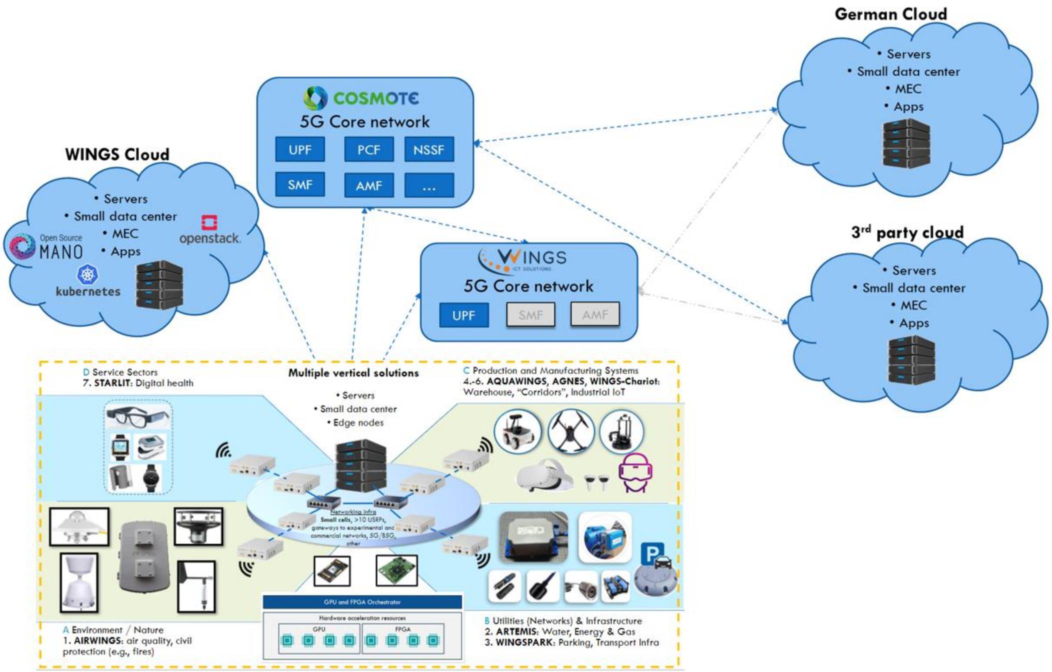


Figure 27 : WINGS 5G NPN testbed with RAN and cloud/edge elements, environmental monitoring sensors, robotic platforms, and GPU/FPGA resources

WINGS has progressively extended the existing software, hardware, and network functionality to support Cloud, Mobile Edge Computing, Extreme Edge and IoT functionalities. The site offers testing of new services such as Autonomous Guided Vehicles (AGVs) and Drones for smart warehousing, healthcare, public safety, disaster recovery, and network coverage extension. 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.

WINGS testbed utilizes AI mechanisms, trustworthy infrastructure, diagnostics, and intelligent management and orchestration. The management of the facility is done using a combination of existing and new software, covering DevOps, AI/MLOps, monitoring, profiling, diagnosis, and service-aware resource allocation. The site provides a flexible, scalable, reliable, and secure infrastructure for verticals to run their pilots in the 6G era. Monitoring, profiling, and diagnostic components provide information on available resources and network capabilities to help find the optimal deployment of a vertical service.

2.3.4 Use case enablers

Table 15 is listing the enablers to be used with the use case.

Table 15 : Enablers for P1 use case

Category	Technology Enablers	Sub enabler/UC Related Functionality
Communication enablers	Automated gNB Configuration	The sub-enabler is extremely important for P1 as it enables rapid deployment of temporary or permanent gNB in disaster areas

	Network Performance Monitoring and Control	In order to monitor and control the slice deployment that serves the rescuers and their PPDR campaign, slice performance monitoring ensures the PPDR slice maintains priority across operators and/or private/public network deployment.
	Identification and Selection of Backhauling.	In the P1 use case, the availability of backhaul network to interconnect an isolated cell is not guaranteed. However, the high-performance slice that may be provisioned assumes high quality transport network availability especially when interconnection with cloud resources and/or remote (central) control Center is assumed. Intelligent selection of backhaul links among available ones based on performance requirements and backhaul availability is vital for interconnecting the mobile private network with the central infrastructure.
	NTN Integration / Emergency Communication	During catastrophic situations where terrestrial networks are unavailable, damaged, or congested, NTN communications can ensure service continuity and ubiquitous connectivity for PPDR operators, which is critical for emergency response operations. OQTEC will develop a state-of-the-art NTN-enabled gNB capable of providing direct 3GPP-compliant 5G connectivity to unmodified handheld devices, without requiring specialized user equipment. The proposed solution will enable resilient emergency communications and continuity of mission-critical PPDR services across affected areas, while supporting seamless integration with terrestrial B5G/6G infrastructures and autonomous network deployments
Compute-as-a-Service enablers	Intelligent service and resource orchestration in extreme edge/edge/cloud compute continuum	The enabler is extremely important for the P1 use case as it enables extreme edge computing (on-site MEC servers, drones, or even private networks with portable base stations) to process possible AR)/VR rendering and sensor fusion locally, while offloading only heavy AI/ML tasks to central cloud when transport network is available, in order to ensure continuous Situational Awareness even in disrupted networks and seamless mobility of operatives across operators without service interruption.
	Creation of Kubernetes clusters on demand	For the P1 use case, Patras5G testbed will be able to deploy on demand 5G networks. To this end, a Kubernetes cluster will be created on demand on which the 5G Core be deployed and with the use of previously described enablers the deployed gNB will be connected to, providing a fully operation 5G network.
Application enablers and AI	AI-as-a-Service framework	In the P1 use case, AI functionality is essential for environment monitoring and incident detection.
	TM Forum Open APIs	In the P1 use case, TM Forum Open APIs are required to enable standardized, cross-operator orchestration of network slices and compute resources, allowing PPDR agencies to dynamically deploy, scale, and assure AR/VR mission-critical services across the edge-cloud continuum in a vendor-neutral and automated way.

2.3.5 KPIs definition

Table 16 introduces the KPIs for the use case.

Table 16 : KPIs for P1 use case

KPI name	Description/KPI definition	Scenario/profile	KPI target
Communication service availability	Percentage of time the service can be delivered	Scenario 1: UE ↔ RAN ↔ Local Core ↔ Edge Scenario 2: UE ↔ RAN ↔ Core	≥ 99.999%
End-to-end latency	Time between the source application/node sending a data packet and the destination application/node receiving a data packet in ms for all applications for Scenario 1 and 2	Scenario 1: UE ↔ RAN ↔ Local Core ↔ Edge Scenario 2: UE ↔ RAN ↔ Core	< 100 ms
Uplink Bit rate	Maximum achievable data rate successfully transmitted from the UE to the network in uplink direction toward edge-hosted MC and non-MC services and for VR-enabled services	Scenario 1: UE ↔ RAN ↔ Local Core ↔ Edge Scenario 2: UE ↔ RAN ↔ Core	> 100Mbit/s
# of UEs connection	Maximum number of UEs connected from one private and one public network or two private networks which may connect to the 6G System within a defined area while satisfying the other KPIs	Scenario 3: UE ↔ RAN ↔ Local Core ↔ Edge and 2X UEs ↔ RAN ↔ Core	4 UEs from more than one private network connected on the fly to the application and Core
Service area	Description of the area within which the UE could find itself while satisfying the other KPIs with and without enabler	Scenario 3: UE ↔ RAN ↔ Local Core ↔ Edge and 2X UEs ↔ RAN ↔ Core	100% increase of the initial coverage area (5G In A BOX) through AMAZING 6G enablers
Slice provisioning	Service Configuration/slice provisioning for each of the MC and non-MC services	Scenario 2: UE ↔ RAN ↔ Core	< 1 min
AI-related Capabilities: Model accuracy	Accuracy of detection of PPDR incidents (e.g. fire etc)	All scenarios	>= 99%
AI-related Capabilities: Time for	Time for detection of PPDR incident (e.g. fire etc)	All scenarios	<1 min

detection of incident			
AI-related Capabilities: False positives	False positives for detection of PPDR incident (e.g. fire etc)	All scenarios	Up to 1 per day per camera

2.3.6 KVIs definition

Table 17 lists the KVIs for the use case.

Table 17 : KVIs for P1 use case

KVI name	Description/KVI definition	KVI target
Improved end-user experience through optimal connectivity selection	Evaluates the perceived improvement in service quality experienced by PPDR users (first responders and control Center operators) through dynamic selection of the most suitable connectivity option (terrestrial or satellite backhaul) based on real-time network performance monitoring.	≥75% users rate service quality improvement ≥4/5
Network operational cost savings through performance optimization	Measures perceived reduction in operational costs enabled by automated network deployment, dynamic orchestration of network and compute resources, and optimized performance management of B5G/6G infrastructure during emergency response operations.	≥60% operators report perceived cost reduction ≥10%
Network resource efficiency improvement through multi-connectivity	Assesses the improvement in network resource utilization achieved through the combined use of multiple connectivity solutions (private/public B5G networks, alternative backhaul options and cross-operator slices), dynamically orchestrated through standardized APIs and monitoring mechanisms.	≥15% improvement in network resource utilization

2.3.7 Description of the trial setup

Table 18 shows the pre-trial and trial setup for Scenario A and all its phases (1 , 2 and 3).

Table 18 : P1 pre-trial and trial setup - Scenario A

P1 Pre-trial and Trial	Scenario A
Trial Infrastructure / Venue	Deployment of the Pre-trail setup at Patras 5G Lab facility (Figure 25) Trail for Scenario A will run with the same system configuration at Patras campus with the Autonomous Edge (IN-A-BOX)

Trial Description	P1 trial will take place in the UPAT/PNET facility in three phases, aiming at showcasing all Scenario A service deployment in autonomous private B5G network in a box, with and without backhaul connectivity. In phase 1 various B5G gNB are tested with a data service (live video to Local Control Center), in phase 1 all enablers are integrated and MCC is tested and integrated, while in final phase 3 all services and enablers are showcased in the field.	
Technical Setup	**System Components**	Autonomous Edge with three RAN available gNodeBs: AMARISOFT 5G RAN (Classic boxes), 5G RAN open-source radio and AW2S Local B5G SA Core Network (Amarisoft and Open 5GS with AMF, SMF, UPF). Edge computing servers hosting Group and video call applications for first phase, MC services for second phase. Two available backhaul options for pre-trial (Phase B), three options with NTN for final trial (Phase 3)
	System Configuration	Phase 1: Standalone operation with local control and user plane, Integrating data services with various optimized configurations (measuring TCP/UDP throughput, reliability and latency) in the lab Phase 2: Standalone operation with local control and user plane, Integrating MC services with various optimized configurations (measuring TCP/UDP throughput, reliability and latency) and availability of wired/wireless backhaul options in the lab, all enablers integrated and tested. Phase 3: Standalone operation with local control and user plane, Integrating MC services with various optimized configurations (measuring TCP throughput, reliability and latency) and wireless backhaul options and NTN in the field
Pre-Trial execution (initial phase, included in this deliverable, Section 4.3)	**Pre-conditions**	Scenario A requires portable gNB integrated on portable box Local SA Core and edge service instantiated Emulated Local Control Center Emulated UEs and body cameras Live video app (for Local Control Center) developed and integrated
	Trial Steps	Choose suitable gNB and integrate with service. Activate local SA Core, connect UEs and validate registration and service provisioning, Test live video app, measure KPIs in the lab
	Methodology	Phase 1: Functional validation before KPI measurement. Controlled traffic generation for data services, comparison between one and more devices, comparison between with and

		without enablers, Local Control Center, 6 UEs and body cameras connected, comparison against dry-run KPIs and measurements
	Technical Enablers	Communication, Compute-as-a-Service, Application enablers and AI
	Expected Outcome	Choice of operational Autonomous Edge to be verified, operational readiness of Autonomous Edge, ensure functional data services without external connectivity, test various configurations with QoS Class Identifiers (QCIs) and gNodeBs, test emulated Local Control Center app and UEs, ensure 5G IN-A-BOX availability for Scenario A. Benchmark KPI measurements for trials
Trial Execution (final phase, to be included in final deliverable D4.2)	**Pre-conditions**	Integration of MC services on Autonomous Edge with Enablers and backhaul (Phase 2) Incremental activation of backhaul selection, tested and integrated backhaul options with Enabler (also NTN) Pre-defined PPDR scenarios Connectivity to Local Control Center and number of UEs and body cameras
	Trial Steps	Live deployment in UPAT field trial area Execute PPDR scenarios with responder groups Switch dynamically between backhaul-connected and standalone modes Enable multicast/broadcast dissemination Simultaneous services delivery for MC and video streaming
	Methodology	PPDR story-driven execution of Autonomous Edge setup Repeated measurements under load and mobility/field in autonomous mode KPI collection from RAN, core, edge, and UEs Repeated measurements under load and mobility when backhaul arises KPI collection from RAN, core, edge, and UEs Parallel subjective assessment for KVIs
	Complementary Measurements	Time to service (from rescuers arrival to complete connectivity between Local Control Center and team) Power consumption Resource utilization (CPU, memory, radio) Coverage (UEs per m^2)

		Repeat KPIs measurements in three distinct points in the campus areas
	Calculation Process	Latency: timestamped packet probes (UE ↔ edge) Throughput: controlled DL/UL traffic sessions Backhaul delay: satellite probe analysis Aggregation over multiple runs and scenarios
Technical Enablers	**Communication Enablers**	Automated gNB Configuration Network Performance Monitoring and Control Identification and Selection of Backhauling
	Compute-as-a-Service (CaaS) Enablers	Intelligent service and resource orchestration in extreme edge/edge/cloud compute continuum Creation of Kubernetes clusters on demand
	Application enablers and AI, including network exposure APIs and AI-driven application services	AI-as-a-Service framework OpenAPIs for Network Exposure TM Forum APIs
Expected Outcome	Fast service set up tested by rescuers ≤5 ms network latency Seamless MC operation in standalone mode Efficient group communication Demonstrated resilience and autonomy for PPDR missions	

Table 19 shows the pre-trial and trial setup for Scenarios C and B.

Table 19 : P1 pre-trial and trial setup - Scenario B & C

P1 Pre-Trial 1 and Trial	Scenario B and C
Trial Infrastructure / Venue	These scenarios will utilize the Patras5G pre-commercial site, which is based on Ericsson 5G equipment
Trial Description	P1 trial will take place in the UPAT/PNET facility in three phases, aiming at showcasing all Scenario B service deployment in private pre-commercial B5G network, and Scenario C. In the first phase 1 integration of new services will take place, in phase 2 all enablers are integrated, while in final phase 3 all services and enablers are showcased, including Scenario C

Technical Setup	**System Components**	The site hosts an Ericsson Micro NR covering the Patras Campus outdoor area, where the trial will take place. In particular for the pre-trial phase 1, the indoor Ericsson Dots NR can be utilized. It also includes a dedicated edge UPF, while the 5G Core is co-hosted remotely by a Greek operator (Nova). This setup offers the opportunity to test the PPDR scenarios, including mission-critical services and the incident detection platform, through the connectivity to Patras5G edge-cloud servers and the Internet.
	System Configuration	Phase 1: Private network operation with control and user plane, Integrating data services with various optimized configurations (measuring TCP/UDP throughput, reliability and latency). Also, wi.breathe is integrated and tested. Drone services are integrated and tested. NTN services integrated and tested. Phase 2: Testing L4S operation with VR optimized service and local control and user plane, integrating all new services (like closed loop configurations) with optimized configurations (measuring TCP/UDP throughput, reliability and latency) in the field. Phase 3: All services with optimized configuration and scenarios tested in the field
Pre-Trial execution	**Pre-conditions**	Dry run execution of indoor testbed, edge and cloud Each service is integrated and tested over the trial testbed, as described in the previous section. L4S is verified. Deployment of sensing UEs and devises (sensors, drones and cameras etc.) End to end testing with all enablers Definition of specific scenarios for Scenario B Definition of test cases and scenarios for Scenario C Integration with Operation Center (Central)
	Trial Steps	Dry run of pre-trial testbed Test with various backhaul networks – test Enabler Integration and Testing of each application (see section above) Testing simultaneously all services
	Methodology	For measuring Round Trip Time (RTT): a packet stream is emitted from a source and received by a data sink (destination). The data sink shall acknowledge the correct reception of the data packet back to the sink. The time of emitting the packet at

		the data source and receiving the acknowledgement at the data source are to be captured and the RTT is calculated as the difference between the two events. The test case shall include the consecutive execution of several replica (iterations) according to the following properties : - Duration of a single replica (iteration) → at least 2 minutes o Note, the duration has to ensure that at least 100 ICMP ECHO_REQUESTs are sent during a single replica (iteration) - Number of replica (iterations) → at least 25
	Technical Enablers	Communication, Compute-as-a-Service, Application enablers and AI
	Expected Outcome	The pre-trials will highlight integration issues of services and PPDR related applications (wi.breathe and closed-loop-control with drone)
Trial Execution (final phase, to be included in final deliverable D4.2)	**Pre-conditions**	All applications integrated in outdoor testbed NTN backhaul tested All enablers tested Scenario C test cases developed and Scenario A ready
	Trial Steps	Live deployment in UPAT/PNET field trial area PPDR scenarios with multiple responder groups executed for Scenario A, B and C Especially for scenario C two applications (MC and closed loop) run over two networks
	Methodology	PPDR story-driven execution of Autonomous Edge setup Repeated measurements under load and mobility/field in autonomous mode KPI collection from RAN, core, edge, and UEs Repeated measurements under load and mobility when backhaul arises KPI collection from RAN, core, edge, and UEs Parallel subjective assessment for KVIs To be updated after pre-trials completion
	Complementary Measurements	Packet Loss Rate, signal-level measurements

		Time between incident (fire) detection and various service deployments
	Technical Enablers	Communication, Compute-as-a-Service, Application enablers and AI
Expected Outcome	Fast service provisioning Seamless MC operation in the end-to-end scenarios Efficient group communication and with the remote Centers Demonstrated communications res and autonomy for PPDR missions	

2.4 P2 Mission critical services interoperability with other systems

2.4.1 Description of the Use Case

The P2 use case focuses on achieving interoperability between B5G/6G networks and non-3GPP technologies such as Wi-Fi and satellite systems. Its primary goal is to deliver seamless, reliable connectivity for mission-critical services, particularly for first responders operating across national networks. Use cases P2, P3, and P4 are closely interconnected and build on each other within the PPDR framework of AMAZING-6G. P2 establishes the foundation by enabling seamless interoperability across B5G/6G, Wi-Fi, and satellite networks, ensuring reliable connectivity in heterogeneous environments. P3 builds on these capabilities by applying them in mobile, on-the-move emergency scenarios, demonstrating how interoperable connectivity supports dynamic field operations. P4 then integrates the solutions developed in P2 and P3 into a complete end-to-end operational scenario (Arctic search and rescue) to support situational awareness and coordination between field responders and command centers.

Key innovations include automated roaming and intelligent network selection to maintain continuous service, multi-network utilization for redundancy and performance optimization, and real-time monitoring supported by AI-driven/ready decision-making. Service prioritization ensures that critical applications maintain high quality of service even under challenging conditions. The use case aligns with broader project objectives by addressing technical challenges in cross-network interoperability at both network and application levels. Real-world scenarios, such as a first responder vehicle switching between 5G and satellite connectivity in remote areas, illustrate the practical benefits of these solutions. Use case aims to enable robust, uninterrupted communication for emergency services.

The use case utilizes two main instances a vehicle and command and control center (CCC) depicted in Figure 28 and Figure 29. A vehicle equipped with multiple connectivity options including Wi-Fi, 5G, and satellite. The vehicle selects the optimal communication link based on network performance metrics, Network Exposure APIs, and/or energy efficiency considerations. The vehicle sends live video stream to CCC. In addition, other real data, e.g., from Light Detection and Ranging (LiDAR), thermal camera, or generated data using iPerf3 client. On the CCC side, the video server receives the video stream and forwards it to the video player. In addition, the iPerf3 server can be used to send and receive data. The system continuously monitors network KPIs and power consumption, providing real-time data to the network manager.

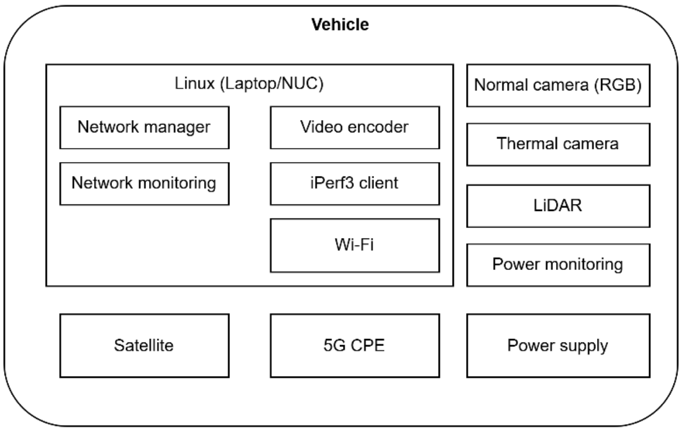


Figure 28 : Main components in vehicle (P2)

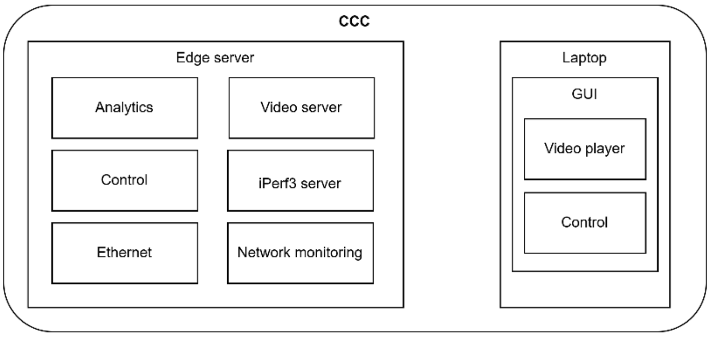


Figure 29 : Main components in CCC (P2)

2.4.2 Deployment and implementation details

2.4.2.1 *Application Design*

The P2 use case develops applications including a network manager and monitoring system, adaptive live video streaming, and power monitoring. These applications demonstrate how multi-network connectivity enables real-time situational awareness, efficient resource management, and reliable service continuity in mission-critical environments.

2.4.2.1.1 Network Manager and monitoring

A network manager chooses the active network from a list of available networks, which are ranked according to factors like service plan, energy usage, or performance. The manager then monitors QoS parameters of the active network, such as packet loss, latency (RTT), signal strength, and UL/DL throughput. When necessary, the network manager selects a new active network based on these QoS parameters.

Network monitoring for QoS parameters are monitored primarily using proprietary software Qosium, which is based on passive measurement technology without interfering or stressing with the actual measured data flow. Qosium nodes are placed usually on the endpoints of the measured path, in our case one in the vehicle UE and another at CCC. QoS parameters can be stored to database with the location information to be used later in the decision–making by the network manager or visualizing the KPI-specific information either in real-time or retrospectively.

Time synchronization between the nodes is important especially for accurate latency assessment, and it can be performed using GPS, precision time protocol (PTP) or network time protocol (NTP). In the pre-trials (indoor laboratory) PTP daemon is used to synchronize both encoder and server with PTP master, which is a common edge server in 5G test network with fixed connection. The synchronization is done over ethernet interfaces while as the actual measured traffic over 5G/NTN is routed over another interface. In the field tests we will use NTP with Chrony or GNSS-based synchronization in the vehicle.

Network manager uses the information by network performance monitoring and control as well quality on demand enablers for selecting the appropriate network from the list of available networks based on the ranking and QoS requirements. Target is also to enable service-based prioritization at least for B5G networking. In addition, energy management enabler can be used for gathering energy consumption statistics from the network devices, and to direct the service towards the possible energy consumption requirements for battery-powered devices.

2.4.2.1.2 Live video streaming

The live video streaming architecture is designed to deliver real-time content with high reliability and low latency. The system consists of the encoder and the video (edge) server.

The encoding process is handled by FFmpeg, a versatile and widely adopted multimedia framework. FFmpeg captures and compresses raw video into efficient formats suitable for streaming. To enhance adaptability, the encoder can be configured with adaptive bitrate (ABR) functionality. ABR dynamically adjusts the video bitrate based on network conditions, ensuring uninterrupted playback even when network bandwidth fluctuates. The input to the video encoder can be, for example, an RGB camera, a thermal camera or a LiDAR image.

Once encoded, the video stream is ingested by MediaMTX, which acts as the central streaming server. MediaMTX is responsible for managing incoming streams, handling client connections, and redistributing videos to viewers e.g., to CCC.

For transmission, the system supports multiple protocols including Real-Time Messaging Protocol (RTMP), Secure Reliable Transport (SRT), and Real-Time Streaming Protocol (RTSP). RTMP is widely used for compatibility with existing streaming platforms, while SRT provides secure, low-latency transport optimized for unpredictable networks. RTSP offers flexibility for real-time applications and integration with IP cameras. The choice of protocol can be tailored to the deployment environment and application requirements. In PPDR scenarios efficient and secure transmission is recommended.

ABR encoder control can be based on the video viewed by the CCC operator, video analytics, or network monitoring. For example, video is sent at a higher bitrate if the operator is viewing the video in full screen, if a person is detected in the video, or if the network capacity is sufficient.

2.4.2.1.3 Power monitoring

The VTT energy measurement framework is designed to monitor real-time power consumption within the test network. The energy measurement system is integrated with the test network infrastructure and device-level power monitoring setups include both application-specific devices as well as B5G RAN both for commercial and Open Radio Access Network (O-RAN). Energy meters from Carlo Gavazzi are used for precise 1/s measurement of electricity consumption using Modbus RTU/TCP protocols for data collection directly into database or to be redistributed or consumed via Message Queuing Telemetry Transport (MQTT) broker. In addition, UE modem power consumption can be measured accurately using Otii ACE meter or Shelly Plugs. Currently the energy measurement framework is running indoor facilities in VTT lab, and option for measuring consumption from the field from moving vehicle is under investigation.

2.4.2.2 *Devices, sensors and supporting equipment /software*

Details on the connectivity of digital infrastructure in Table 20.

Table 20 : Equipment for P2 use case

Category	Component	Technical Details	Units
Sensor	Camera	RGB camera	1
Sensor	Thermal camera	Thermal Master P2 pro	1
Network device	5G modem	Teltonika Altos	1
Network device	Starlink Kit	Starlink Performance (Gen3) hardware	2
PC	Dell mini-PC	PC in the vehicle	1
Hardware	Power monitor	Carlo Gavazzi/Otii ACE/Shelly Plug S Gen3	3
Software	iPerf3 client	Network traffic generator	1
Software	iPerf3 server	Network traffic generator	1
Software	Qosium Probe	Network traffic monitoring	2
Software	Qosium Scope	Network traffic monitoring	1
Software	Video encoder	FFmpeg	2
Software	Video player	Mpv	1
Software	Video server	MediaMTX	1
Software	MQTT server	Mosquitto	1
Software	Database	InfluxDB/Qosium Storage	1
Software	Visualization	Grafana	1

2.4.3 Network infrastructure

5GTN test network sites are Espoo, Oulu and Sodankylä in Finland. In the AMAZING-6G use cases tests are performed in Oulu (lab with indoor and outdoor cells) and Sodankylä (arctic test area). In the 5GTN radio networks include Carrier-grade 3GPP 5G NR (NG-RAN) and open-source O-RAN solutions (commercial disaggregated). Non-3GPP solutions Wi-Fi and NTN provide short-range wireless network systems and enablers with satellite communication links. We have permission for 5G NR licensed frequencies for R&D purposes. Frequency bands are 5GNR: 3.5 GHz (bandwidth: 60 MHz), 3.9 GHz (bandwidth : 100 MHz), 26 GHz (bandwidth: 800 MHz). Open5GS instances are used for 5G core.

The O-RAN architecture and interfaces introduce additional flexibility into the RAN management framework as well as in the development of P2. The open interfaces in the virtualized implementation with RAN Intelligent Controller (RIC) provide the required platform and means for intelligent centralized control going beyond the functionality of 3GPP Next Generation Radio Access Network (NG-RAN). The O-RAN architecture hierarchy is divided to Service and Management Orchestration Framework (SMO), Near-RT RIC, and E2 node comprising O-RAN Radio Unit (O-RU), Distributed Unit (O-DU) and Central unit (O-CU). Roughly these levels introduce different processing times on the control loops and enable optimization methods i.e. with energy efficiency. The P2 experiments are considered to use one outdoor gNB with single UE modelling one of the members in search and rescue crew.

The 5G infrastructure includes NTN connectivity with two optional setups for stationary and mobile tests. The stationary setup contains Starlink dish placed in on top of VTT roof with fixed connection to our laboratory. The other option comprises Starlink Mini, which can be used in outdoor tests connected to UE via Ethernet or Wi-Fi 6. The service plan has an unlimited data rate.

As P2 targets intelligent network management and selection, it is essential to possess sophisticated testing infrastructure. VTT's existing outdoor testing environment in Oulu enables simultaneous testing between 5G NR, Wi-Fi 6 and NTN (LEO satellites) with outdoor base stations. Another advantage of the testing environment is to provide low coverage corners as well.

2.4.4 Use case enablers

Table 21 lists the enablers for the use case.

Table 21 : Enablers for P2 use case

Domain & Enablers Reference Task3.x	Enabler	Sub enabler/ UC Related Functionalities
T3.1	Network performance monitoring and control	Accurate time synchronization between the nodes of interest. Collect real-time performance indicators from the system.
T3.1	Wi-Fi integration	Multiple networks are employed to increase resilience, guarantee reliable connectivity, and service continuity.
T3.1	NTN integration	Multiple networks are employed to increase resilience, guarantee reliable connectivity, and service continuity.
T3.3	CAMARA APIs Quality on Demand	QoD API is used to ensure service QoS requirements are met when having seamless connectivity in between different connectivity solutions.
T3.3	CAMARA APIs Energy management	Energy management API can be used for monitoring and selecting energy-savvy configuration for the used network and services in order to reduce carbon footprint and to maintain the system operability for battery-operated devices.

2.4.5 KPIs definition

Table 22 introduces the KPIs for the use case.

Table 22 : KPIs for P2 use case

KPI name	Description/KPI definition	Scenario/profile	KPI target
User-Experienced uplink data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time	-	>20Mbps

Network latency	Time between the source node sends a data packet to when the destination node receives it	-	<30ms
Service reliability and availability	Percentage of time the service can be delivered	-	> 99.999
Coverage	Geographic area where a network signal can be received and used by a device	-	Country wide including rural areas
Energy Efficiency	Power/energy consumption reduction in the source/destination nodes (W/J) per bit or bit per W/J))	-	>20%

2.4.6 KVIs definition

Table 23 introduces the KVIs for the use case.

Table 23 : KVIs for P2 use case

KVI name	Description/KVI definition	KVI target
Reduced power/energy consumption, reduced carbon footprint (CO2 emission)	Using energy-efficient video/network parametrization	Lower carbon footprint of video feed from the field
Perceived Increase in Renewable Energy Utilization	Using solar-powered B5G small cells/networking	Grid-based energy reduction on daily basis
Maintain satisfying quality of experience for video services in CCC	Using multi-RAT connectivity to ensure and maintain video service continuity when streaming from avalanche site towards CCC.	Decrease video stalls or erroneous packets
Network operational cost savings through multi-connectivity	Using the most optimal available communication network, or combining multiple networks, to ensure the best possible connection.	Cost reduction ≥10%

2.4.7 Description of the trial setup

Table 24 describes the pre-trial and trial setup of the use case.

Table 24 : P2 pre-trial and trial setup

Trial P2.1	Mission critical services interoperability with other systems
Trial Infrastructure / Venue	5GTN test network Oulu Finland

Trial Description	A vehicle equipped with Wi-Fi, 5G, and satellite connectivity, selects the optimal communication link based on network performance metrics, The vehicle sends live video stream to CCC. In addition, other real-time data (e.g., from lidar, thermal camera). The system continuously monitors network KPIs and power consumption, providing real-time data to the network manager.	
Technical Setup	**System Components**	5G: 5GTN, gNB, Core network (N3IWF) Satellite: Starlink (LEO) Wi-Fi: Wi-Fi 6 network
	System Configuration	5G, satellite and Wi-Fi networks in operation.
Pre-Trial execution (initial phase, included in this deliverable, Section 4.4)	**Pre-conditions**	A vehicle equipped with Wi-Fi, 5G, and satellite terminals. Terminals connected to the network. Edge services initiated. The vehicle sends live video stream from normal to CCC.
	Trial Steps	• Send data over 5G to CCC • Send data over Wi-Fi to CCC • Send data over Satellite to CCC • Use N3IFW to send data to CCC • Use multi-connectivity (mptcp) to send data to CCC
	Methodology	Energy consumption measured Network KPIs (throughput and latency) measured using Qosium. Comparison between: 5G/Wi-Fi/Satellite/N3IFW/MPTCP
	Technical Enablers	Communication Enablers • Network performance monitoring and control • Wi-Fi integration • NTN integration Application enablers and AI • CAMARA APIs Quality on Demand • CAMARA APIs Energy management
	Expected Outcome	Verify the basic functionality of the system and validate the functionality of the key components
Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	Pre-trial validated. Multi-connectivity solutions are available and active
	Trial Steps	Live deployment in Oulu or Sodankylä. On operation using a moving vehicle that sends sensor data to CCC. Vehicle switch dynamically access network or use multiple networks concurrently.

	Methodology	Repeated measurements under load and mobility Network KPIs (throughput, delay or RTT, jitter, packet loss, availability)
	Complementary Measurements	Energy consumption
	Calculation Process	UL/DL latency and throughput measured using Qosium
Technical Enablers	**Communication Enablers**	• Network performance monitoring and control • Wi-Fi integration NTN integration
	Application enablers and AI	• CAMARA APIs Quality on Demand • CAMARA APIs Energy management
Expected Outcome	Seamless network switching with less than 1s service recovery. Video continuity	

2.5 P3 Emergency private B5G/6G communication on-the-move

2.5.1 Description of the Use Case

The use case focuses on enabling independent private B5G/6G networks for PPDR operations in areas where public networks are unavailable. The approach involves deploying essential RAN and core network components at the network edge, ensuring secure and reliable connectivity without Internet access. Two main configurations are considered: independent private network and integrated private network. Both setups include edge services such as video streaming, object detection, and LiDAR processing.

Key enablers include network slicing and Network Exposure APIs, while innovations focus on tailored deployments, customized services for mission areas, and an analytics framework for traffic monitoring. Challenges include integrating private networks with slicing, optimizing resource allocation between public and private networks, and managing architectural complexity.

An integrated private network using slicing will be set up and tested. The slice will be configured to support mission critical services. Multiple users can access the private network and utilize selected services that are exclusively available within this network. Private network performance will be measured in different test cases.

An integrated private network leveraging network slicing will be deployed and tested to ensure robust and secure connectivity. The slice will be configured to support mission-critical services, providing guaranteed performance and reliability. This private network will allow multiple users to access and utilize selected services that are exclusively available within the network environment, ensuring isolation from public traffic and enhanced security. To maintain service quality under varying load conditions, traffic prioritization is implemented using QoS policies. Certain UEs are assigned higher priority ensuring that critical applications receive guaranteed bandwidth and low latency, supporting mission-critical operations even under heavy network load. High-level architecture and main components of the integrated private network is shown in Figure 30. In this setup, Vehicle-1 is equipped with multiple sensing and monitoring components, including a camera, thermal camera, and LiDAR, along with network monitoring tools and an iPerf3 client for traffic generation and performance evaluation. Video streams encoded and streamed to video server in the edge using a video encoder. Additionally, the vehicle integrates power supply and power monitoring units to track energy consumption during operation. A local CCC provides on-site access to video, sensor data, and network monitoring for immediate control, while the centralized CCC enables remote supervision, analytics, and coordination across deployments.

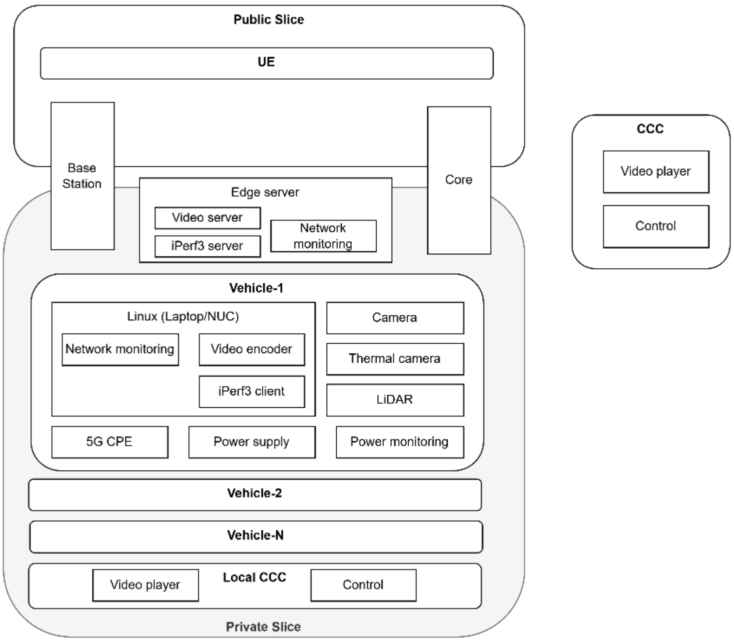


Figure 30 : High-level architecture and main components of the integrated private network in P3

An independent private network will be built as a static private network based on Open RAN, incorporating essential RAN and core network components to ensure full functionality without relying on the public Internet. Such a network operates autonomously, making it ideal for secure and isolated environments. For mobility scenarios, a private network on-the-move enables connectivity for vehicles or temporary deployments while maintaining local control. At the edge, Multi-access Edge Computing (MEC) provides localized services such as video streaming, object detection, and LiDAR data processing, reducing latency and improving efficiency. Additionally, traffic prioritization mechanisms ensure that critical applications receive guaranteed bandwidth and low latency, supporting mission-critical operations even under heavy network load.

An independent private network designed for mission-critical or specialized applications can be implemented using a static private network architecture based on Open RAN principles. High-level architecture of the independent private network is depicted in Figure 31. This approach leverages disaggregated RAN components including the DU, CU, and RU combined with a dedicated core network to provide full connectivity without dependency on external infrastructure. The network operates completely offline, meaning it functions without Internet access, ensuring security and resilience in isolated environments. Figure 32 shows main components of the independent private network in P3. The components are same as integrated slice.

For dynamic scenarios, a private network on-the-move can be deployed using portable RAN and core elements integrated into vehicles or temporary sites. This enables seamless connectivity for PPDR operations. At the edge, MEC nodes host localized services to minimize latency and reduce backhaul requirements. MEC provides localized services such as video streaming, object detection, and LiDAR data processing, reducing latency and improving efficiency.

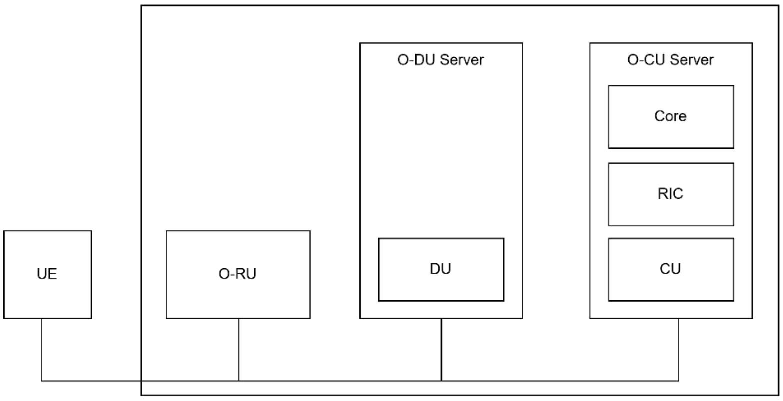


Figure 31 : High-level architecture of the independent private network (P3)

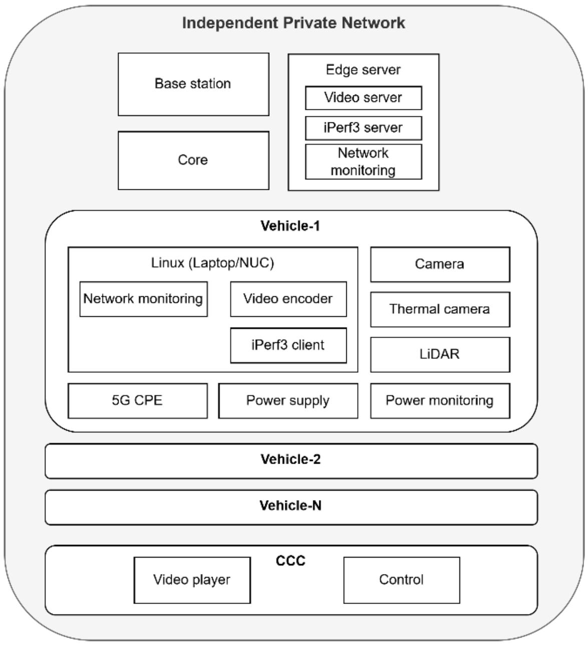


Figure 32 : Main components of the independent private network in P3

2.5.2 Deployment and implementation details

2.5.2.1 *Application Design*

The P3 use case develops adaptive live video streaming, network and power monitoring applications (described in Section 2.4.2). These applications demonstrate how on-the-move connectivity enables reliable operation and coordination in dynamic mission-critical environments.

2.5.2.1.1 Live video streaming

The live video streaming architecture is designed to deliver real-time content with high reliability and low latency in the private network. The system consists of the encoder and the video server which is in the edge.

The video encoder is FFmpeg which captures and compresses raw video into efficient formats suitable for streaming. To enhance adaptability, the encoder can be configured with adaptive bitrate (ABR) functionality. ABR dynamically adjusts the video bitrate based on network conditions, ensuring uninterrupted playback even when bandwidth fluctuates.

The video server is MediaMTX and it is located in the private network's edge server. MediaMTX is responsible for managing incoming streams, handling client connections, and redistributing videos to viewers in the private network.

For transmission, the system supports multiple protocols including RTMP, SRT, and RTSP. RTMP is widely used for compatibility with existing streaming platforms, while SRT provides secure, low-latency transport optimized for unpredictable networks. RTSP offers flexibility for real-time applications and integration with IP cameras. The choice of protocol can be tailored to the deployment environment and application requirements.

2.5.2.2 *Devices, sensors and supporting equipment/software*

Details on the connectivity of digital infrastructure in Table 25.

Table 25 : Equipment for P3 use case

Category	Component	Technical Details	Units
Sensor	Camera	RGB camera	1
Network device	5G modem	Teltonika Altos	1-2
Hardware	Power monitor	Carlo Gavazzi/Otii ACE/Shelly Plug S Gen3	1
Software	iPerf3 client	Network traffic generator	1
Software	iPerf3 server	Network traffic generator	1
Software	Qosium Probe	Network traffic monitoring	2
Software	Qosium Scope	Network traffic monitoring	1
Software	Video encoder	FFmpeg	2
Software	Video player	Mpv	1
Software	Video server	MediaMTX	1
Software	Database	InfluxDB/Storage	1
Software	Visualization	Grafana	1

2.5.3 Network infrastructure

5GTN test network sites are Espoo, Oulu and Sodankylä in Finland. In the AMAZING-6G use cases tests are performed in Oulu (lab with indoor and outdoor cells) and Sodankylä (arctic test area). In the 5GTN radio networks include Carrier-grade 3GPP 5G NR (NG-RAN) and open-source O-RAN solutions (commercial disaggregated). Non-3GPP solutions Wi-Fi and NTN provide short-range wireless network systems and enablers with satellite communication links. We have permission for 5G NR licensed frequencies for R&D purposes. Frequency bands are 5GNR: 3.5 GHz (bandwidth : 60 MHz), 3.9 GHz (bandwidth : 100 MHz), 26 GHz (bandwidth : 800 MHz). Open5GS instances are used for 5G core.

The O-RAN architecture and interfaces introduce additional flexibility into the RAN management framework as well as in the development of P3. The open interfaces in the virtualized implementation with the RIC controller provide the required platform and means for intelligent centralized control going beyond the functionality of 3GPP NG-RAN. The O-RAN architecture hierarchy is divided to SMO, Near-RT RIC, and E2 node comprising O-RU, O-DU and O-CU. Roughly these levels introduce different processing times on the control loops and enable optimization methods i.e. with energy efficiency. The P3 experiments are considered to use one outdoor gNB with single UE modelling one of the members in search and rescue crew. Another UE can be used to produce additional traffic in the scenario for modelling on-site congestion.

From the network perspective, P3 focuses on service prioritization i.e. transmitting the most important data from the emergency unit in the field towards CCC. This can be done by using QCIs or by allocating dedicated network slice for the specific service/s in O-RAN.

2.5.4 Use case enablers

Table 26 lists the enablers for the use case.

Table 26 : Enablers of P3 use case

Domain & Enablers Reference Task3.x	Enabler	Sub enabler/ UC Related Functionalities
T3.1	Network slicing	Integrated private network is based on network slicing.
T3.3	CAMARA APIs Quality on Demand	QoD API is used for optimizing QoS for the search and rescue team in the field.
T3.3	CAMARA APIs Energy management	Energy management API is used for optimizing energy usage for the search and rescue team in the field.

2.5.5 KPIs definition

Table 27 lists the KPIs for the use case.

Table 27 : KPIs for P3 use case

KPI name	Description/KPI definition	Scenario/profile	KPI target
User-Experienced data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time	-	>20Mbps Uplink >100Mbit/s Downlink
Network latency	Time between the source node sends a data packet to when the destination node receives it	-	<30ms
Reliability and Availability	Percentage of time the service can be delivered	-	> 99.999
Coverage	Geographic area where a network signal can be received and used by a device	-	200m radius

2.5.6 KVIs definition

Table 28 introduces the KVIs for the use case.

Table 28 : KVIs for P3 use case

KVI name	Description/KVI definition	KVI target
Maintain satisfying quality of experience for video services in CCC	Using network slicing to ensure and maintain video service continuity when streaming from avalanche site towards CCC	Decrease video stalls or erroneous packets
Network operational cost savings through multi-connectivity	Using the most optimal available communication network configuration to ensure the best possible connection.	Cost reduction ≥10%

2.5.7 Description of the trial setup

Table 29 describes the pre-trial and trial setup of the use case scenario with slicing

Table 29 : P3 pre-trial and trial setup (scenario with slicing)

Trial P3.1		Emergency private B5G/6G communication using slicing
Trial Infrastructure / Venue	5GTN test network Oulu Finland	
Trial Description	An integrated private network using slicing will be set up. The slice will be configured to support mission critical services. Multiple users can access the private network and utilize e.g., video service that is exclusively available within this network.	
Technical Setup	**System Components**	Benetel RU, Acceleran DU, Acceleran CU, Acceleran near-RT RIC, Open5Gs core. UEs
	System Configuration	A static integrated private network using slicing will be set up on the 5GTN Oulu test site.
Pre-Trial execution (initial phase, included in this deliverable, section 4.5)	**Pre-conditions**	A private slice setup and UE can connect to it
	Trial Steps	- Connect UE to the slice - Measure throughput, delay, packet loss, power consumption Change slice configuration and repeat measurements
	Methodology	Measuring slice performance in the private network using static location. Different traffic models (iPerf3, video) and different slice configurations will be tested.

	Technical Enablers	Communication Enablers • Network slicing Application enablers and AI • CAMARA APIs Quality on Demand • CAMARA APIs Energy management
	Expected Outcome	UE can connect to the private slice, access and utilize selected services that are exclusively available within the slice.
Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	UE can connect to the slice, access and utilize selected services that are exclusively available within the slice. Configure slice based on the pre-trial tests
	Trial Steps	• Two UEs connect to the private slice • UEs can access the slice and use the slice services • One UE connect to the public slice and tries to access the service without success Measure moving UE performance in the slice (UE send live video)
	Methodology	Throughput, delay or RTT, jitter, packet loss, availability,
	Complementary Measurements	Power consumption
	Calculation Process	UL/DL latency and throughput measured using Qosium
Technical Enablers	**Communication Enablers**	Network slicing
	Application enablers and AI	• CAMARA APIs Quality on Demand • CAMARA APIs Energy management
Expected Outcome	UE can connect to the private slice, access and utilize selected services that are exclusively available within the slice. UEs in the public slice cannot access the services.	

Table 30 describes the setup for the use case scenario with private network.

Table 30 : P3 pre-trial and trial setup (scenario with private network)

Trial P3.2		**Emergency private B5G/6G communication using a private network**
Trial Infrastructure / Venue	5GTN test network Oulu Finland	

Trial Description	An integrated private network using static private network architecture based on Open RAN will be set up. The network will be configured to support mission critical services. Multiple users can access the private network and utilize e.g., video service that is exclusively available within this network.	
Technical Setup	**System Components**	Benetel RU, Acceleran DU, Acceleran CU, Acceleran near-RT RIC, Open5Gs core. UEs
	System Configuration	A static integrated private network using static private network will be set up on the 5GTN Oulu test site.
Pre-Trial execution (initial phase, included in this deliverable, section 4.5)	**Pre-conditions**	A private network setup and UE can connect to it
	Trial Steps	- Connect UE to the private network - Measure throughput, delay, packet loss, power consumption
	Methodology	Measuring private network performance using static location. Different traffic models (iPerf3, video) and different slice configurations will be tested.
	Technical Enablers	Application enablers and AI • CAMARA APIs Quality on Demand • CAMARA APIs Energy management
	Expected Outcomes	UE can connect to the private network, access and utilize selected services that are exclusively available within the network.
Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	UE can connect to the network, access and utilize selected services that are exclusively available within the network.
	Trial Steps	• UE connects to the private slice • Network is moving and UE can access it • Measure UEs performance in the moving network (UE send live video)
	Methodology	Throughput, delay or RTT, jitter, packet loss, availability,
	Complementary Measurements	Power consumption
	Calculation Process	UL/DL latency and throughput measured using Qosium
Technical Enablers	**Application enablers and AI** • CAMARA APIs Quality on Demand • CAMARA APIs Energy management	

Expected Outcome	UE can connect to the private network, access and utilize selected services that are exclusively available within the network also when network is moving.

2.6 P4 Arctic area search and rescue operation

2.6.1 Description of the Use Case

Arctic Area Search and Rescue Operation aims to provide effective ways of using B5G/6G connectivity to communicate between First Responders (FR) in the field and the CCC to achieve fast situational awareness. In case of natural disasters such as an avalanche in an arctic area, immediate and effective rescue response is critical for locating missing people with the help of enhanced connectivity by the rescue team. A pilot is planned to demonstrate the use case at the Sodankylä airport test track (Sod5G) and in the Luosto area in Lapland, Finland. Arctic Area Search and Rescue Operation aims to provide effective ways of using B5G/6G connectivity to communicate between FR in the field and the CCC to achieve fast situational awareness. In case of natural disasters such as an avalanche in an arctic area, immediate and effective rescue response is critical for locating missing people with the help of enhanced connectivity by the rescue team. A pilot is planned to demonstrate the use case at the Sodankylä airport test track (Sod5G) and in the Luosto area in Lapland, Finland.

The high-level use case description is provided in Figure 33. In high level, we have two actors FR and CCC located on- and remote site, respectively. eSled is equipped with the instrumentation depicted in previous subsection, and CCC is in charge of supervising and instructing the system on remote distance. The connectivity between FR and CCC is done using B5G/5G, Wi-Fi being the alternative communication solution in local area. The use case actors FR and CCC are linear to two main instances of P2, a vehicle and command and CCC depicted in Figure 28 and Figure 29.

The use case event is also shown in Figure 33, and progresses as follows. An avalanche has occurred in the mountain area with uncertain information of possible victims. CCC in charge of the rescue operation sends a rescue unit to the area using eSled electrical snowmobile with carry-on sensor instrumentations capable of monitoring the area and terrain changes after the avalanche. The rescue unit consisting of first responder(s) interconnects from on-site to CCC using the best available connectivity powered by B5G, Wi-Fi, or NTN depending on the network coverage and service requirements. Data and service prioritization plays an essential role in weak signal/coverage areas, where all the data from various sensor devices cannot be transmitted to CCC in real-time or within QoS requirements. Visualization of the data from various sensor devices as well as network performance indicators will help the viewer to understand the benefit and adaptiveness of the developed system in the use case demonstrations and pilots.

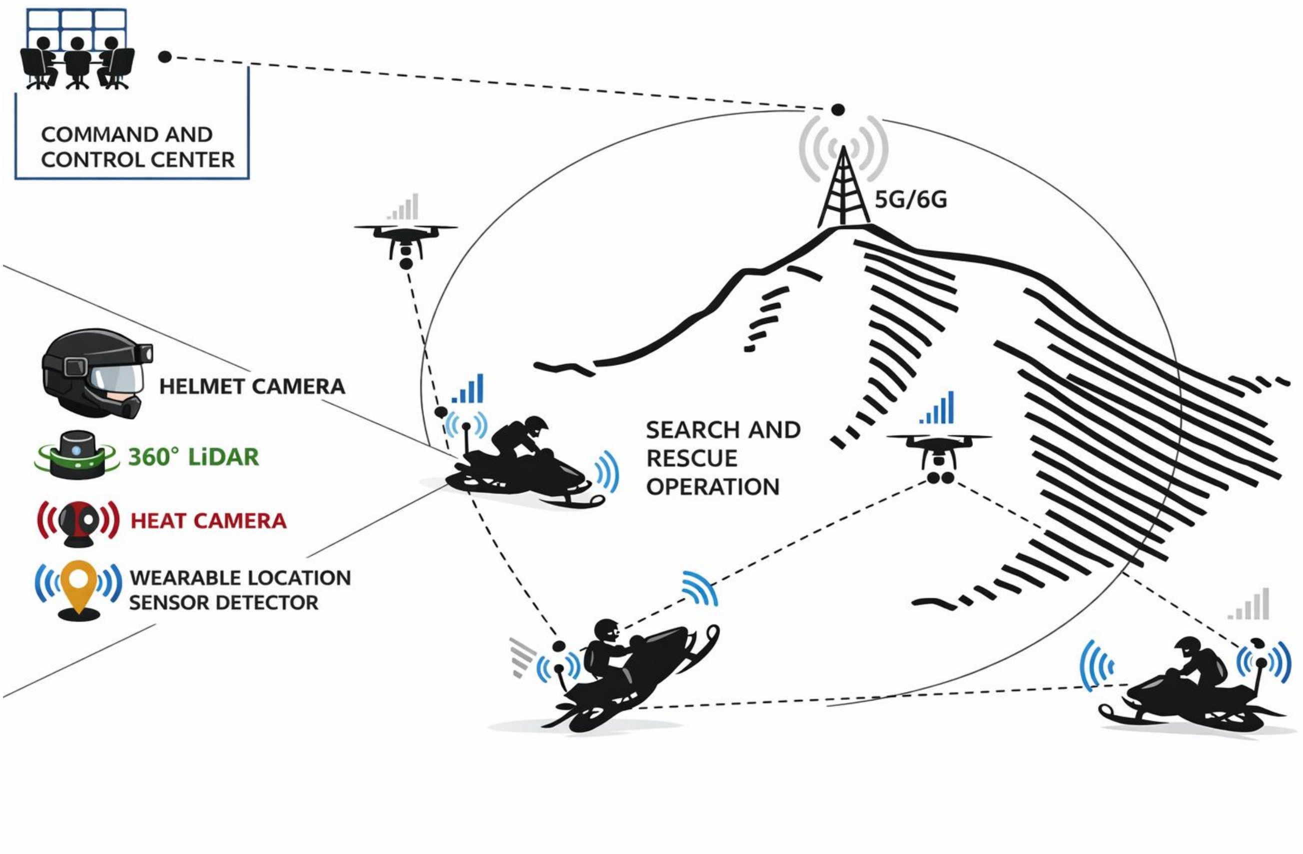


Figure 33 : Use case overview for Arctic Area Search and Rescue Operation (P4)

2.6.2 Deployment and implementation details

The P4 use case integrates applications from the P2 and P3 use cases (described in 2.4.2 and 2.5.2) and integrates them into a mobile test bed, for example to the eSled snow mobile. These applications are tested in demanding arctic environment in this use case. The use case also creates a view of the current situation in the eSled environment and sends the processed video stream to the CCC.

2.6.2.1 *Application Design*

FMI is responsible of deploying on-board monitoring systems and local communications systems, hosting Sodankylä test track, CCC operator and drone operator. It will define the accident site rescue operation FR. FMI is not rescuing operator, but the personnel have experience and induction in voluntary rescue operations. FMI will provide measurement devices (e.g. video camera, LiDAR, thermal camera, wearable sensor monitoring) for the FR unit, along with monitoring data collection unit and CCC monitoring equipment. The profile of detected (avalanche) site as a combination of measurement systems will be provided. The main development site of use case is FMI Sodankylä test track, with private 5G test network and a variety of meteorological monitoring instrumentation. Part of the work will be conducted in Luosto skiing center (with partial 5G coverage) and Aurora Powertrains depot in Pyhätunturi (no 5G coverage). Primary FR team vehicle is eSled. The reference and optional platform is drone, and FMI hosts the drone measurements when applicable. Drones/robotic ground vehicles are optional platforms, acting as alternative measurement platform for eSled and can act as CPEs with Wi-Fi).

VTT is responsible of the ICT R&D technology development and is acting as 5GTN operator for Sodankylä test track. It coordinates the design, deployment and evaluation of communication systems (5G, B5G, alternative communication with optional Wi-Fi 6/7 and satellite) with existing and temporary networks in site. It performs pre-testing of the essential components together with P2 and P3 use cases.

Aurora Powertrains provides the eSled used in the use case. It is acting as eSled operator and is responsible of the eSled battery systems management. It hosts the eSled fleet and designs and develops the alternative power source of measurement and communication systems based on eSled battery systems.

2.6.2.2 *Devices, sensors and supporting equipment/software*

Details of the digital infrastructure in Table 31.

Table 31 : Equipment for P4 use case

Category	Component	Technical Details	Units
Sensor	Camera	Pilot helmet camera/360 camera; USB web camera Logitech or Insta360 X5	2
Vehicle	eSled/Robotic vehicle	Electric snowmobile by Aurora powertrains or Robotic vehicle	2
Hardware	Sensor back-bag	Sensor instrumentation in the back-bag, embedded with fixed installation to eSled trunk box.	1
Sensor	GPS tracker	Ardusimple GPS RTK Simplertk3b	2
Sensor	LiDAR	Oyster Os1-128 or Velodyne VLP-16	2
Sensor	Heat camera	Thermal Master P2	1
Sensor	Spectrum analyzer	Aaronia	1
Hardware	First responder portable screen	Denver PMO-15601 Windows tablet; Lamina Tablet	1
Hardware	Gimbal	DJI Ronin-SC	1

2.6.3 Network infrastructure

5GTN test network sites are Espoo, Oulu and Sodankylä in Finland. In the AMAZING-6G use cases tests are performed in Oulu (lab with indoor and outdoor cells) and Sodankylä (arctic test area). In the 5GTN radio networks include carrier-grade 3GPP 5G NR (NG-RAN) and open-source O-RAN solutions (commercial disaggregated). Non-3GPP solutions Wi-Fi and NTN (inherited from P2/P3) provide short-range wireless network systems and enablers with satellite communication links. We have permission for 5G NR licensed frequencies for R&D purposes. Frequency bands are 5GNR : 3.5 GHz (bandwidth : 60 MHz), 3.9 GHz (bandwidth : 100 MHz), 26 GHz (bandwidth : 800 MHz). Open5GS instances are used for 5G core.

2.6.4 Use case enablers

Table 32 lists the enablers for the use case.

Table 32 : Enablers of P4 use case

Domain & Enablers Reference	Enabler	Sub enabler/UC Related Functionalities
T3.1	Network performance monitoring and control	Accurate time synchronization between the nodes of interest Collect real-time performance indicators from the system
T3.1	Wi-Fi integration	Multiple networks are employed to increase resilience and guarantee reliable connectivity
T3.3	CAMARA APIs Quality on Demand (QoD)	QoD API is used to ensure QoS requirements are met when having seamless connectivity in between different connectivity solutions
T3.3	CAMARA APIs Energy management	Energy management API can be used for monitoring and selecting energy-savvy configuration for the used network and services in order to reduce carbon footprint

2.6.5 KPIs definition

Table 33 introduces the KPIs for the use case.

Table 33 : KPIs for P4 use case

KPI name	Description/KPI definition	Scenario/profile	KPI target
Network service latency	Time between the source node sends a data packet to when the destination node receives it	-	10 ms
User-Experienced data rate	Number of bits, originating from the source node, correctly received by the destination node over a certain period of time	-	>20Mbps Uplink >100Mbit/s Downlink
Network latency	Time between the source node sends a data packet to when the destination node receives it	-	<30ms
Reliability and Availability	Percentage of time the service can be delivered	-	99.999

2.6.6 KVIs definition

Table 34 lists the KVIs for the use case.

Table 34 : KVIs for P4 use case

KVI name	Description/KVI definition	KVI target

Maintain satisfying quality of experience for video services in CCC	Using multi-RAT connectivity to ensure and maintain video service continuity when streaming from avalanche site towards CCC	Decrease video stalls or erroneous packets
Network operational cost savings through multi-connectivity	Using the most optimal available communication network, or combining multiple networks, to ensure the best possible connection.	Cost reduction ≥10%

2.6.7 Description of the trial setup

Table 35 describes the pre-trial and trial setup of the use case, 1st scenario.

Table 35 : P4 pre-trial and trial setup (1st scenario)

P4_AASR_MVS_1	Arctic area search and rescue operation	
Trial Infrastructure / Venue	Sodankylä airport test track (Sod5G)	
Trial Description	Continuous uploading all sensor data from the First Encounter Team (FET) communication system to the CCC in ideal communication entity	
Technical Setup	**System Components**	Insta360 X5, Ardusimple GPS RTK Simplertk3b Oyster Os1-128 or Velodyne VLP-16, Thermal Master P2 Aaronia, Denver PMO-15601
	System Configuration	A static communication link composed and evaluated
Pre-Trial execution (initial phase, included in this deliverable, section 4.6)	**Pre-conditions**	Communication entities established into ideal conditions, minimum distance and environmental interference
	Trial Steps	Establish measurement system with all monitoring instruments. Measure throughput, delay, packet loss, power consumption Enable measurement systems one by one and repeat measurements.
	Methodology	Measuring performance in the private network using static location. Different traffic models (iPerf3, video) and different measurement configurations will be tested.
	Technical Enablers	Network performance monitoring and control, Wi-Fi integration
	Expected Outcomes	Reference performance and resource consumption of each monitoring system remote operation estimated.

Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	FET and CCC communication link can be established. Access and utilize selected measurements, configure the setup based on the pre-trial tests
	Trial Steps	All measurement systems employed simultaneously. Each measurement system operating individually. Selected sensor combinations evaluated, if found essential.
	Methodology	Throughput, delay or RTT, jitter, packet loss, availability,
	Complementary Measurements	Power consumption
	Calculation Process	UL/DL latency and throughput measured using iPerf3/ping
Technical Enablers	**Communication Enablers**	Network performance monitoring and control
Expected Outcome	Communication entities established into ideal conditions, minimum distance and environmental interference	

Table 36 describes the pre-trial and trial setup of the 2nd use case scenario.

Table 36 : P4 pre-trial and trial setup (2nd scenario)

P4_AASR_MVS_2		Artic area search and rescue operation
Trial Infrastructure / Venue	Sodankylä airport test track (Sod5G)	
Trial Description	Continuous uploading all sensor data from FET communication system to CCC in challenging communication entity, static; FET in optimal position in network service area. Adaptation of services	
Technical Setup	**System Components**	Insta360 X5, Ardusimple GPS RTK Simplertk3b Oyster Os1-128 or Velodyne VLP-16, Thermal Master P2 Aaronia, Denver PMO-15601, Sensor back-bag
	System Configuration	A static communication link composed and evaluated
Pre-Trial execution (initial phase,	**Pre-conditions**	Communication entities established into outdoor configuration, short distance and trivial environmental interference

included in this deliverable, section 4.6)	**Trial Steps**	Establish measurement system with all monitoring instruments. Measure throughput, delay, packet loss, power consumption Enable measurement systems one by one and repeat measurements.
	Methodology	Measuring performance in the private network using static location. Different traffic models (iPerf3, video) and different measurement configurations will be tested.
	Technical Enablers	Network performance monitoring and control, Wi-Fi integration
	Expected Outcome	Reference performance and resource consumption of each monitoring system remote operation estimated.
Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	FET and CCC communication link can be established. Access and utilize selected measurements, configure the setup based on the pre-trial tests
	Trial Steps	All measurement systems employed simultaneously. Each measurement system operating individually. Selected sensor combinations evaluated, if found essential.
	Methodology	Throughput, delay or RTT, jitter, packet loss, availability,
	Complementary Measurements	Power consumption
	Calculation Process	UL/DL latency and throughput measured using iPerf3/ping
Technical Enablers	**Communication Enablers**	Network performance monitoring and control
Expected Outcomes	Communication entities established into outdoor configuration, short distance and trivial environmental interference	

Table 37 describes the pre-trial and trial setup of the 3d use case scenario.

Table 37 : P4 pre-trial and trial setup (3rd scenario)

P4_AASR_MVS_3	Artic area search and rescue operation
Trial Infrastructure / Venue	Sodankylä airport test track (Sod5G)

Trial Description	Continuous uploading all sensor data from FET communication system to CCC in challenging communication entity; FET moving away from network service area. Adaptation of services	
Technical Setup	**System Components**	Insta360 X5, Ardusimple GPS RTK Simplertk3b Oyster Os1-128 or Velodyne VLP-16, Thermal Master P2 Aaronia, Denver PMO-15601, eSled/Robotic vehicle Sensor back-bag
	System Configuration	A mobile communication link composed and evaluated
Pre-Trial execution (initial phase, included in this deliverable, section 4.6)	**Pre-conditions**	Communication entities established into outdoor configuration, short distance origin, FET moving away from network service area. Adaptation of services and moderate environmental interference
	Trial Steps	Establish measurement system with all monitoring instruments. Measure throughput, delay, packet loss, power consumption Enable measurement systems one by one and repeat measurements.
	Methodology	Measuring performance in the private network, while FET moving away from network service area. Different traffic models (iPerf3, video) and different measurement configurations will be tested.
	Technical Enablers	Network performance monitoring and control, Wi-Fi integration
	Expected Outcomes	Reference performance and resource consumption of each monitoring system remote operation estimated.
Trial Execution (final phase, to be included in final deliverable D2.2)	**Pre-conditions**	FET and CCC communication link can be established. Access and utilize selected measurements, configure the setup based on the pre-trial tests
	Trial Steps	All measurement systems employed simultaneously. Each measurement system operating individually. Selected sensor combinations evaluated, if found essential.
	Methodology	Throughput, delay or RTT, jitter, packet loss, availability,
	Complementary Measurements	Power consumption

	Calculation Process	UL/DL latency and throughput measured using iPerf3/ping
Technical Enablers	**Communication Enablers**	Network performance monitoring and control
Expected Outcome	Communication entities established into outdoor configuration, short distance origin, FET moving away from network service area. Adaptation of services and moderate environmental interference. Environmental: Reduced carbon footprint through novel eSled battery-powered snowmobiles in search and rescue operations. Reduced energy consumption in selected components of the use case through dynamic network and application orchestrations. Societal: Reduced search and rescue time through the usage of novel devices and fast co-operation between CCC and rescue team, leading to a higher survival rate. Reduced hazards for rescue workers through the usage of novel devices and fast co-operation between CCC and rescue team, leading to a higher survival rate. Economic: Lower costs and more efficient ways to conduct search and rescue operations through wireless technology.	

2.7 P5 Emergency private B5G/6G communication on-the-move

P5 use case focuses on the design, deployment, and validation of a rapidly deployable private B5G/6G tactical communication network for Public Protection and Disaster Relief (PPDR) operations. The primary aim is to ensure resilient, low-latency, and mission-critical communications in situations where public networks are unavailable, congested, or partially destroyed. The solution targets on-the-move operations, enabling emergency responders to establish local connectivity within minutes and maintain operational continuity under dynamic and harsh conditions. The approach is aligned with current 3GPP Mission Critical Services specifications and with the vision promoted under the Smart Networks and Services Joint Undertaking (SNS JU) program, which identifies 5G and 6G as key enablers for next-generation PPDR systems [5], [6]. The initial testing phase will be conducted in a controlled laboratory environment in order to thoroughly assess the technical feasibility of the proposed solution and to validate that all system components and interconnections are correctly implemented and fully operational. This approach allows for the early identification and mitigation of potential integration issues under stable and reproducible conditions.

Subsequently, during the trial phase, the solution will be deployed and evaluated in a geographically isolated area characterized by minimal radio coverage, a lack of critical communication infrastructure, or public network connectivity. This environment is intentionally selected to reduce external interference and to ensure that the system's performance can be accurately assessed under near-worst-case radio conditions, thereby providing a realistic and reliable validation of its operational capabilities.

For the execution of the trial in the isolated environment, a portable B5G radio access system will be integrated into a dedicated tactical vehicle, enabling mobility, rapid deployment, and reliable operation at the target test location. This system is shown in Figure 34.

Figure 34 : Dedicated tactical vehicle used in the April 2026 pre-trial (P5)

The use case emphasizes operational autonomy at the network edge by deploying only essential RAN and Core Network components within the mission area. By combining portable B5G radio access, local SA Core Network functions, edge computing, and optional non-terrestrial (satellite) backhaul, the system supports uninterrupted Mission Critical Services (MCx) regardless of backhaul availability. The use case also investigates advanced B5G/6G features such as end-to-end network slicing, prioritization mechanisms, and Multicast and Broadcast Services (MBS) to efficiently serve heterogeneous PPDR stakeholders with strict performance and reliability requirements.

2.7.1 Description of the Use Case

Emergency private B5G/6G communication on-the-move is a mobile, mission-critical communication system designed to provide localized high-performance connectivity in emergency and disaster scenarios. The use case supports Mission Critical Push-to-Talk (MC-PTT), Mission Critical Video (MC-Video), and Mission Critical Data (MC-Data) services [7], enabling coordinated operations between multiple responder groups operating in the field.

The tactical network (see Figure 35) is deployed from a utilitarian truck hosting the core elements of the communication infrastructure. A portable B5G cell site is used to create an outdoor “tactical bubble” that extends coverage over the intervention area. The truck hosts a B5G Baseband Unit (BBU), a local B5G SA Core Network, edge computing servers and a satellite backhaul terminal. This configuration allows the system to operate either in connected mode, leveraging a satellite backhaul to reach a macro B5G Core Network, or in fully autonomous mode when the backhaul is unavailable.

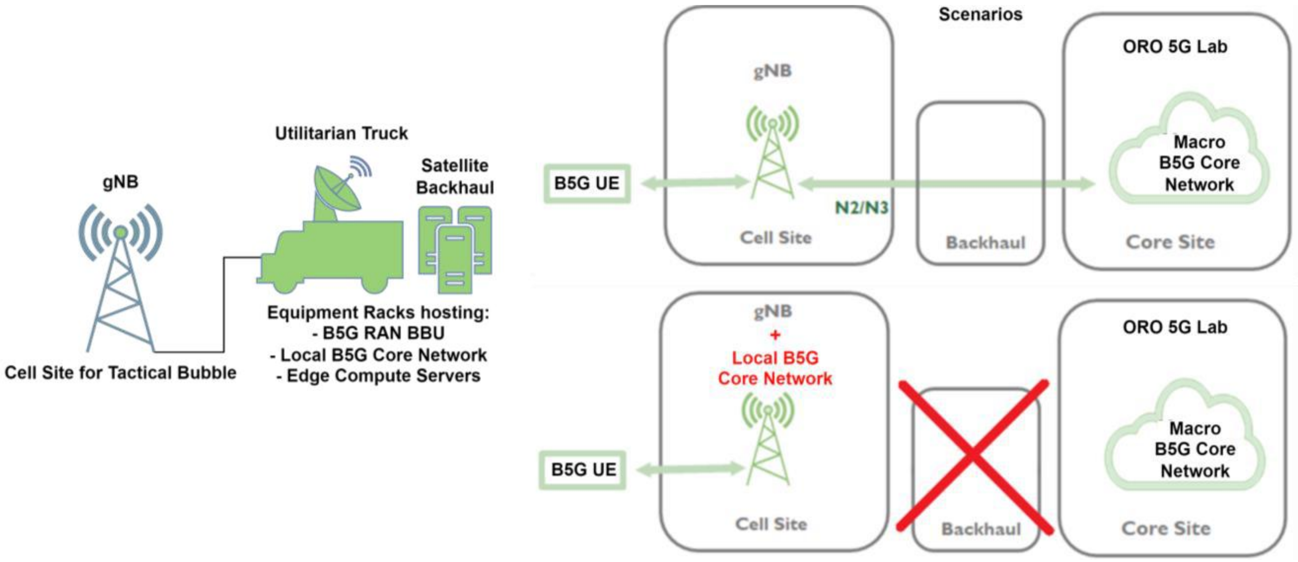


Figure 35 : P5 use case architecture

The satellite backhaul, when available, provides connectivity to the Internet (for the standalone network variant) and to ORO's macro B5G SA Core Network located in the Bucharest 5G Lab through the standardized N2 and N3 interfaces. For security reasons, access to ORO's macro B5G SA Core is done through a secured VPN tunnel over the Internet connection provided by the satellite link. This ensures protected transport of signalling and user traffic in the mission critical setup.

If a dedicated Very Small Aperture Terminal (VSAT) link is used (subject to feasibility), the Internet connectivity can operate without additional encryption, as it runs over a private network with limited capacity and controlled access.

When the satellite link is unavailable or shadowed, the tactical gNB connects only to the local B5G SA Core Network and edge computing resources, ensuring service continuity and local control of all mission-critical functions.

To accommodate the diverse communication needs of PPDR actors, the use case implements B5G end-to-end network slicing across RAN, transport and core domains.

The use case is piloted in two complementary operational scenarios. In the first scenario, the satellite backhaul is available and the tactical gNB is directly connected to the macro B5G SA Core Network, enabling extended connectivity and centralized coordination. In the second scenario, the satellite backhaul is unavailable and the system operates in standalone mode using the local core and edge compute infrastructure. This dual-mode approach demonstrates the resilience and adaptability of the proposed B5G/6G architecture in real PPDR conditions. Moreover, the system can operate in a third mode with the standalone 5G network accessing the Internet and cloud-based services over satellite backhaul.

The use case introduces several innovations relevant to next-generation PPDR communications. These include the use of non-terrestrial networks for backhaul connectivity between local gNBs and a macro B5G Core Network, enabling deployment in remote or infrastructure-degraded areas. An interworking mechanism between macro and local B5G SA Core Networks supports seamless operation and service continuity across connected and disconnected modes. In addition, the implementation of B5G-Advanced Multicast and Broadcast Services over a sliced tactical network enhances scalability and efficiency in delivering mission-critical information.

The main challenges addressed by the use case include maintaining low-latency and reliable signalling over satellite backhaul links and integrating local and macro core network functions without service disruption. These challenges are compounded by the mobility, limited infrastructure, and unpredictable conditions inherent to emergency response environments.

2.7.2 Deployment and implementation details

2.7.2.1 *Design of the application*

The application designed for Use Case P5 addresses the delivery of MCx services over a private B5G/6G tactical network deployed in PPDR operations. The application layer is responsible for enabling reliable group-based communication, real-time information exchange and operational coordination among heterogeneous responder teams, while remaining agnostic to the availability of external backhaul connectivity.

The application is designed following a modular and service-oriented approach, where mission-critical functions are decoupled from transport and radio specifics but tightly integrated with network slicing and edge computing capabilities. It operates across specialized B5G user equipment, edge and cloud-hosted service components and control interfaces exposed by the local and macro core networks. This design ensures that application behaviour dynamically adapts to network conditions, user roles, and operational priorities defined by PPDR procedures.

At a logical level, the application architecture (see Figure 36) is composed of three main layers: the user-facing MCx clients, the mission-critical service platform, and the network exposure and control layer. MCx client applications run on ruggedized B5G UEs used by field personnel and support MC-PTT, MC-Video, and MC-Data services.

The mission-critical service platform is deployed both on the cloud and at the network edge, co-located with the local B5G SA Core Network when operating in standalone mode. When backhaul connectivity exists, selected control and monitoring functions may synchronize with centralized platforms hosted in the macro network.

The network exposure and control layer provides the interface between the application and the underlying B5G/6G network. Through standardized APIs and control hooks, the application interacts with network slicing management, QoS enforcement mechanisms, and MBS configuration functions. This allows the application to request differentiated connectivity for specific MCx services and user groups, and to react to changing network conditions in real time.

The application natively supports MC-PTT, MC-Video, and MC-Data services as defined by 3GPP specifications. Group-based communication is a core design element of the application. The application includes dynamic group management functions that allow the creation, modification, and dissolution of operational groups based on mission needs.

Edge computing plays a central role in the application design. By hosting mission-critical application components at the edge, the system achieves low latency, reduced dependency on external connectivity and improved resilience.

When operating without backhaul connectivity, the application maintains full functionality using locally available resources and data. When connectivity is restored, synchronization mechanisms shall allow selective exchange of logs, recordings and status information with centralized systems, ensuring continuity of records and post-incident analysis without disrupting ongoing operations.

Security is addressed through end-to-end authentication, authorization, and encryption mechanisms aligned with PPDR requirements.

2.7.2.2 *Devices, sensors and supporting equipment /software*

Table 38 presents the list of devices used for the deployment of the P5 use case, considering both IoT devices and 5G network devices.

Table 38 : Devices used in P5 deployment

Category	Component	Technical Details	Units
5G Core and vBBU	OAIBOX MAX 	OAIBOX MAX is an "in-a-box" open-source 5G testing platform that integrates an OAI gNB with CN5G (5G Core) and provides a dashboard and lab procedures to start/stop and validate 5G connectivity [8]	1
RU - SDR module	USRP N310 	USRP N310 is a networked software-defined radio (SDR) platform with multiple RX/TX channels, designed to support remote operation and software-based waveform development using Ettus Research's UHD/RFNoC ecosystem [9]	1
Satellite backhaul	Starlink Performance Gen 2 kit 	The Starlink Performance Gen 2 kit is a portable satellite terminal that is used as an alternate backhaul link by delivering IP connectivity between a remote site and network via its satellite uplink/downlink [10]	1
Satellite backhaul	Starlink Mini kit 	The Starlink Mini kit is a compact satellite terminal that can also serve as a back-up backhaul for the private 5G network.	1

2.7.3 Network infrastructure and functional components

The network infrastructure proposed for P5 is reconfigured to support a rapidly deployable, mission-oriented private B5G/6G communication system designed for PPDR operations under degraded or unavailable public network conditions. While leveraging the same foundational 5G SA principles validated in the Romanian testbed, the architecture is restructured to prioritize mobility, autonomy, and edge-centric operation rather than fixed smart campus or energy management scenarios.

The proposed infrastructure is based on a portable and self-contained B5G/6G, OAIBOX MAX system that integrates radio access, core network control, user plane processing, and application hosting within a compact deployment footprint. The operational setup targets temporary intervention areas, where the communication system must be activated within minutes and sustain reliable service under dynamic topology changes and limited backhaul availability. The overall deployment context is illustrated in Figure 36.

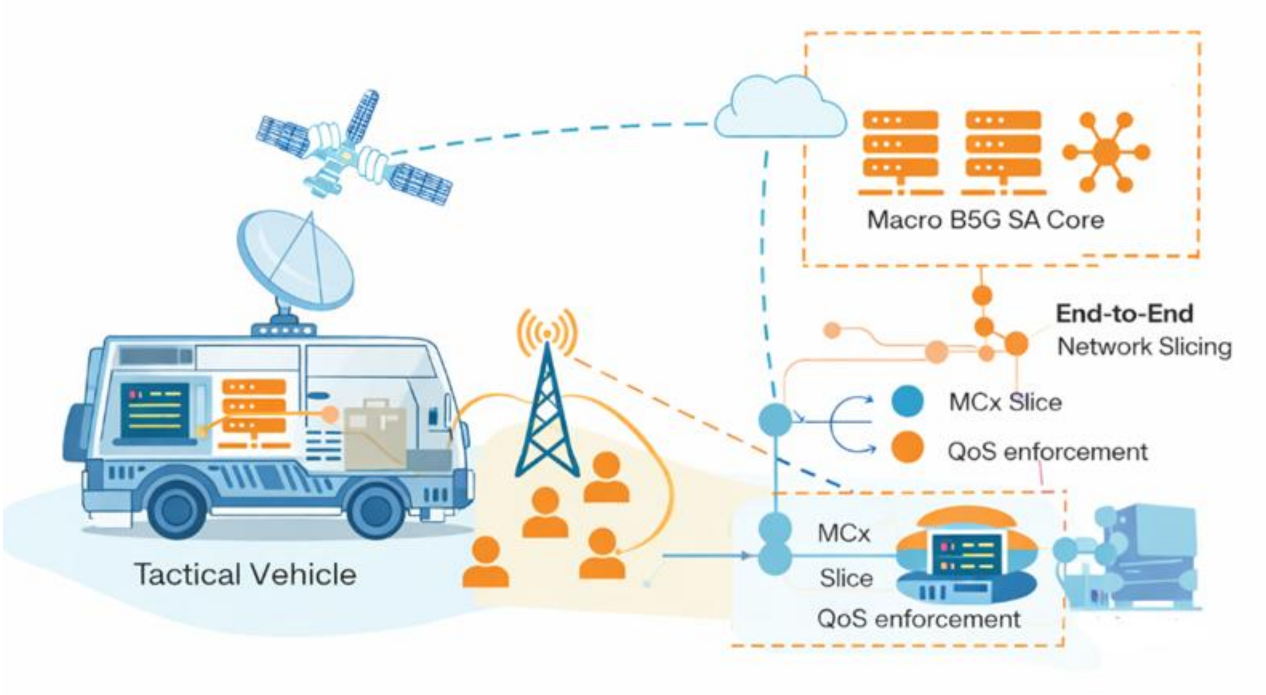


Figure 36 : High-level network infrastructure for P5

At the access layer, the system relies on a transportable B5G gNB providing localized outdoor coverage over the intervention zone. The radio configuration is optimized for rapid installation and supports flexible spectrum usage consistent with PPDR allocations. The gNB terminates both control and user plane interfaces locally, enabling full standalone operation without mandatory dependency on external network elements.

The core network functions are instantiated as a local B5G SA Core Network deployed on edge-grade computing infrastructure hosted within a tactical vehicle. The local core implements the essential 3GPP control plane functions, including access and mobility management, session management, authentication, and policy control, required to sustain MCx services within the mission area. User plane functions are co-located with the control plane to minimize packet traversal delay and to maintain deterministic latency for voice, video, and data services.

The local user plane is configured to provide immediate breakout for application traffic toward edge-hosted services, ensuring that mission-critical data flows remain confined to the tactical domain whenever external connectivity is unavailable. When a non-terrestrial backhaul is present, the local gNB can be connected to a macro B5G SA Core Network hosted in the ORO Bucharest 5G Lab. This interconnection follows standardized N2 and N3 reference points and allows selected control and user plane traffic to be extended beyond the local domain. The dual-core operational model, depicted in Figure 37, enables seamless transition between connected and disconnected modes without reinitialization of user sessions.

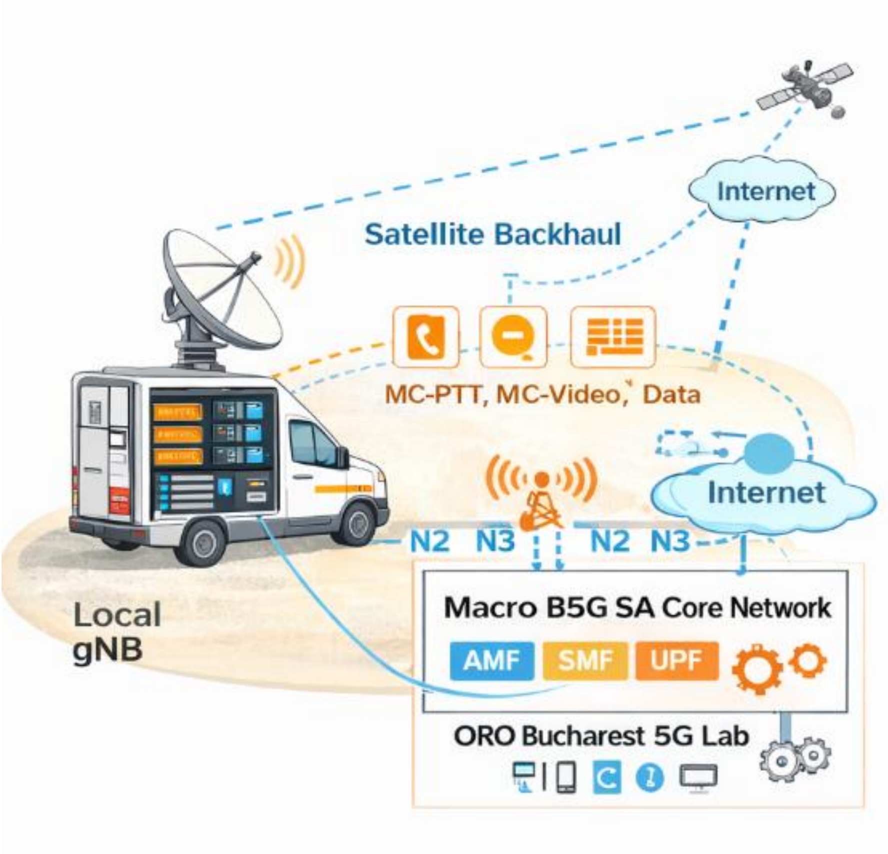


Figure 37 : Local and macro core interworking for P5

Edge and cloud computing play a central role in the P5 infrastructure and is treated as an integral component of the network rather than an auxiliary extension. Compute resources hosted alongside the local core execute will support the MCx application server.

The transport and backhaul segment of the P5 infrastructure is designed to tolerate high latency and intermittent availability. A satellite terminal provides optional connectivity to external networks and centralized systems, but the local network remains fully functional in its absence. Control plane synchronization and data exchange with the macro network are opportunistic and non-blocking, ensuring that local services are not disrupted by backhaul degradation.

2.7.4 Use case enablers

The P5 use case relies on a set of technical enablers that support rapid deployment, autonomous operation, and mission-critical performance of a private B5G/6G tactical network. These enablers are aligned with the overall objective of providing reliable MCx services in emergency scenarios where public networks are unavailable, congested, or partially damaged.

Given that P5 targets on-the-move PPDR operations, the main design principle is operational autonomy at the edge combined with optional integration to a macro network through satellite backhaul. Therefore, the selected enablers focus on communication resource management, edge compute management, telemetry, and remote operational control.

Communication enablers are essential to ensure that the portable gNB and local SA Core Network can be deployed and activated within minutes. Automated gNB configuration and predefined slice templates are used to simplify instantiation of the tactical radio “bubble.” These capabilities are especially important in scenarios where the tactical vehicle is relocated, and the radio parameters must be adapted quickly to local spectrum and coverage conditions.

Communication resource management also includes real-time monitoring of latency, throughput, packet loss and radio load.

Compute-as-a-Service enablers address the need to host mission-critical application components at the edge. In the final phase of P5, the MCx application server will be deployed on edge infrastructure co-located with the local core.

Overall, the technical enablers presented in Table 39, provide the functional foundation for the P5 tactical B5G/6G system.

Table 39 : List of enablers and sub-enablers for P5

Category	Technology enablers	Sub enabler/ UC Related Functionalities
Communication enablers	Communication resource management	Automated gNB configuration. Enables fast instantiation and reconfiguration of portable gNBs deployed on-the-move.
	Communication resource management	Supports real-time monitoring of latency, throughput, and reliability for MCx services under dynamic conditions
Compute-as-a-Service enablers	Compute resource management	Intelligent service instantiation in edge and cloud required for the MCx services.

2.7.5 KPIs definition

Table 40 summarizes the set of KPIs that will be measured during the final trial phase of the P5 use case, scheduled for mid-2027, to quantitatively evaluate the performance of the private B5G/6G tactical network under realistic on-the-move PPDR conditions. The KPIs cover end-to-end latency within the local tactical domain, additional delay introduced by the satellite backhaul and achievable throughput both at the radio interface and toward external IP networks.

Measurements will be performed during live deployments in the isolated trial area, with the system operating in both standalone and satellite-connected modes. KPI collection will rely on a combination of network-native monitoring functions from the B5G Core and gNB, edge-based performance probes and active traffic generation tools deployed on mission-critical user equipment and edge servers.

Table 40 : P5 defined KPIs

KPI name	Description/KPI definition	Scenario/profile	KPI target
Network service latency	Time between the source node sends a data packet to when the destination node receives it	Local tactical B5G/6G network (on-the-move PPDR deployment)	20 ms
Satellite Backhaul Latency	One-way latency introduced by the satellite backhaul segment, measured as the time for a packet to traverse the satellite link between	Satellite-backed PPDR connectivity	30 ms

	the local edge/core and the remote network.		
Downlink User Throughput	Maximum achievable data rate successfully delivered to the user equipment in downlink direction.	Local tactical network (edge-based services)	800Mbps
Uplink User Throughput	Maximum achievable data rate successfully transmitted from the user equipment to the network in uplink direction.	Local tactical network (edge-based services)	100Mbps
Internet Downlink Throughput	Achievable downlink data rate between the local tactical network and external IP networks via backhaul connectivity.	Internet connectivity via satellite backhaul	100Mbps
Internet Uplink Throughput	Achievable uplink data rate from the local tactical network to external IP networks via backhaul connectivity.	Internet connectivity via satellite backhaul	20Mbps

2.7.6 KVIs definition

Table 41 presents the set of KVIs that will be assessed during the final trial phase of the P5 use case, planned for Q2 2027, with the objective of capturing the perceived operational impact of the private B5G/6G tactical network in PPDR on-the-move scenarios. The KVIs focus on how emergency responders and operators evaluate aspects such as operational safety, availability and continuity of mission-critical communications, energy efficiency compared to legacy PPDR systems, reduction of operational downtime, and perceived cost benefits.

During the trial execution, interested stakeholders, including field responders, command personnel, and network operators, will be invited to attend live deployments and system demonstrations in the test area. Following these activities, participants will be asked to complete structured questionnaires tailored to their roles, using predefined questions and Likert-scale scoring. The feedback collected through these questionnaires will be aggregated and analysed to derive the KVIs reported in the table, ensuring a direct link between observed system behaviour during the trials and stakeholder perception of the effectiveness and suitability of the P5 solution in real PPDR operations.

Table 41 : P5 defined KVIs

KVI name	Description/KVI definition	KVI target
Operational Safety Improvement	Measures how emergency responders and command personnel perceive the contribution of the private B5G/6G tactical network to operational safety during PPDR missions, including coordination, situational awareness, and reliability of communications.	At least 75% of respondents rate the perceived safety improvement as “good” or “very good” (≥4 on a 5-point Likert scale), with an average score ≥4.0/5
Mission-Critical Communication Availability	Assesses user and operator confidence in the availability and continuity of communication services during on-the-move operations,	An average score of ≥4.0/5 across availability and reliability questions, with ≥70% of

	including standalone mode without backhaul.	respondents expressing confidence in using the system as the primary communication means during missions
Energy Efficiency Compared to Legacy PPDR Systems	Captures stakeholder perception of reduced energy consumption achieved by replacing legacy PPDR technologies (e.g., TETRA) with a B5G-based tactical communication solution.	At least 65% of respondents report a perceived improvement in energy efficiency (≥4/5)
Reduction in Operational Downtime	Measures operator perception of reduced service downtime and faster restoration of communications due to rapid deployment, local core autonomy, and edge-based operation	At least 70% of operators rate downtime reduction as “good” or “very good” (≥4/5), with an average score ≥3.8/5.
Reduction in Operational and Energy-related Costs	Assesses perceived cost savings related to improved power efficiency, reduced dependency on fixed infrastructure, and minimized service interruptions during PPDR operations.	At least 60% of operators report perceived cost reductions corresponding to ≥10% savings (≥4/5)

2.7.7 Description of the trial setup

Table 42 summarizes the information about the trial setup for P5 use case.

Table 42 : P5 trial setup

Trial P5.1		**Emergency private B5G/6G communication on-the-move**
Trial Infrastructure / Venue	Remote location in Romania, Isolated outdoor area for PPDR deployment.	
Trial Description	Rapidly deployable private B5G/6G tactical network for PPDR. On-the-move operation with local RAN, local SA Core and edge compute. Dual operation modes: Standalone (no backhaul / backhaul used for Internet connectivity) and Satellite-connected gNB.	
Technical Setup	**System Components**	Portable B5G gNB (outdoor tactical cell) Local B5G SA Core Network (AMF, SMF, UPF, PCF, AUSF) Edge computing servers hosting MCx services Satellite backhaul terminals: LEO (Starlink) – mobile deployment Ruggedized B5G UEs
	System Configuration	Standalone SA operation with local control and user plane

		Optional N2/N3 interworking with macro B5G SA Core (ORO Bucharest Lab) End-to-end network slicing
Pre-Trial execution (initial phase, included in this deliverable, section 4.7)	**Pre-conditions**	Portable gNB integrated on tactical vehicle Local SA Core and edge services instantiated Satellite terminals available and configured MCX application running on edge and cloud
	Trial Steps	• Deploy tactical vehicle and portable gNB • Activate local SA Core and edge services • Attach MCx UEs and validate registration • Execute MC-PTT, Video, MC-Data flows • Test satellite connectivity • Measure main KPIs
	Methodology	Measure end-to-end P5 KPIs by running controlled MCx (MC-PTT/Video/MC-Data) traffic sessions in both Standalone and Starlink LEO–connected modes while collecting synchronized RAN/core/edge metrics (under predefined UE mobility and service loads.
	Technical Enablers	Communication Enablers • Preliminary deployment of communication resource management functions • Initial configuration of portable gNB for tactical operation • Basic monitoring of latency and throughput for MCx service validation Compute-as-a-Service (CaaS) Enablers • Instantiation of edge compute resources • Instantiation of MCx application components at the edge or cloud • Basic monitoring of compute resource availability and load
	Expected Outcome	Verified operational readiness of tactical B5G system Functional MCx services without external connectivity Confirmed interworking with satellite backhaul
Trial Execution (final phase, to be included in	**Pre-conditions**	Stable pre-trial configuration validated Final MCx service profiles and slice defined Monitoring and logging tools active

final deliverable D2.2)	**Trial Steps**	Live deployment in isolated area On-the-move operation using tactical vehicle Execute PPDR scenarios with multiple responder groups Switch dynamically between backhaul-connected and standalone modes
	Methodology	Scenario-driven execution (PPDR operational flows) Repeated measurements under load and mobility KPI collection from RAN, core, edge, and UEs Parallel subjective assessment for KVIs
	Complementary Measurements	Satellite link availability and stability Service continuity during backhaul loss
	Calculation Process	Latency Throughput: controlled DL/UL traffic sessions
Technical Enablers	**Communication Enablers**	End-to-end network slicing MCx-optimized user profiles
	Compute-as-a-Service (CaaS) Enablers	Edge and cloud-hosted MCx application execution Local compute resource monitoring Autonomous operation without cloud dependency
Expected Outcome	≤20 ms local tactical network latency Seamless MCx operation in standalone mode Validated satellite backhaul integration Demonstrated resilience and autonomy for PPDR missions	

3 Use case planning

This section presents the planning, phased execution strategy, and risk-aware development approach for the seven use cases defined within the Amazing-6G project, comprising two healthcare scenarios (H1 and H2) and five PPDR scenarios (P1–P5). The described use cases span a wide range of advanced 6G service domains, including wearable and implantable medical systems, AI-enabled remote diagnostics, edge-assisted predictive control, and mission-critical communications for emergency and field operations. For each use case, a structured lifecycle is defined, covering system definition, device procurement, infrastructure and application design, preliminary integration, iterative development cycles, and full trial execution in realistic operational environments. The planning approach ensures progressive validation of key technologies such as NR-RedCap connectivity, edge intelligence, AI-based inference, integrated sensing and communication, and secure multi-domain orchestration. Furthermore, each use case is aligned with a harmonised KPI and KVI collection framework, enabling consistent performance evaluation across heterogeneous scenarios and supporting comparative analysis of system behaviour under varying network conditions and operational constraints. Each use case has used a similar tabular format that helps us follow the progress of the Tasks in WP4. Also, in this section the main risks that have been identified in each use cases have been analysed, and a mitigation plan has been defined.

3.1 H1 planning

The H1 *Wearable ultrasound patch for cardiac function monitoring* Use Case plan is shown in the Table 43. The use case definition, acquisition of the necessary devices and design of the application and infrastructure were performed in the first year of the project. Preliminary integration and first tests have started and will continue until Q2 2026. These experiments serve as a baseline for the 3 pre-trial parts: (1) Ultrasound capture and processing, (2) Energy-assessment, (3) Integrated demonstration. Until the full trial integration by Q3 2027, three optimisation cycles are planned to assess feasibility and make improvements towards the target KPIs. KPIs and KVIs data will be collected for analysis during the experiments in the pre-trial and trial phases.

Table 43 : H1 planning

Phase	Details	Schedule
UC Definition	A pre-trial phase to lay the foundations of the activities and define the Use Case	Q3 2025-done
Devices	Acquisition and delivery of hardware end devices (sensors, redcap devices, etc.)	Q2-Q4 2025-done
Infrastructure & Application Design	Design of energy assessment and integrated demonstration setups within the Hi5 Facility in The Hague. Design of the ultrasound acquisition setup and setup for AI algorithm development in Oslo.	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial and partial integration of key subsystems to verify interoperability.	Q4 2025 – Q2 2026
First Tests & Initial Demonstration	Execute first tests to assess baseline KPIs (energy consumption/battery life, network latency and AI	Q1-Q2 2026

	algorithm execution time). May also serve as a first concept demonstration.	
Final Application Development	Incremental development in 3 iterations, focused on assessing feasibility and refining and improving KPIs.	Q2 2026 –Q3 2027
Full Trial Integration	End-to-end table-top integration of the use case concept, including ultrasound capture, processing, transmission, edge-based processing and presentation on the "clinical backend". Potentially, ultrasound capture and processing (in Oslo) may result in a recorded video and supplied to the B5G system (in The Hague) as a separate step for practical reasons.	Q3 2027
Trial Execution	Conduct full UC trials, including operational scenarios and real-time monitoring.	Q3 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial results.	Q2 2026 –Q4 2027
Final Demonstrations & Dissemination	Present final trial results, publish findings, and perform end-of-project demonstrations.	Q2–Q4 2027

3.1.1 H1 risks and mitigation plan

A few risks have been identified for this use case and the mitigation measures outlined:

- Verasonics and/or adaptor not being in place, resulting in delayed availability of realistic ultrasound measurements.
    - Mitigation measure: Capturing ultrasound images with a conventional US probe or using a handheld ultrasound device to capture images.
- The patch not functioning as expected.
    - Mitigation measure: Capturing ultrasound images with a conventional US probe or using a handheld ultrasound device to capture images.
- NR-RedCap modem does not reach required bandwidth.
    - Mitigation measure:
        i. H1A: spread transmission over longer period, optimizations aimed at data reduction (planned).
        ii. H1B: optimizations aimed at data reduction (planned), use of 5G-NR modem.
- Containerization, CAMARA API instantiation failing.
    - Mitigation measure: Early integrations to test.

3.2 H2 planning

The H2 *Predictive remote reprogramming of implantable cardiac devices* Use Case plan is shown in the Table 44. The use case definition, acquisition of the necessary devices and design of the application and infrastructure were performed in the first year of the project. Preliminary integration and first tests have started and will continue until Q2 2026. These experiments serve as a baseline for the 3 pre-trial parts: (1) Ultrasound capture and processing, (2) Energy-assessment, (3) Integrated demonstration. Until the full trial integration by Q3 2027, three optimisation cycles are planned to assess feasibility and make improvements towards the target KPIs. KPIs and KVIs data will be collected for analysis during the experiments in the pre-trial and trial phases.

Table 44 : H2 planning

Phase	Details	Schedule
UC Definition	A pre-trial phase to lay the foundations of the activities and define the Use Case	Q3 2025-done
Devices	Acquisition and delivery of hardware end devices (sensors, redcap devices, etc.)	Q2-Q3 2025-done
Infrastructure & Application Design	Design of energy assessment and integrated demonstration setups within the Hi5 Facility in The Hague. Design of the ECG/EGM acquisition setup and setup for AI algorithm development in Oslo.	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial and partial integration of key subsystems to verify interoperability.	Q4 2025 - Q1 2026
First Tests & Initial Demonstration	Execute first tests to assess baseline KPIs (energy consumption/battery life, network latency and AI algorithm execution time). May also serve as a first concept demonstration.	Q1-Q2 2026
Final Application Development	Incremental development in 3 iterations, focused on assessing feasibility and refining and improving KPIs.	Q2 2026 –Q3 2027
Full Trial Integration	End-to-end integration of the use case concept, including ECG/EGM data processing, transmission, edge-based processing and presentation on the “clinical backend”.	Q3 2027
Trial Execution	Conduct full UC trials, including operational scenarios and real-time monitoring. An NR-RedCap modem continuously transmits recorded ECG/EGM data to an edge server performing AI-based inference and pacing timing prediction. By using an attenuator and noise generator in the transmitter, pacing timing accuracy is monitored in terms of instantaneous Signal-to-Noise Ratio (SNR).	Q3 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial Q2 2026 –Q4 2027 results.	
Final Demonstrations & Dissemination	Present final trial results, publish findings, and perform end-of-project demonstrations.	Q2–Q4 2027

3.2.1 H2 risks and mitigation plan

- Cellular communication link does not reach required latency.

Mitigation measures:

  - Proper choice and tweaking of modem, RAN and Core
  - Include forecasting algorithm in the model for latency compensation
- Containerization, CAMARA API instantiation failing.

Mitigation measure: Early integrations to test

- Backscatter link implementation is challenging.

Mitigation measure: Excluding this part and streaming a pre-recorded signal directly to the edge.

3.3 P1 planning

Careful planning of the P1 PPDR use case pre-trials and trials is essential to ensure that all scenarios, operational phases, technical components, and stakeholder interactions are evaluated in a structured and repeatable manner. The division into scenarios A, B and C, phases 1, 2 and 3, enables the partners to progressively validate system readiness, operational workflows, interoperability, and service performance under different conditions and levels of complexity. Pre-trial activities that concern mainly Phase 1 help identify technical issues, integration gaps, and operational constraints before the execution of the full trials, thereby reducing risks and improving the reliability of the collected results. In particular, Phase 1 focuses exclusively on pre-trial activities, allowing partners to verify system readiness, validate configurations, perform integration and connectivity checks, and identify potential issues before live trial execution. In some cases the partners use their own testbed or remote access to Patras5G facility to execute integration and testing in this phase.

In parallel, the phased trial approach supports consistent KPI measurement, facilitates comparison across scenarios, and ensures that lessons learned from earlier phases can be incorporated into subsequent activities. This planning framework also provides a common reference for all participating partners, supporting coordination, resource allocation, timeline management, and the production of coherent and traceable deliverables. The overall use case planning is presented in Table 45.

Table 45 : P1 planning

Phase	Details	Schedule
UC Definition	Planning of the services and deployments	Q2 2026 - done
Devices	Acquisition of hardware end devices (sensors, redcap devices, etc.)	Q3 2026 - partly done/still some equipment is required like drone and some servers that have been delayed
Infrastructure & Application Design	Design of two pre-trail and trial facilities infrastructure and applications for Patras5G	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial integration of all subsystems to verify interoperability Scenario A: Integration of available subsystems Scenario B: Integration of available subsystems	Q1 2026-done

Final Application Development	Complete application implementation, optimize performance and reliability (Phase 2)	Q4 2026
First Tests & Initial Demonstration - Phase A	Phase 1/Scenario A: Autonomous Edge operation with local control and user plane, Integrating data services with various optimized configurations (measuring TCP/UDP throughput, reliability and latency)	Q2 2026-done
First Tests & Initial Demonstration- Phase A,B	Autonomous Edge operation with local control and user plane, Integrating MCx services with various optimized configurations (measuring TCP throughput, reliability and latency) and wired/wireless backhaul options and NTN in the field	Q2 2027
	Phase 3/Scenario B: Integration of all services in the outdoor facility (in the field)	Q2- 2027
	Phase 3/Scenario C: Integration of all services in the outdoor facility (in the field) with the Autonomous Edge in a Box, backhaul connectivity and private /public integration	Q2- 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial results	Q2–Q3 2027
Final Demonstrations & Dissemination	Present final UC results, publish findings, and perform end-of-project demonstrations	Q2–Q4 2027

3.3.1 P1 risks and mitigation plan

- The major risks associated with the project include the availability and reliability of the MC-PTT service, in time for Phase 2 of pre-trial in order to ensure operational coordination for Trial phase 3.
    - Mitigation plan: Various options for MC application are currently sought
- In addition, the availability of NTN network connectivity represents another key risk, since network outages, latency issues, or insufficient bandwidth may affect system accessibility, data transmission, and overall service continuity.
    - Mitigation plan: Testing will be initiated with Starlink

Enablers at the time of delivery of this report have already been developed and integrated, hence the pre-trials will be performed with other types of backhaul networks. Both risks could lead to operational delays, reduced efficiency, and potential service disruptions if not properly mitigated, however mitigation plans are already under way with MC-PPT testing of open-source solutions and backhaul options.

3.4 P2 planning

Use case planning in Table 46.

Table 46 : P2 planning

Phase	Details	Schedule
UC Definition	A pre-trial phase to lay the foundations of the activities and define the Use Case	Q3 2025-done
Devices	Acquisition of hardware end devices (sensors, redcap devices, etc.)	Q2 2025-done
Infrastructure & Application Design	Design of B5G infrastructure and applications for the 5GTN Finland	Q4 2025-done
Preliminary Integration including enablers	Initial integration of all subsystems to verify interoperability	Q1 2026-done
First Tests & Initial Demonstration	Execute first tests and demonstrate preliminary UC scenarios	Q2 2026-done
Final Application Development	Finalize application implementation, optimize performance and reliability	Q2–Q4 2026
Full Trial Integration	Integrate all UCs, devices, and applications into the final testbed	Q1 2027
Trial Execution	Conduct full UC trials, including operational scenarios and real-time monitoring	Q2 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial results	Q2–Q3 2027
Final Demonstrations & Dissemination	Present final UC results, publish findings, and perform end-of-project demonstrations	Q2–Q4 2027

3.4.1 P2 risks and mitigation plan

- Risk in full trial integration: integrating devices, and applications into a single testbed may cause configuration conflicts or interoperability issues, increasing integration effort.
  - Mitigation: use version-controlled configurations and documented integration procedures, perform staged integration (vehicle → edge → CCC), validate interoperability after each integration step.
- Risk in trial execution Real-world conditions (network instability, mobility, environmental factors like weather) may disrupt trials or reduce consistency of results.
  - Mitigation: plan multiple trial runs (in different dates), monitor system health and network performance in real time. Log events and failures for post-trial analysis.

3.5 P3 planning

Use case planning in Table 47.

Table 47 : P3 planning

Phase	Details	Schedule
UC Definition	A pre-trial phase to lay the foundations of the activities and define the Use Case	Q3 2025-done
Devices	Acquisition of hardware end devices (sensors, redcap devices, etc.)	Q2 2025-done
Infrastructure & Application Design	Design of B5G infrastructure and applications for the 5GTN Finland	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial integration of all subsystems to verify interoperability	Q2 2026-done
First Tests & Initial Demonstration	Execute first tests and demonstrate preliminary UC scenarios	Q3 2026
Final Application Development	Finalize application implementation, optimize performance and reliability	Q4 2026
Full Trial Integration	Integrate all UCs, devices, and applications into the final testbed	Q1 2027
Trial Execution	Conduct full UC trials, including operational scenarios and real-time monitoring	Q2 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial results	Q2–Q3 2027
Final Demonstrations & Dissemination	Present final UC results, publish findings, and perform end-of-project demonstrations	Q2–Q4 2027

3.5.1 P3 risks and mitigation plan

- Risk: Combining integrated slicing, independent Open RAN private networks, MEC services, and exposure APIs increases system complexity and the likelihood of integration or configuration errors.
    - Mitigation: Adopt staged integration (RAN → core → MEC → applications), use version-controlled configurations with rollback capability, and maintain simplified fallback deployment modes for trials.
- Risk: Fully offline operation and mobile private network deployments may suffer from synchronization, mobility management, or service continuity challenges without external infrastructure support.

- Mitigation: Ensure all critical services operate locally (time, identity, monitoring), pre-stage software and data, test air-gapped operation explicitly, and validate mobility scenarios through repeated outdoor and vehicle-based trials.

3.6 P4 planning

Arctic Area Search and Rescue Operation aim to provide effective ways of using B5G/6G connectivity to communicate between FRs in the field and the CCC to achieve fast situational awareness. The P4 use case plan. Is shown in Table 48.

Table 48 : P4 planning

Phase	Details	Schedule
UC Definition	A pre-trial phase to lay the foundations of the activities and define the Use Case	Q3 2025-done
Devices	Integration of hardware end devices (sensors, redcap devices, etc.) into backpack system.	Q2 2025-done
Infrastructure & Application Design	Design of the 5G infrastructure and applications for the 5GTN Finland	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial integration of all subsystems to verify interoperability	Q1 2026-done
First Tests & Initial Demonstration	Execute first tests and demonstrate preliminary UC scenarios in EuCNC	Q2-Q3 2026
Final Application Development	Complete application implementation, optimize performance and reliability	Q2–Q4 2026
Full Trial Integration	Integrate all UCs, devices, and applications into the final testbed	Q1 2027
Trial Execution	Conduct full UC trials, including operational scenarios and real-time monitoring	Q2 2027
KPIs & KVIs Collection & Analysis	Collect performance indicators and analyse trial results	Q2–Q3 2027
Final Demonstrations & Dissemination	Present final UC results, publish findings, and perform end-of-project demonstrations	Q2–Q4 2027

3.6.1 P4 risks and mitigation plan

- Risk: Network frequency availability. Frequency on loan from commercial network operator.
  - Mitigation: Using radio equipment that have the possibility to change frequency bands.
- Risk: Fully offline operation and mobile private network deployments may suffer from synchronization, mobility management, or service continuity challenges without external infrastructure support.

- Mitigation: Ensure all critical services operate locally (time, identity, monitoring), pre-stage software and data, test air-gapped operation explicitly, and validate mobility scenarios through repeated outdoor and vehicle-based trials.

3.7 P5 planning

Table 49 presents use case implementation for P5.

Table 49 : P5 planning

Phase	Details	Schedule
UC Definition	Use case architecture definition including, 5G on the GO, MCX application and satellite backhaul integration	Q2-Q3 2025-done
Devices	Acquisition of hardware end devices	Q2 2025-done
Infrastructure & Application Design	Design of B5G infrastructure and applications for the Bucharest site	Q2–Q4 2025-done
Preliminary Integration including enablers	Initial integration of all subsystems to verify interoperability in Orange 5G Lab testbed	Q1 2026-done
First Tests & Initial Demonstration	Execute first tests and demonstrate preliminary UC scenarios	27 April 2026-done
Final Application Development	Implement additionally MCX scenarios, prepare full field tests	Q2–Q4 2026
Full Trial Integration	Integrate all 5G on the GO elements, MCX application, backhauling into the final testbed	Q1 2027
Trial Execution	Conduct full UC trials, MCX scenarios, backhaul interruption tests, KPIs and KVIs measurements	Q2 2027
KPIs & KVIs Collection & Analysis	Analyse and provide recommendations following KPIs and KVIs results	Q2-Q3 2027
Final Demonstrations & Dissemination	Present the trial results, main outcomes and recommendations to the emergency responders' stakeholders	Q2-Q4 2027

3.7.1 P5 risks and mitigation plan

As of this moment, no relevant or significant deviation has been noticed, since the pre-trial was successfully executed on 27 April 2026.

3.8 WP4 planning

Overall, the presented planning framework demonstrates a coherent and structured approach to the development, integration, and validation of the AMAZING-6G use cases across both healthcare and PPDR domains. The phased methodology—from initial definition and infrastructure setup through iterative integration cycles to full trial execution and final demonstrations—ensures systematic maturation of all technological components while mitigating risks associated with system complexity, interoperability, and real-world deployment conditions. The incorporation of multiple optimisation cycles, combined with continuous KPI and KVI monitoring, enables evidence-based refinement of system performance and supports the achievement of project objectives under realistic 6G operational scenarios. In addition, the identified risks and corresponding mitigation strategies provide robustness to the overall execution plan, ensuring continuity of experimentation even under constrained or degraded network conditions. Collectively, this structured planning approach establishes a strong foundation for validating next-generation 6G-enabled services in both critical healthcare applications and demanding PPDR environments, while ensuring reproducibility, scalability, and alignment with the broader goals of advanced European 6G research initiatives.

4 Preliminary integration and results

This section presents the outcomes of the preliminary integration activities conducted across the seven use cases of the Amazing-6G project, covering two healthcare (H1–H2) and five PPDR (P1–P5) scenarios. The preliminary integration phase constitutes a critical milestone in the overall system development lifecycle, enabling early verification of interoperability between heterogeneous subsystems, including end devices, communication infrastructures, edge computing platforms, and application-layer services. In this context, initial end-to-end configurations were established to assess the functional interaction of key components such as NR-RedCap devices, AI-enabled processing modules, network slicing mechanisms, and mission-specific applications under controlled testbed conditions. The results obtained from these early integrations provide essential baseline insights regarding system performance, stability, and integration readiness, while also supporting the identification of technical limitations, configuration issues, and optimisation opportunities prior to large-scale trial execution. Furthermore, this phase lays the groundwork for subsequent iterative development cycles and ensures alignment with the defined KPIs and KVIs across all use cases.

4.1 H1 Wearable ultrasound patch for cardiac function monitoring

This section describes the development and integration status in Section 4.1.1 (what has been built and any integration steps); the tests performed and results in Section 0 (tests carried out, results and comparison with target KPIs); and the next steps towards the full trial in Section 0. In each sub-section, the 3 pre-trial parts: (1) Ultrasound capture and processing, (2) Energy-assessment, (3) Integrated demonstration, are described separately. These were introduced in Section 2.1.7.

4.1.1 H1 Integration status

4.1.1.1 *Ultrasound capture and processing pre-trial*

OUS has developed an AI-based, automatic segmentation algorithm and a live-stream pipeline based on a traditional transthoracic ultrasound probe and US scanner E-95 from GE. The AI algorithm can be further trained on US-patch data or use the same neural network but retrained on ultrasound patch data solely.

4.1.1.2 *Energy-assessment pre-trial*

The hardware for the energy measurement setup (see Section 2.1.3.1) has been finalized. The objective of this setup is to enable accurate and repeatable energy consumption measurements of a (RedCap) module. To achieve this, the connection between the UE and the gNB is implemented using a coaxial cable rather than a wireless link. This approach ensures that the measurements are not influenced by the environment in which they are conducted. Moreover, the use of a coaxial cable allows precise control over the channel attenuation, thereby enabling the emulation of different distances between the gNB and the UE. One limitation of this approach is that experiments involving multipath fading cannot be performed. If such experiments are required, a dedicated multipath simulator must be employed.

The software for the measurement setup (see also Section 2.1.3.1) is still under development. Using the current version, preliminary experiments can be conducted in which multiple measurements are executed sequentially. The software is capable of logging throughput, packet loss, and energy consumption. At present, data transmission is performed via a Point-to-Point Protocol (PPP) link between the laptop and the modem. Consequently, packet generation (e.g., HTTPS and TCP traffic) is handled by the laptop. In a subsequent version of the software, AT commands will be used so that packet generation is performed directly by the modem. This change will result in more realistic energy consumption measurements.

4.1.1.3 *Integrated demonstration pre-trial*

An initial version of the AI model was made available to the TNO-team. This version of the algorithm is currently a monolithic application that reads an input video file, runs the algorithm on it, does analysis all locally. The TNO-team containerized the provided application and deployed it in the edge.

Moreover, we made an initial attempt of splitting the provided application into two parts:

- An HTTPS client application (that will read the input video file and send frames) that will run on the UE.
- An HTTPS server application (that will receive the frames on a network socket, process them, run the algorithm, and send results back) that will run on the edge.

Moreover, as for H2 (see Section 4.2.1.3), we added trace points into both applications to record timestamps at various processing stages (e.g., when packets are sent/received by the UE application and during different processing stages in the edge application).

This version is currently under further development by OUS. Upon completion of this step, we aim to run the baseline experiments similar to the one for H2 (see Section 4.2.1.3).

4.1.2 H1 Test cases and test results

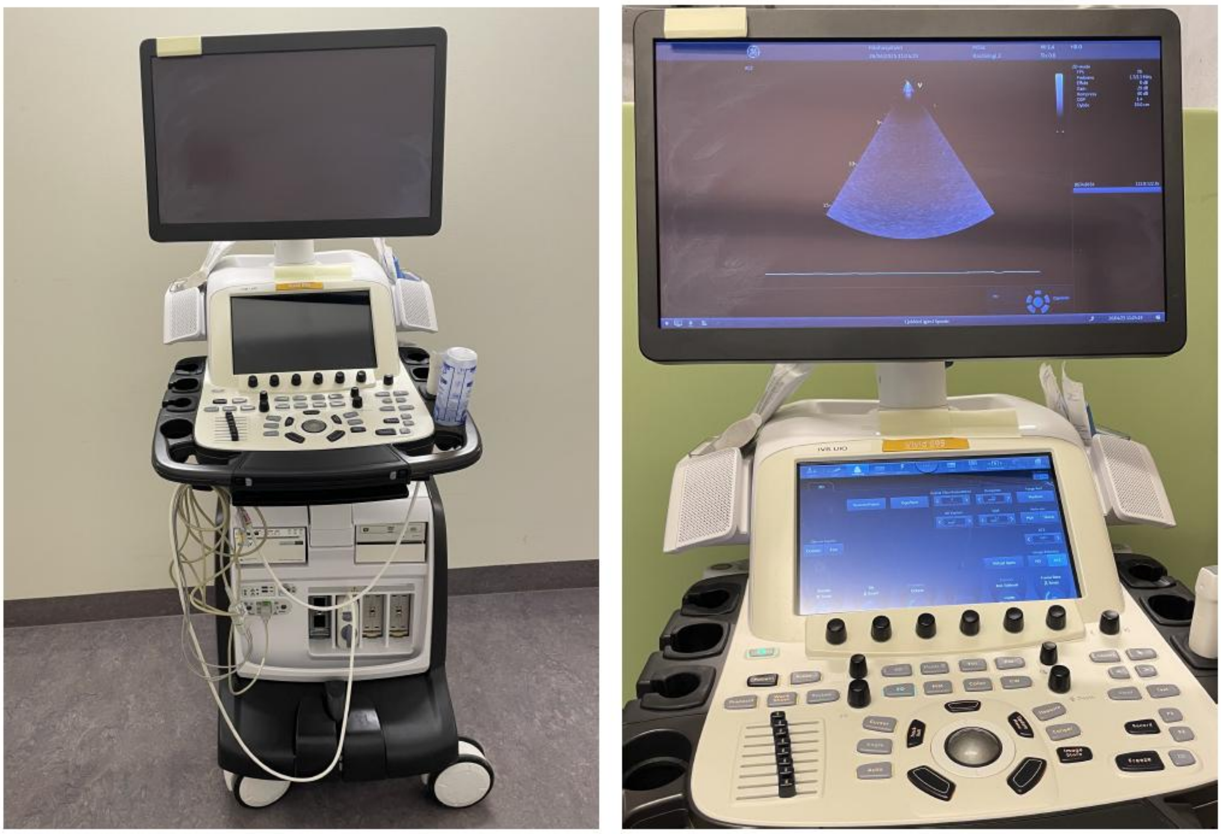
4.1.2.1 *Ultrasound capture and processing pre-trial*

Lab trial execution results are included in Table 50.

Table 50 : H1.1 lab trial execution

H1 / Lab01	Ultrasound capture and processing
Facility / Site	The Intervention Center, Oslo University Hospital, Rikshospitalet, Sognsvannsveien 20, 0372 Oslo, Norway
Objective / Description	Establish a live stream real-time echocardiography monitoring system with a wearable ultrasound patch or portable devices
Executed By	Dr. Varatharajan Nainamalai PhD (Technical, Researcher), Professor Dr. Henrik Brun, MD. PhD (Clinical), and Professor Olle Jakob Elle PhD (Technical).
Devices / Components Involved	GE Ultrasound Machine, 24GB Video memory, 64GB CPU, Conda packages, PyTorch and Python based programs.
5G Infrastructure	Not applicable
Ethics / Beta Users	Not applicable
Technical Enablers	Not applicable

Live Stream Setup



(a) (b)

Figure 38 : Images of the Vivid E95 machine used for this work

The GE Healthcare Vivid E95 ultrasound system and M5Sc-D probe (see Figure 38) was used for this study. A connection between the ultrasound machine and the GPU-enabled computer was established using an internet cable. The AppAPI (a GE Healthcare library) provides the necessary tool for real-time data streaming and interaction with the streaming data. AppSandbox is an application provided in the AppAPI library. It is used to authenticate the connection between the Vivid E95 machine and the Windows computer before live streaming echo frames.

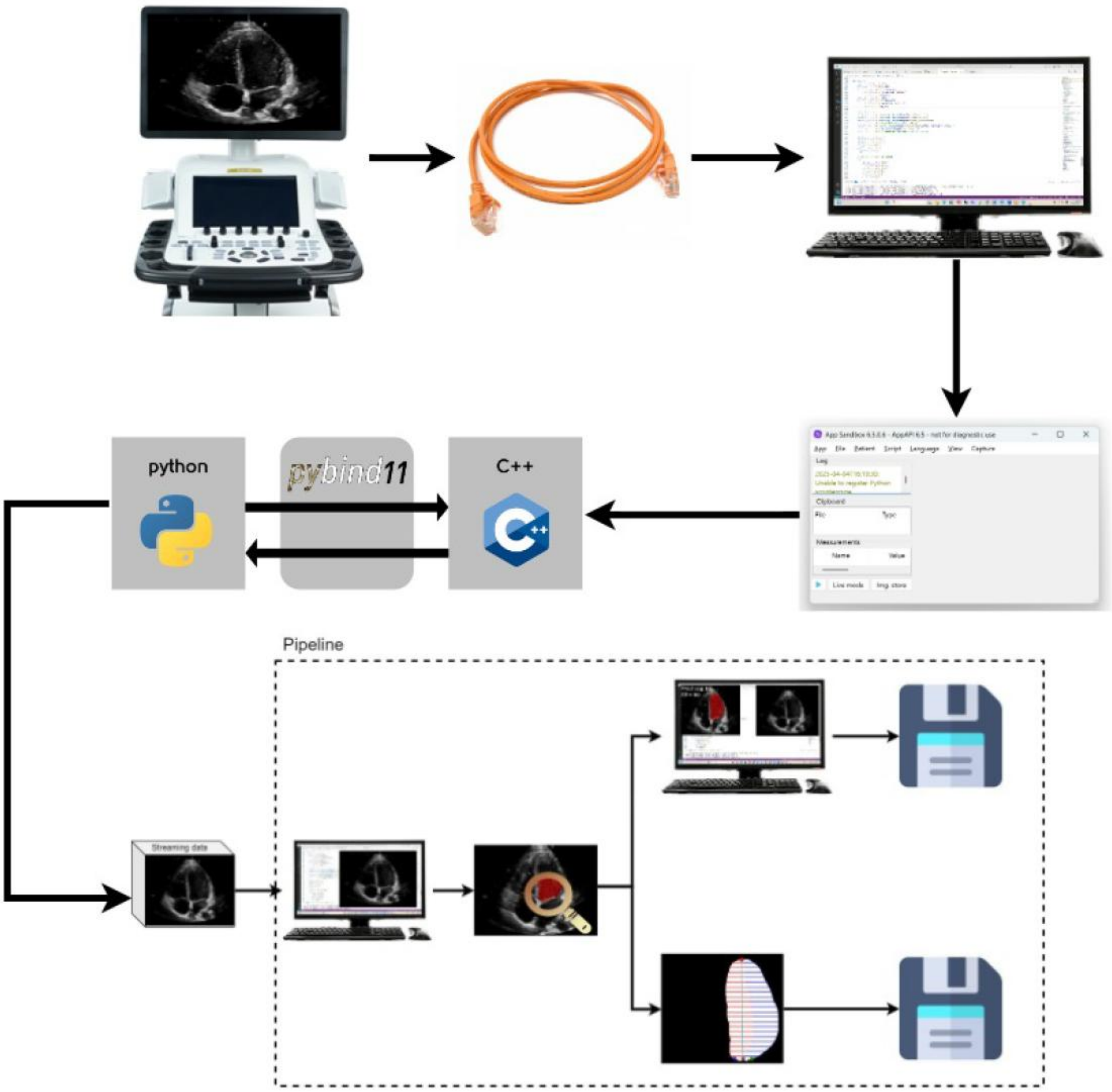


Figure 39 : The workflow of live streaming echocardiography images from the Vivid E95 machine in real time.

The multi-thread setup

To efficiently process frame acquisition, inference, metrics calculation, and save the real-time ultrasound stream from the Vivid E95, the main program was designed as a multi-threaded application (see Figure 39). This multi-thread setup ensured that the proposed system/pipeline could handle streaming data while performing deep learning-based inference and analysis without performance bottlenecks.

Streaming Frame Acquisition

The streaming process of the original live stream was managed by establishing a connection to the Vivid E95 ultrasound machine. The streaming thread continuously retrieved frames from the machine along with their corresponding affine matrix. These frames were displayed in a window using OpenCV and then passed to a queue, allowing other threads to process the data in parallel.

Real-Time LV Segmentation and metrics Computation

A UNet model, initialized with trained weights, was used to segment the LV of each frame. To minimize processing delays and optimize real-time performance, both segmentation and overlay frame creation were handled within the same function before being sent to the visualization queue. The frames from the queue of the streaming thread pass to the GPU for the segmentation process, and it has the following steps:

Preprocessing: The incoming grayscale ultrasound frames were resized (256x256) and normalized.

Inference: The deep learning model predicted binary masks highlighting the LV region.

Postprocessing: The predicted masks were resized back to their original dimensions.

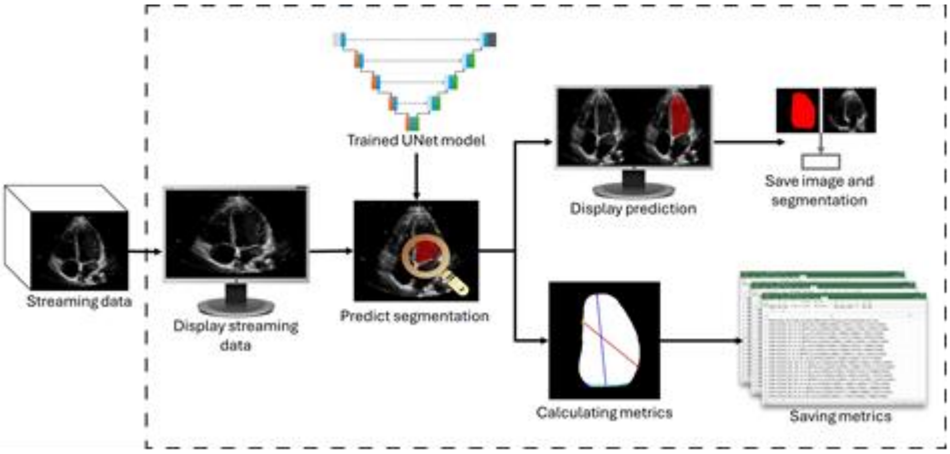


Figure 40 : The workflow of displaying the live stream echocardiography images

Predicting LV segmentation, displaying the prediction, calculating metrics, saving predictions and metrics

The saving thread was responsible for storing the original frames and the predicted segmentations as NIfTI files with the same affine as the streaming data. The files were named using an index value passed through all the threads. Hence, it would be possible to identify which performance metrics calculated in the Performance Metric Computation thread corresponded to which frames and predicted segmentations.

We have used the Dice scores were calculated independent of the overlay visualization. The calculations were performed in a dedicated thread that pulled data from a queue. First, the LV volumes and LV longitudinal length were computed and stored in arrays within a global dictionary. Once these arrays held more data points than a specified interval, the EF was calculated using the maximum and minimum values in the arrays, corresponding to ED and ES, respectively. Finally, a function was called to save all the calculated metrics into a file.

Live Stream Experiment

We recruited five healthy volunteers (no history of cardiac diseases), all were males, aged in the range of 25-40 years, for our prospective live stream experiment. We anonymized the data of all volunteers. Informed and written consent was obtained from all volunteers.

The live stream images are processed through the GPU-enabled computer. The echo images are streamed, displayed, used to infer the LV area, predict the LV volume, and the inference time per frame. The LV volume was obtained using the single-plane Simpson method. Also, the echo images of these five healthy volunteers were analysed using EchoPAC (a GE Healthcare offline tool to calculate EF, strain, etc.) for EF calculation, after the live experiment.

Both training of all deep learning models, and the live-inference experiment were performed using an Intel(R) Core (TM) i7-7700 CPU 4.20 GHz (8 cores), 64 GB RAM, and NVIDIA GeForce GTX 3090 Ti-PCIE-24 GB of video RAM.

Experimental Design

The primary goal of this experiment was to assess the performance impact of varying:

- Initial number of feature maps: 8, 16, 32
- Loss function: Dice loss, Binary Cross-Entropy loss, and a Combined loss
- Training dataset: CAMUS, EchoNet-Dynamics, and PACCS

We fixed there the batch size to 32, and the learning rate to 1e-4. For validation of the models, only the dice score was utilized. Each model configuration was trained independently, and the best performing configurations for each dataset were identified based on segmentation performance metrics.

Training Setup

All models used a 2D UNet architecture. The number of initial feature maps was varied across experiments (8, 16, or32), with each encoder block doubling the number of filters. The decoder path mirrored the encoder, using transposed convolutions to reconstruct the segmentation mask. All training was performed using the AdamW optimizer. Models were trained for up to 150 epochs, with early stopping applied if the validation Dice score did not improve at all for 20 consecutive epochs. Input images were pre-processed using MONAI transforms: grayscale normalization to [0,1], conversion to a single-channel format, and resizing of both images and segmentation masks to a uniform resolution of 256×256 pixels.

For the model training phase, various combinations of the CAMUS, EchoNet-Dynamics, and PACCS datasets were explored to assess generalization and improve segmentation accuracy. Initial models trained on the CAMUS and EchoNet-Dynamics datasets demonstrated limited performance in accurately segmenting the apex of the LV, particularly on real-time frames from the Vivid E95 machine. This observation motivated the creation and inclusion of the PACCS (The Physical Activity and Fitness in Childhood Cancer Survivors Study) dataset, composed of clinical ultrasound recordings from Rikshospitalet, Oslo University Hospital, Oslo, Norway to better represent the image domain encountered during live inference.

To evaluate the benefit of dataset composition, the following combinations were tested:

- CAMUS +EchoNet-Dynamics
- CAMUS + PACCS
- EchoNet-Dynamics + PACCS
- CAMUS +EchoNet-Dynamics + PACCS

Each model was trained using a consistent data split of 75% for training, 15% for validation, and 10% for testing. The loss function was either Dice loss, Binary Cross Entropy loss, or Dice loss + Binary Cross Entropy loss to balance region overlap and pixel-level accuracy.

For each experiment:

1. A model was initialized with a given number of feature maps.
2. The selected dataset was loaded and pre-processed.
3. The model was trained with a learning rate of 1e-4 and batch size of 32.
4. The best model was saved based on the validation metrics.

The trained models were evaluated during testing using Dice score metric. Metric was calculated using the ground truth segmentation and predicted segmentation for each model combination. As the number of test images for each dataset is different (CAMUS 200, EchoNet-Dynamics 1077, and PACCS 975), the metrics were calculated for each dataset on its own.

From the three different hyper parameters implemented in this work, 36 models were trained. The inference time differences between models were negligible. Hence, we decided to select a model for the live-stream experiment based on the best average Dice score. Given that the PACCS dataset was specifically designed to resemble live-stream data from the Vivid E95 machine, model performance on this dataset was used to guide selection.

For each dataset combination (CAMUS + EchoNet-Dynamics, CAMUS + PACCS, EchoNet-Dynamics + PACCS, and CAMUS + PACCS + EchoNet-Dynamics), the model with the highest average Dice score on the RH-LV test set was shortlisted.

Table 51 : Average performance metrics on the RH-LV dataset for the best-performing model from each dataset combination

Dataset	Initial Feature Maps	Loss functions	Dice Score	Inference Time in Seconds
Camus + EchoNet	16	Dice + BCE	0.7910	0.0045
Camus + PACCS	32	Dice + BCE	0.9358	0.0045
EchoNet + PACCS	32	Dice + BCE	0.9356	0.0045
Camus + EchoNet + PACCS	32	Dice	0.9350	0.0045

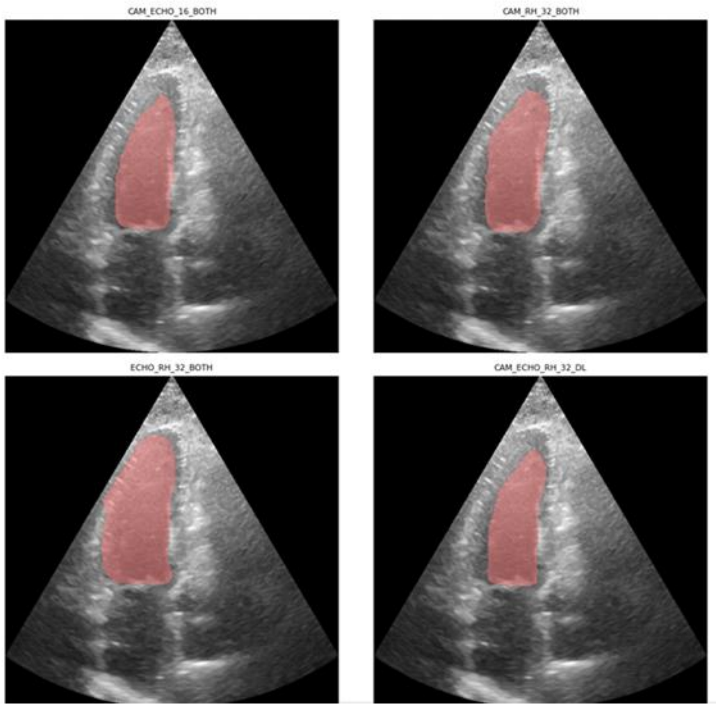


Figure 41 : Comparison of live predictions from the four top-performing models on a frame from the Vivid E95 live-stream

While these models showed comparable metrics (see Table 51) it was also important to evaluate their visual segmentation quality in a real-time clinical context (see Figure 41). To that end, a cardiologist reviewed the live segmentation overlays for each model in real time and selected the one that best matched expected anatomical contours. Figure 42 illustrates the live predictions of the four candidate models on a representative Vivid E95 frame.

Based on both the quantitative metrics and qualitative clinical evaluation, the model trained on the CAMUS and RH-LV datasets, with 32 initial feature maps and a combined Dice + BCE loss, was thus selected for use in the live-stream experiment.

Applying Trained UNet Model to Vivid E95 Live-Stream Data

The experiment was conducted on a small sample of 5 participants from Rikshospitalet, Oslo University Hospital. For each participant: The written informed consent was obtained from those 5 healthy participants to use the dataset for research. The data is anonymized. Live streaming was initiated from the Vivid E95 using the APPAPI interface.

Real-time LV segmentation was performed on each incoming frame using the best performing UNet model from the previous experiment. Also, Ejection Fraction (EF) were calculated on-the-fly based on the inferred segmentations.

The real-time inference system has evaluated the following:

- Inference Speed: Measured as average frames per second (FPS) processed, and average latency between frame acquisition and segmentation output.
- Segmentation Accuracy: Assessed by comparing live segmentations (and resulting EF) results.

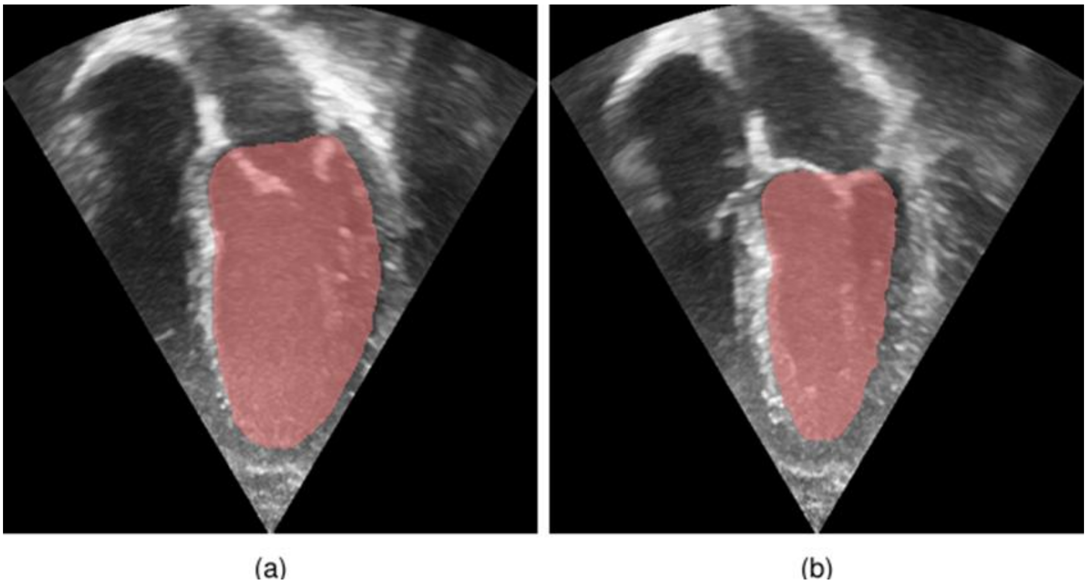


Figure 42 : Live stream predictions from participant 3. (a) Inference at EDV, (b) inference at ESV

Table 52 : Comparison between EchoPAC and inference EF values using different LVV calculations.

Participants	EchoPAC(%)	Single Plane Simpson Method(%)	Time
1	56	81	0.0279
2	56	87	0.303
3	61	69	0.0287
4	56	74	0.0294
5	57	87	0.0306

During the live-stream experiment, it was clear to see that there was some underestimation, and most underestimation during ESV frames. Figure 42 depicts inference of the five participants during a frame depicting EDV and ESV, visualizing this. The live-stream experiment gave the following EF values presented in Table 52. It is clear to see that there is a significant difference between the EchoPAC values and live-stream predicted values. Figure 43 shows participant 3 EchoPAC prediction of the EF in offline.

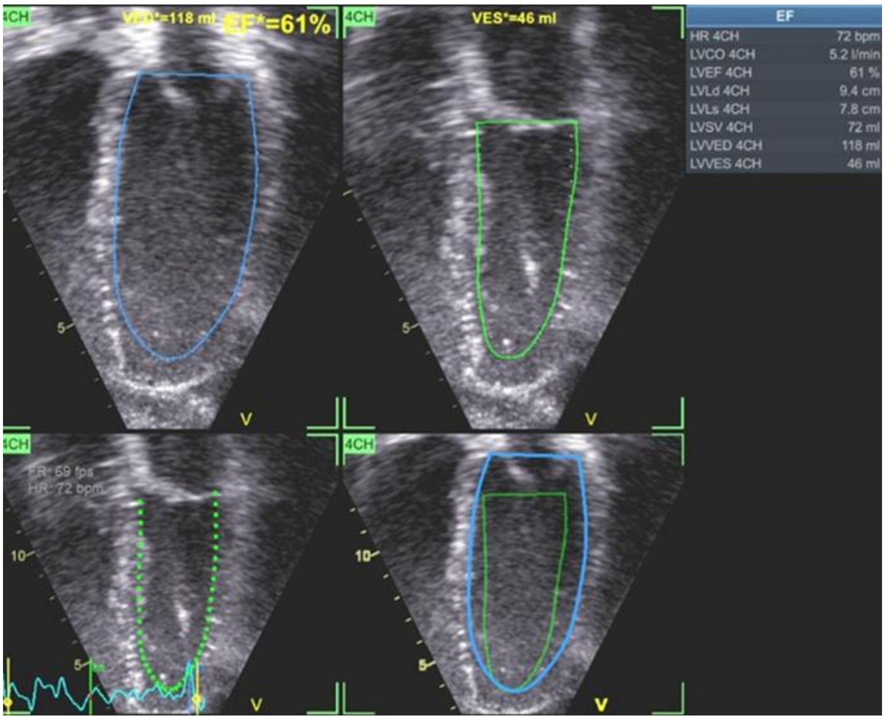


Figure 43 : EF calculation from EchoPAC of the same participant 3 Live stream predictions from a participant

Discussions

Although several models achieved Dice scores exceeding 0.93 on CAMUS and RH-LV, these values did not always translate into clinically accurate functional metrics. For instance, models trained with RH-LV over segmented LV contours, especially at the apex, leading to higher EDV values in some cases. In contrast, predictions on real-time frames tended to underestimate volumes during ESV, resulting in higher EF values.

Limitations of Quantitative Metrics: Traditional segmentation metrics, such as Dice score provided useful benchmarks but did not fully capture downstream clinical reliability, especially in tasks such as EF estimation. This finding highlights the importance of integrating both anatomical segmentation quality and clinical outcome accuracy in future evaluation protocols.

Real-Time Live-Stream Experiments - Inference Performance: The trained UNet model (32 feature maps, combined loss) was successfully deployed in a real-time pipeline connected to the GE Vivid E95 ultrasound system. The offline pipeline operated with minimal latency (approx. 30 ms per frame), confirming that deep learning-based LV segmentation can be performed live on streaming echocardiography data using conventional hardware.

Real-Time Live-Stream Experiments - Segmentation Accuracy in Real-Time Context: Visual evaluation of EDV frames confirmed acceptable anatomical LV segmentations, but ESV predictions often suffered from under segmentation. This led to systematic overestimation of EF across all five participants. The discrepancy was most notable in comparisons with EchoPAC measurements, with EF differences exceeding 20% in some participants.

The cardiologist noted that while segmentations during EDV were often satisfactory, ESV masks appeared truncated or incomplete. However, the system's ability to calculate and display EF trends over time was seen as clinically promising, suggesting potential for near-future clinical adoption with further refinement.

The live-stream experiment demonstrated the possibility of real-time cardiac monitoring. The system was able to obtain streaming data, display inferred LV segmentation, and calculate cardiac health metrics like Ejection Fraction (EF) with an average delay of 0.03 seconds. When comparing the inferred

EF values with EchoPAC, there were some variations. However, this is most likely a result of the model in the live stream that underestimates the LV boundary significantly. Therefore, training a model with greater data variability is expected to enhance its ability to predict LV boundaries from real-time data, leading to improved EF score estimation.

With real-time inference capability and demonstrated segmentation performance, future research can explore broader clinical applications:

- Wearable Ultrasound Integration: Combining the real-time segmentation system with emerging wearable ultrasound devices (e.g., ultrasound patches) could enable continuous cardiac monitoring in settings like ICUs, ambulatory care, or telemedicine.
- Clinical Decision Support: Real-time segmentation and cardiac metric extraction could support clinicians by flagging abnormal function, suggesting probe repositioning, or prompting further imaging.
- Surgical, procedural tool tracking: Expand the segmentation capabilities of the model to be able to detect medical tools inside the LV, enabling real-time tracking during procedures.

4.1.2.2 *Energy-assessment pre-trial*

Initial baseline measurements have been conducted, and presented in Table 53.

Table 53 : H1 base line energy measurements

H1 / Lab02	Energy-assessment
Facility / Site	TNO Hi5 facility in The Hague, The Netherlands
Objective / Description	Conducting baseline energy measurements.
Executed By	TNO
Devices / Components Involved	• 6G Radio Box (NUC + USRP N320 SDR + RF Switch) + Open Air Interface software • Energy Consumption Testbed (Laptop + OTII Power meter + Quectel RG255C 5G Redcap modem) + Server/Testbed/Client software • Variable Attenuator • Hi5 Research Cloud + Open5GS software
5G Infrastructure	Software: Open AIR interface. Hardware: USRP B210 as gNB and Quectel RG255C as modem
Targeted KPIs	Device Energy efficiency
Measurement Tools	QOITECH Otii Arc Pro for energy measurements
Ethics / Beta Users	Not applicable
Technical Enablers	5G Redcap

The configuration used for these baseline measurements can be found in Table 54. For the initial baseline measurement, a relatively good Reference Signal Received Power (RSRP) of -77 dBm is used. This emulates a situation where the UE is closely located to the gNB. Also note that the number of uplinks slots is higher than the default settings to increase the maximal throughput.

Table 54 : Configuration base line energy measurements for H1

Configuration	Value
RSRP	-77 dBm
Modulations	QAM64
Nr of uplink slots	4.5
Nr of downlink slots	5.5
Payload size	645 MB
Packet count	1
Protocol	HTTPS

The results for the baseline can be found in Table 55. With the current setup, a maximum throughput of 12.6 Mbit/s is achieved. This is lower than expected because, based on existing literature, the expected throughput should be something between 25 and 35 Mbit/s. More research is needed to see why the throughput is on the low side.

The results show a power consumption of 38.7 mWh. This is the total power needed to send 645 MB of data using the RedCap module. Assuming a battery of 1000 mAh at 3.6 volts, in total 3600/38.7 = 93 packets can be send. If only one message a day would be sent, the battery would last 93 days, if only the transmission is considered. However, in practice, other components will also draw power so the total battery live will be less than these 93 days. Furthermore, it is expected that in practice a much lower RSRP may occur which may potentially reduce the energy consumption per (645 MB) message by one or more orders of magnitude (and hence reduce the battery life by the same factor).

Table 55 : Result baseline measurements H1

Measurement parameter	Value
Packets sent (separated in 1MB chunks)	1
Packet loss	0
Energy	38.7 mWh
Average power	89.7 mW
Minimal power	31.6 mW
Maximal power	195.2 mW
Duration	6:51 minutes
Voltage	3.8 V
Average throughput	12.6 Mbit/s

The results in Table 55 can be compared with the data rate and battery live KPI target in section 2.1.5 for both H1A and H1B. Note, that the focus of the experiments until now have been on clinical case H1A. Only the throughput and latency number are applicable to both clinical cases.

For latency only an initial ping test has been done resulting in a latency varying roughly between 15 and 30 ms. No further latency tests are done because this already indicates that the latency will be much lower than the targeted 100s for H1A and the 100ms for H1B.

The current data rate of the setup is 12.6 Mbit/s which is lower than the targeted 86 Mbit/s. However, it was never expected that 86 Mbit/s was a realistic data rate for a NR-RedCap modem. Based on a white paper by Ericsson [11], a maximal uplink throughput of 45 Mbit/s can be expected for the most advanced version of the NR-Redcap modem. It needs to be said that our setup uses a simpler NR-RedCap modem with only one antenna. In that case, a maximal uplink throughput of 35 Mbit/s is to be expected. In the next steps it needs to be investigated why the current throughput is still much lower than this 35 Mbit/s.

As mentioned above, with an RSRP of -77 dBm (very good signal) the battery live for the modem only will be around 93 days. Assuming the modem can be switched off between transmissions. This is much better than the several hours described as target.

The abovementioned analysis is summarized in Table 56.

Table 56 : H1 KPIs measurements for energy assessment

Test Case ID	Target KPIs / Requirements	KPIs measurements	Evaluation / Notes [Network or Application Related]
H1_NL_MVS_2	*User Experienced data rate*: < 86 Mbit/s	12.6 Mbit/s	
	Coverage: Urban and rural areas (+ indoor for stationary) e.g., RSRP = -110 dBm	RSRP = -77 dBm	Starting point, deeper coverage to be explored as next steps.
	Device Energy efficiency: Several hours	93 days	This relates to extremely good coverage (see -77 dBm) above and will be (much) worse for typical coverage.
	Network service latency: H1A: 100 s H1B: 100 ms	< 30 ms	Ping time measurement.

4.1.2.3 *Integrated demonstration pre-trial*

Since the step of splitting the application to a client and server side application is still in progress (see Section 4.1.1.3), no integration results are available yet.

4.1.3 H1 Next steps

4.1.3.1 *Ultrasound capture and processing pre-trial*

The next iteration of the application needs to be done for integration. Optimizations of the AI algorithm will also be done.

4.1.3.2 *Energy-assessment pre-trial*

Next steps involve:

- Improve throughput. Research is needed to investigate the current bottleneck
- Upgrade the software to use AT commands instead of utilizing the PPP connection. This will result in a more realistic energy consumption measurements, as the packet generation will be done by the modem itself.
- Conduct more measurements for different circumstances (RSRP, modulation etc.).

4.1.3.3 *Integrated demonstration pre-trial*

Since the step of splitting the application to a client and server-side application is still in progress, we were not able to do a breakdown of the different latency components such as in H2 (see Section 4.2 of this deliverable). Therefore, at the moment, we are not able to conclude what the main bottleneck is. However, in case the results are similar to H2, and edge server processing is the main contributor, we will do similar optimizations as suggested for H2 (see Section 4.2.3.3).

Additionally, we plan to conduct a more extensive long-term test to evaluate the network availability and network reliability KPIs. This test will run for one month, during which we will have multiple parallel client applications streaming HTTPS requests to the edge application at any given time (as indicated in Section 2.1.5 regarding expected connection density). We will monitor whether the network service latency, user experienced data rate and runtime KPIs are met for all processed HTTPS requests throughout the duration of the test.

4.2 H2 Event-aware real-time reprogramming of pacemaker through wearable patch

This section describes the development and integration status in Section 4.2.1 (what has been built and any integration steps); the tests performed and results in Section 4.2.2 (tests carried out, results and comparison with target KPIs); and the next steps towards the full trial in Section 4.2.3. In each sub-section, the 3 pre-trial parts: (1) EGM/ECG capture and processing, (2) Energy-assessment, (3) Integrated demonstration, are described separately. These were introduced in Section 2.2.7.

4.2.1 H2 Integration status

4.2.1.1 *EGM/ECG capture and processing pre-trial*

The AI model has been implemented by OUS on a PC and comprises in three processing steps: (1) signal segmentation (separating the P, QRS, and T- waves), (2) feature extraction (timing and amplitude features), and (3) forecasting (predicting the AV delay of the upcoming beat using four received beats as predictor beats).

For the segmentation step, a U-Net autoencoder detailed in Figure 44, is used.

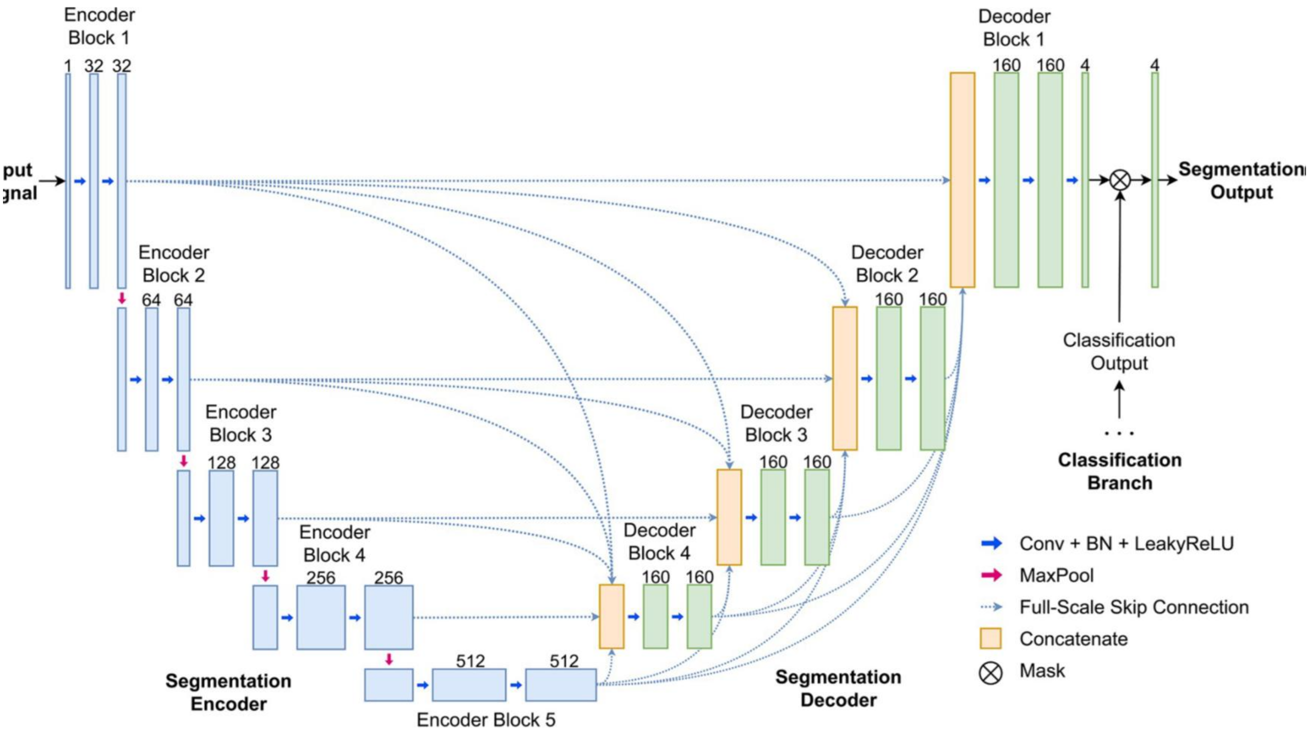


Figure 44 : Four-level U-net autoencoder for the segmentation

This four-class segmentation model (P wave, QRS wave, T wave, other) is trained on a publicly available dataset containing ECG signals (Lobachevsky University Electrocardiography Database [12] annotated with the onset and offset of each wave by clinicians. The dataset contains 200 ten-second, 12-lead ECG recordings collected between 2017 and 2018, with a total of 58,429 annotated waves (16,797 P waves, 21,966 QRS complexes, and 19,666 T waves). The participants' ages ranged from 11 to over 89 years, with an average age of 52. The dataset includes 85 women and 115 men.

We primarily use data from a single ECG leads to train our model. This is important for enabling a compact, one-lead wearable ECG monitor that can be integrated into a small patch. The reconstruction component of the segmentation model improves robustness to noisy inputs, although it comes at the cost of increased complexity. Additionally, the number of convolutional layers and the number of filters in each layer determine the segmentation accuracy, which in turn significantly impacts the overall prediction error of the pipeline.

A total of five features are extracted from each P, QRS, and T-wave, representing the temporal- amplitude characteristics of three waves as shown in Figure 45 with some typical values.

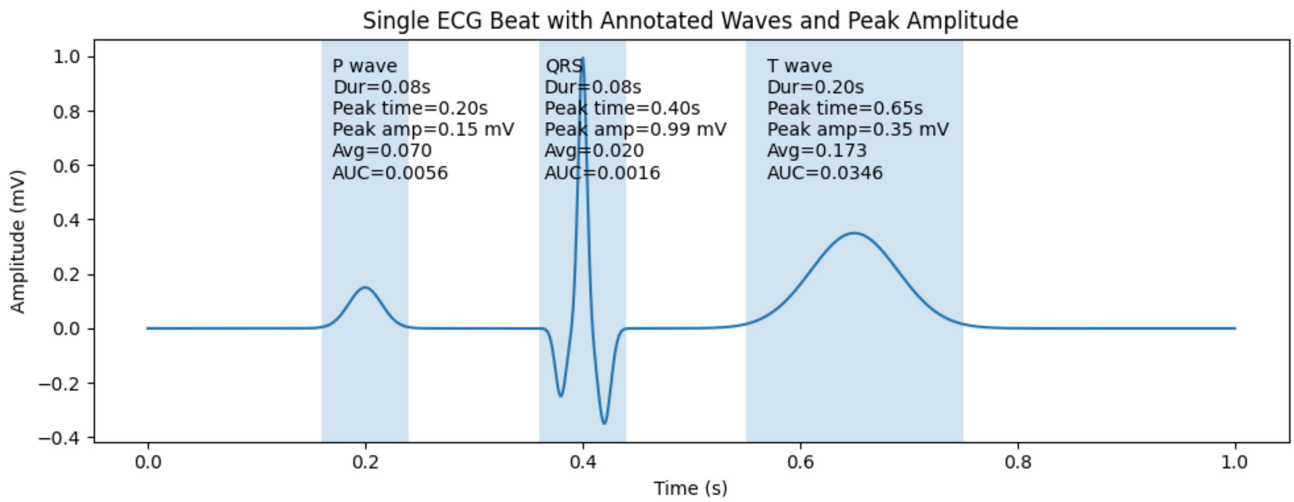


Figure 45 : Temporal and amplitude features extracted from P, QRS and T waves

Amplitude- and timing-based features of the ECG/EGM waves are significant markers of heart status. In general, P-wave duration characterizes the overall timing of right and left atrial depolarization. P-wave peak time reflects the transition from right atrial (RA) to left atrial (LA) depolarization and provides insight into atrial electrical performance. Also, the QRS-wave reflects the status of the ventricles, and the R-peak timing is a reliable indicator of heart rate.

Please note that features capturing the timing of wave occurrence are more relevant for AV delay prediction than those describing the morphology of the waves.

The forecasting model is based on a Temporal Convolutional Network (TCN) architecture designed to capture sequential dependencies in the extracted ECG features for AV delay prediction, as illustrated in Figure 46.

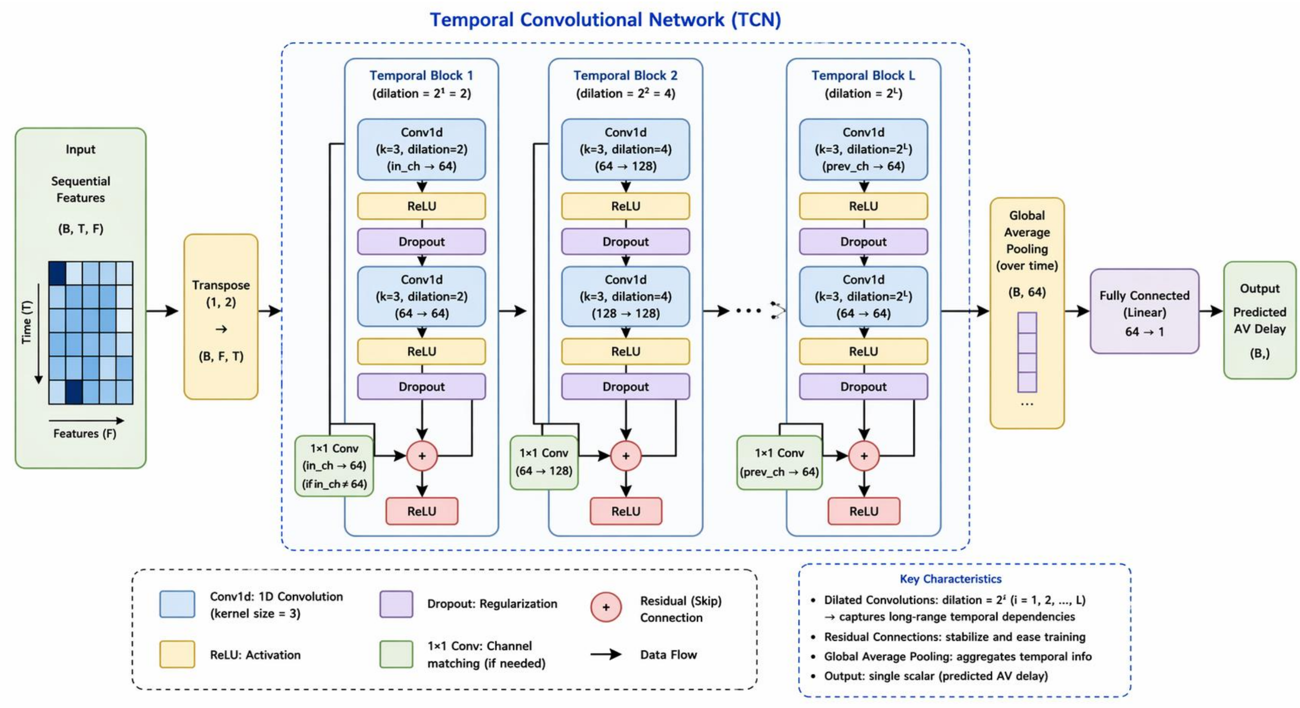


Figure 46 : Temporal Convolutional Network (TCN)

The use of dilated convolutions allows the model to efficiently learn long-range temporal relationships across multiple heartbeats without significantly increasing computational cost. The model stacks several such blocks with exponentially increasing dilation factors, enabling a progressively larger receptive field. After passing through the network, a global average pooling operation aggregates temporal information, and a fully connected layer maps the learned representation to a single scalar output corresponding to the predicted AV delay.

We use the AV delay derived from the ground-truth segmentation to train the forecasting algorithm. This approach ensures that the performance of the prediction model can be evaluated independently of the segmentation accuracy, while also improving the interpretability of the pipeline at different stages. The segmentation and forecasting models are trained separately and then integrated in the final stage. The entire framework is implemented in Python, enabling real-time data acquisition via a UDP port (yet HTTPS is addressed during the integration stage as described in Section 4.2.1.3 below) and providing step-by-step evaluation throughout the processing pipeline.

4.2.1.2 *Energy-assessment pre-trial*

See Section 4.1.1.2 as the development and integration status is the same for H1 and H2 use cases.

4.2.1.3 *Integrated demonstration pre-trial*

The AI model for H2, as implemented by OUS, was prepared and deployed by TNO on its edge node according to the following four steps:

1. **Deployment of the algorithm**. The algorithm provided by OUS was deployed in a Docker container and eventually deployed inside a Kubernetes cluster on our edge node which is a virtual machine within our on-premises research cloud (distributed user-edge-cloud compute continuum enabler from WP3). Additionally, we created a test application that will be deployed on the UE that reads a test ECG signal provided by OUS and sends samples to the edge deployment. The modem we used was the 5G Redcap modem (5G RedCap IoT enabler).
2. **Basic UDP tests**. The algorithm provided by OUS included an option to read data received from the network via a UDP socket. To test this feature, we adjusted our test application to send data via UDP to the edge application. We deployed the test application on our UE and directed it to send data to the edge application. We successfully confirmed that the UE could connect via gNB and UPF to the edge server and that the data exchange between the UE application and the edge application was correct.
3. **Basic HTTPS test**. In this step, we transitioned from using the UDP protocol to HTTPS for improved security and reliability. Since UDP sends data unencrypted and does not acknowledge receipt, we modified the edge application provided by OUS to support HTTPS. Additionally, we updated our test application on the modem to also support HTTPS and created self-signed certificates to facilitate this secure communication. Similar to the UDP test, we instructed the UE application to send data to the edge application, confirming successful connectivity and data exchange.
4. **Baseline measurements**. With support from OUS, we integrated trace points into both applications to record timestamps at various processing stages (e.g., when packets are sent/received by the UE application and during different processing stages in the edge application). We also measured the network latency between the UE and the UPF/edge server by sending ICMP packets. We analysed the results to identify which components most significantly impacted end-to-end latency. For the modem we used 5G Redcap again.

Moreover, we did isolated tests for the slicing and the OpenAPIs for Network Exposure (e.g., CAMARA APIs for Quality on Demand) These tests demonstrate ways QoS could be guaranteed to the flow between the application running on the UE and the edge application.

4.2.2 H2 Test cases and test results

4.2.2.1 *EGM/ECG capture and processing pre-trial*

Pre-trial results are included in Table 57.

Table 57 : H2 pre-trial results

H2 / Lab01	EGM/ECG capture and processing
Facility / Site	OUS Lab
Objective / Description	AI algorithm development
Executed By	OUS
Devices / Components Involved	Laptop (to feed prerecorded EGM/ECG) PC/Edge (to run AI algorithm) RFID link (tag & tag reader) AI algorithm for PM/ICD parameter prediction
5G Infrastructure	Not applicable
Targeted KPIs	Prediction error
Measurement Tools	Not applicable
Ethics / Beta Users	Not applicable
Technical Enablers	Not applicable

In this subsection, we first illustrate the results validating each stage of the implemented three-stage pipeline and then proceed with the whole pipeline test. Figure 47 shows the original and reconstructed signals for one beat at the output of the U-Net autoencoder. This demonstrates the successful retrieval of the signal at the edge, which will be segmented in the next step.

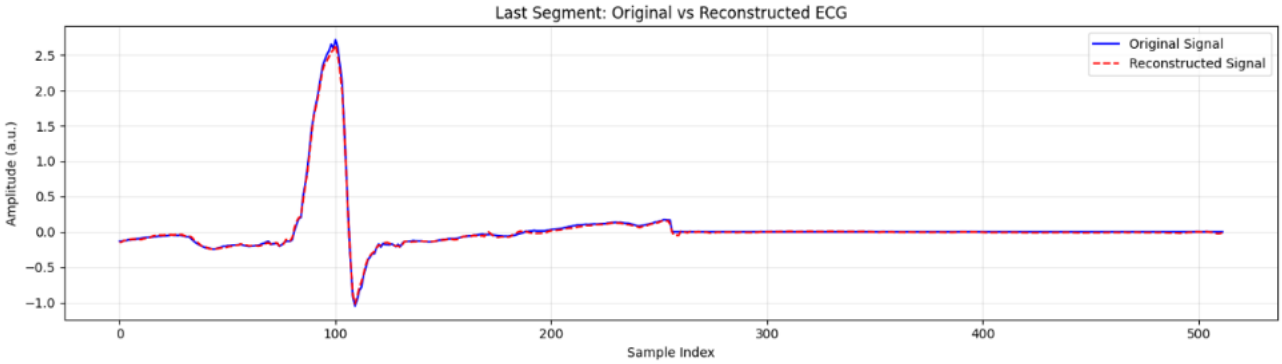


Figure 47 : Original and reconstructed signals for one beat starting with P wave at the output of the U-Net autoencoder

Figure 48 illustrates the segmentation results for 10 consecutive beats, where the P-wave, QRS complex, and T-wave are distinguished by different colours. The AI model achieves a segmentation accuracy of 99.7%. Please note that each beat has been resampled to 512 samples to match the input requirements of the segmentation algorithm.

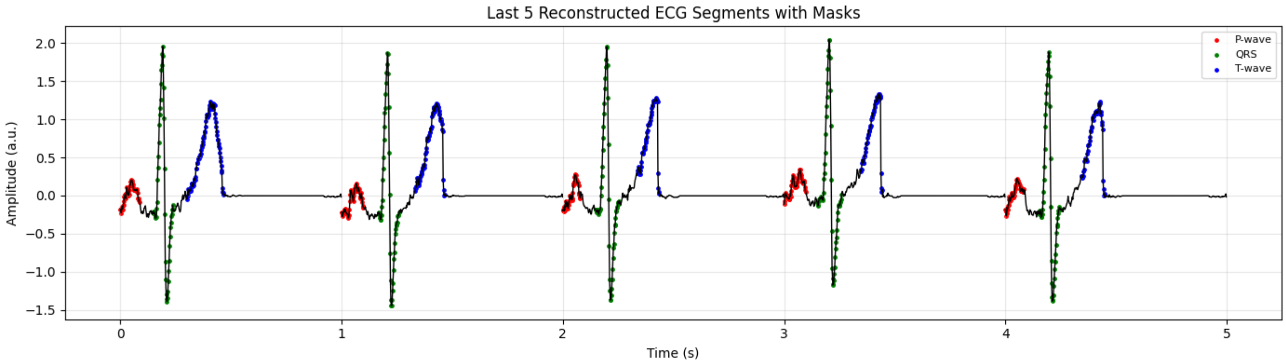


Figure 48 : Segmentation results for 5 consecutive beats starting with P wave

In this test case, the extracted beats for segmentation correspond to the samples between two successive P waves. This is particularly important for applications in which the network is triggered by the onset of P waves, for example through EGM signals captured from the atrium via the atrial lead. However, R peaks are typically more distinct in the ECG and can be reliably detected using a simple peak detector. Therefore, we retrained the model using input segments defined between two consecutive R peaks, and the corresponding results are illustrated in the Figure 49 and Figure 50.

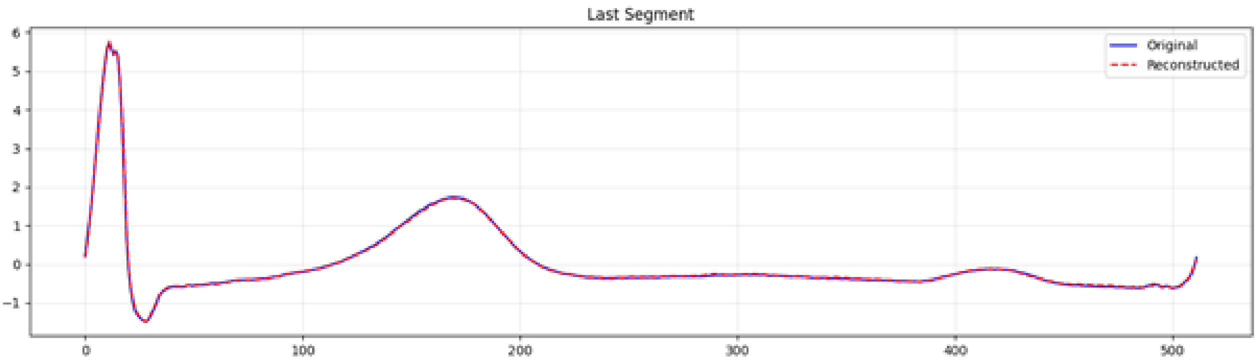


Figure 49 : Original and reconstructed signals for one beat starting with R peak at the output of the U-Net autoencoder

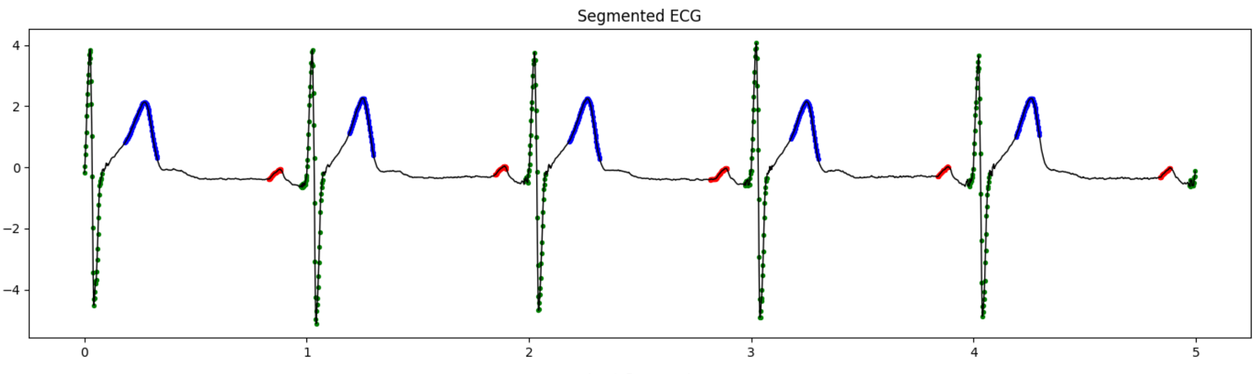


Figure 50 : Segmentation results for 5 consecutive beats starting with R peak

For the forecasting task, we buffer five beats, and the extracted 15 features (5 features for each wave) from each beat are fed into the TCN as described above. We use 20% of the dataset for testing, and the training and validation curves are shown in Figure 51, over 500 epochs. The results indicate that the training and validation losses converge without signs of overfitting. We achieve an RMS error of 5 ms for AV delay prediction on both the training and validation sets. Figure 52 also presents the predicted versus ground-truth AV delay for the trained forecasting model, demonstrating a close match between the results.

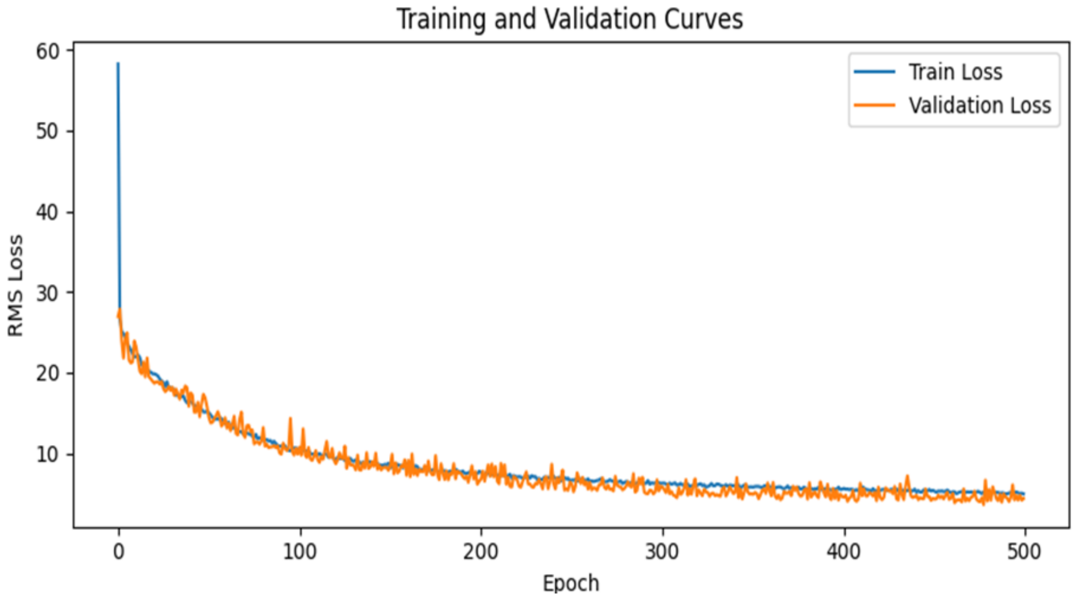


Figure 51 : Training and validation curves for the forecasting algorithm

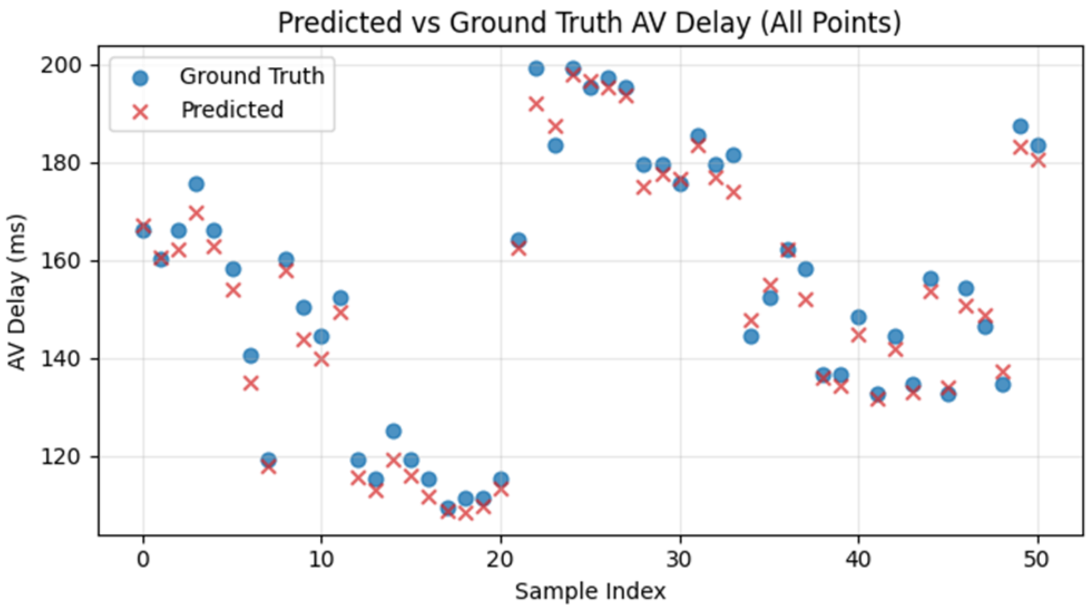


Figure 52 : Predicted and ground truth AV delay for the trained forecasting algorithm

Figure 53 presents the predicted and ground-truth AV delays for 100 ECG beats, generated by the three-step model with samples between two sequential P-waves as one beat. Figure 54 presents the same results as Figure 53, for 95 ECG beats extracted between two sequential R-waves. Each beat is first segmented using the segmentation model, after which 15 features (5 features for each wave) are extracted and used in the forecasting algorithm. The results show an excellent match with the ground-truth values, achieving a Root Mean Square Error (RMSE) of less than 4.9 ms. Also, the model takes around 70ms to execute the pipeline for each prediction. To avoid data leakage and ensure an unbiased performance evaluation, training and testing signals were taken from two separate public datasets [12][13]. The model has also been validated using different numbers of predictor beats, a range of SNRs, and various signal sampling rates.

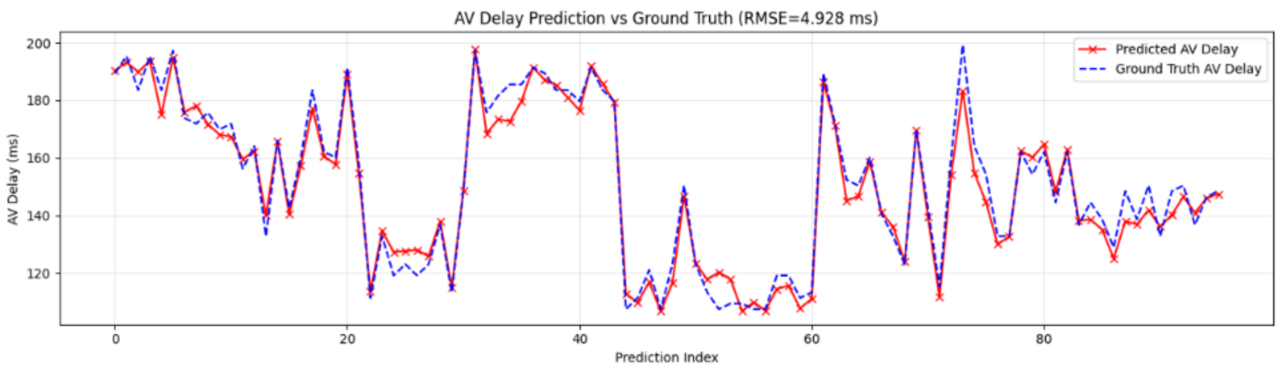


Figure 53 : Predicted and ground-truth AV delays for 100 ECG beats for PP samples

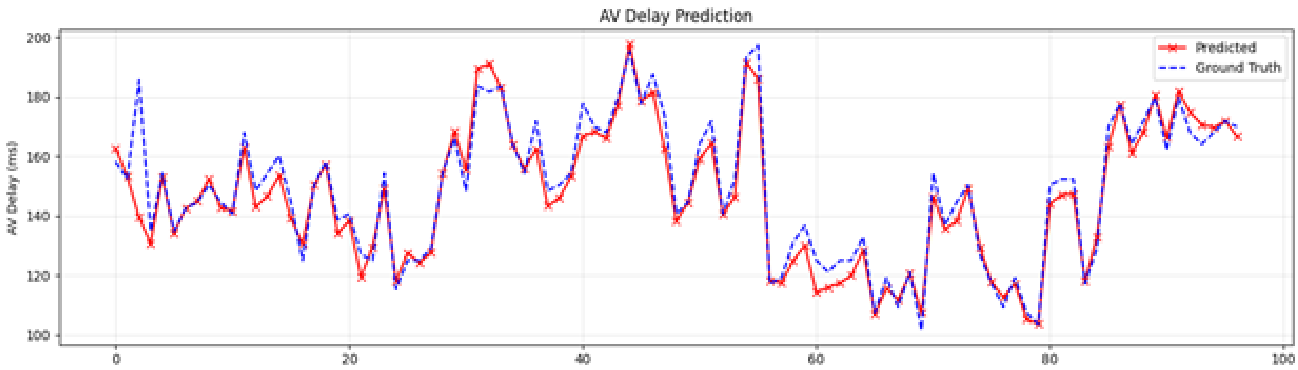


Figure 54 : Predicted and ground-truth AV delays for 95 ECG beats for RR samples

In a closed-loop system for AV delay prediction, the model directly determines the trade-off between accuracy, latency, and energy consumption. For instance, achieving a prediction accuracy on the order of ±5 ms is clinically meaningful, as it enables near-optimal synchronization between atrial and ventricular contractions. However, if the model runtime is approximately 70 ms, this already consumes a significant portion of the available physiological window, especially under high heart rates where the AV delay may be as short as 100–120 ms. In such conditions, the system has limited margin to accommodate additional delays from sensing, communication, and actuation, potentially compromising timely pacing decisions. Also, on-patch energy consumption is primarily governed by the beat transmission frequency. The current method transmits beats individually in packets to fill the buffer at the edge for prediction, which introduces challenges related to increased energy consumption on the patch. Relevant H2 KPI measurements in Table 58.

Table 58 : H2 KPIs measurements for EGM/ECG capture and processing

Test Case ID	Target KPIs / Requirements	KPIs measurements	Evaluation / Notes [Network or Application Related]
H2_NO_MVS_1	Prediction error (application KPI): 10 ms	20ms	The pacing time error is measured over the maximum value. The impact of network latency should be included.

4.2.2.2 *Energy-assessment pre-trial*

Baseline assessment is presented In Table 59.

Table 59 : H2 energy base line assessment

H2 / Lab02	Energy assessment
Facility / Site	TNO Hi5 facility in The Hague, The Netherlands
Objective / Description	Conducting baseline energy measurements.
Executed By	TNO
Devices / Components Involved	• 6G Radio Box (NUC + USRP N320 SDR + RF Switch) + Open Air Interface software • Energy Consumption Testbed (Laptop + OTII Power meter + Quectel RG255C 5G Redcap modem) + Server/Testbed/Client software • Variable Attenuator Hi5 Research Cloud + Open5GS software
5G Infrastructure	Software: Open AIR interface. Hardware: USRP B210 as gNB and Quectel RG255C as modem
Targeted KPIs	Device Energy efficiency
Measurement Tools	QOITECH Otii Arc Pro for energy measurements
Ethics / Beta Users	Not applicable
Technical Enablers	5G Redcap

Similar to H1, the first baseline measurements have been conducted, however instead of transmitting a large amount of data all at once, in this pre-trail, small packets of 512 bytes will be transmitted every second by the RedCap module. The complete list of configurations can be found in Table 60.

Table 60 : Configuration base line energy measurements for H2

Configuration	Value
RSRP	-77 dBm
Modulations	QAM64
Nr of uplink slots	4.5
Nr of downlink slots	5.5
Payload size	512 bytes
Packet count	1000
Transmission interval	1 second
Protocol	HTTPS

The results are shown in Table 61. As expected, the total duration of the measurements took 16 minutes and 42 seconds, that is roughly 1000 seconds. The total energy consumption for 1000 packets (and the time in between the transmissions) is measured to be 57.6 mWh. This would suggest that a battery with 1000 mAh at 3.6 volts (3600 mWh) would last for roughly 17 hours.

Table 61 : Results of H2 baseline energy measurements

Measurement parameter	Value
Packets sent	1000
Packet loss	0
Energy	57.6 mWh
Average power	54.5 mW
Minimal power	13.9 mW
Maximal power	132.2 mW
Duration	16:42 minutes
Voltage	3.8 V

The current testbed software is not yet capable of recording the latency of each packet. Therefore, no clear result can be shown here. However, using a simple ping command we saw that the RTT was something between 14 and 30 ms depending on the selected modulation and coding rate. The ping results can be found in Table 62.

Table 62 : Measured ping latency for different modulation and coding schemes

RSRP (dBm)	Uplink modulation	Code rate x 1024	Throughput (Mbit/s)	Ping (ms)
-77	QPSK	193	2.4	24
-77	16 QAM	378	8.0	14
-77	64 QAM	466	15	15
-77	256 QAM	711	14	23
-77	256 QAM	948	12	30

The results in Table 61 and Table 62 can be compared with the data rate, latency and battery live KPI target in section 2.2.52.1.5.

The best ping latency achieved using the current setup is 14 ms with a 16 QAM modulation and an RSRP of -77 dBm (strong signal). Keep in mind that the ping latency is a round-trip time, so this is a summation of the up and downlink latency. No measurements were done for only the uplink latency; however, we can assume that this would be roughly half the ping latency. Therefore, an uplink latency of 7 ms can be expected and thus the KPI target of < 10 ms could be reached. Better measurement techniques for only uplink latency should be developed in the next steps.

Table 62 also shows the measured throughput for different modulations. Even in the worst case the measured throughput is much higher than the target throughput of 4 kbit/s. Note that these measurements use a RSPR of -77 dBm. New measurements with a lower RSRP should be done to see if the throughput target is also achieved for these lower values.

As mentioned above, with an RSRP of -77 (very good signal) the battery live for the modem only will be around 17 hours. This is in line with the KPI target of several hours. Relevant H2 KPI measurements in Table 63.

Table 63 : H2 KPIs measurements for energy assessment

Test Case ID	Target KPIs / Requirements	KPIs measurements	Evaluation / Notes [Network or Application Related]
H2_NL_MVS_2	Device energy efficiency: several hours	17 hours	
	Network latency: <10ms	7ms	This is for the best case scenario, we did not measure the latency for HTTPS.
	User experienced data rate: 4kbps	15 Mbps	Measured with RSRP of -77 dBm, which is higher than the -110 dBm target KPI. However, we expect to reach the target KPI.

4.2.2.3 *Integrated demonstration pre-trial*

Table 64 : H2 initial baseline measurements

H2 / Lab03	Integrated demonstration
Facility / Site	TNO lab in The Hague, The Netherlands
Objective / Description	Baseline measurement, breakdown of the total latency in components
Executed By	TNO
Devices / Components Involved	See Section 2.1.3.2
5G Infrastructure	See Section 2.1.3.2
Targeted KPIs	Network service latency, Run time
Measurement Tools	Code instrumentation to record timestamps at various processing stages, ping tool
Ethics / Beta Users	Not applicable

Technical Enablers	5G RedCap IoT enabler, distributed user-edge-cloud compute continuum enabler

Initial baseline measurements have been conducted according to the setup described in Section 2.1.3.2, and presented in Table 64. In each experiment, the UE sent data to the application running in the edge, and we recorded timestamps at various processing stages. The total latency was measured by the application running on the UE, as the time between sending a HTTPS request and receiving a corresponding response. In total, we sent 3228 HTTPs requests. Moreover, we measured the network latency between the UE and the UPF/edge ingress server (i.e., entry point for HTTPS packets sent to the edge application) by sending 100 ICMP packets. The results are presented in Table 65.

Table 65 : E2E latency breakdown

Component	Sub-component	Average Latency (ms)	Share of total latency
Total latency		111.68	
Network (UE ↔ Edge Ingress server, Ping)	Total	27.90	25.0%
	UE ↔ UPF	27.52	24.6%
	UPF ↔ Ingress	0.38	0.3%
Edge server processing (HTTPS)	Total	72.37	64.8%
	Segmentation	69.77	62.5%
	Feature Extraction	0.49	0.4%
	TCN Inference	2.00	1.8%
	Other server overhead	0.11	0.1%

Edge server processing accounts for the majority of the total latency, contributing 64.8%. Of this, the segmentation model alone is responsible for 96.4% of the edge server processing time (62.5% of the total latency). In contrast, the TCN prediction model contributes only 3.4% of the edge server processing time (1.8% of the total latency). The network RTT adds approximately 25%. It is important to note that this RTT latency is measured using ICMP packets, while the total latency is measured using HTTPs packets. Hence, the presented network measurements are more an indication of the achievable latencies on the radio link and were not measured using the actual HTTPs traffic sent from the UE.

If we compare the results achieved in this bassline test to the KPIs from section 2.2.5, we can conclude the following:

1. Network service latency KPI (< 10 ms) is not being met. The measured UE-to-ingress round-trip time (RTT) is 27.90 ms, which means that an estimated one-way latency is approximately 14 ms.
2. The algorithm runtime KPI (< 10 ms) is not being met. While the feature extraction and TCN inference average only 2.49 ms, the segmentation takes 69.77 ms on average. Hence, to be able to meet this KPI we must address the segmentation latency in the subsequent optimizations.

Some of the other observations from our baseline test are listed below:

- The total HTTPS latency response time has a narrow 95% confidence interval of [111.28, 112.09] ms. If we break this down by components, we can see a similar trend. That is, we see the following 95% confidence intervals: segmentation has [69.40, 70.14] ms, feature extraction has [0.48, 0.49] ms and TCN inference has [1.99, 2,01] ms. The narrow intervals show that the measurements are stable and reproducible. TLS Handshake Overhead. The first request in each session experiences significantly higher latency due to the TLS handshake (e.g., 374.35 ms for the first request, compared to approximately 119 ms for subsequent four requests). The main reason for this is that, when using HTTPS, the initial connection requires several additional RTTs to negotiate the TLS session before any application data can be exchanged. Subsequent requests reuse the established session (i.e., employ session resumption) and do not have this penalty.
- Buffering vs Prediction requests. The server employs a sliding window of 5 batches before producing a prediction. Hence, the first four requests per session are *buffering* requests, which only require segmentation. Prediction requests, from the fifth request onward, additionally perform feature extraction and TCN inference. Despite this, the measured difference in edge server processing time is small: buffering requests average approximately 70 ms (segmentation only), while prediction requests average 72.37 ms. Hence, there is only an increase of approximately 2.5 ms due to the lightweight feature extraction (0.49 ms) and TCN inference (2.00 ms).

Table 66 : H2 KPI measurements for Integrated demonstration

Test Case ID	Target KPIs / Requirements	KPIs measurements	Evaluation / Notes [Network or Application Related]
H2_NL_MVS_3	Network service latency: <10 ms	14ms	Latency above the limit. The major contributor is the latency in the 5G system (UE – UPF).
	Run time : <10 ms	72.37ms	Run time above the limit. Main contributor to the edge server latency is segmentation model. We intend to address using optimizations proposed in section 4.2.3.3.

4.2.3 H2 Next steps

4.2.3.1 *EGM/ECG capture and processing pre-trial*

To reduce the model runtime and consequently the end-to-end latency of the system, one step would be to use a tiny model, particularly for the segmentation task. This would be achieved through a trade-off between accuracy, latency, and computational complexity over the edge. For example, the normal PR interval is about 100–200 ms, and in this context, an AV delay prediction with around 20 ms accuracy would generally be considered acceptable from a clinical perspective. Also, this would set an upper limit of 100ms for E2E latency before noticeable accuracy degradation.

One step toward device-level energy optimization, a sparse communication and predictive control scheme can be adopted in which data transmission is not performed for every heartbeat. Instead, the system operates on a short buffer (e.g., two consecutive beats) and employs a multi-step prediction model to estimate the AV delay for the next two upcoming beats. In this framework, only every other beat is transmitted to the edge (or processed with higher computational resources), while intermediate beats rely on locally available predictions. This reduces the frequency of communication events by approximately 50%, leading to a significant decrease in energy consumption. However, this approach introduces a trade-off, as prediction errors may accumulate over the prediction horizon in the absence of real-time feedback.

4.2.3.2 *Energy-assessment pre-trial*

Next steps involve:

- Improving energy consumption. Currently, the modem does not go into sleep mode between transmission. Next research would involve the possibility to use DRX in such a way that it will sleep in-between messages.
- Updating the testbed software such that latency for each packet can be measured.
- Updating the testbed software to use AT commands instead of utilizing the PPP connection. This will result in a more realistic energy consumption measurements as the packet generation will be done by the modem itself.

4.2.3.3 *Integrated demonstration pre-trial*

As shown in Section 4.2.2.3, at the moment, the biggest impact on latency is the edge server processing time, especially the segmentation component. To reduce this, as the next step, we plan to investigate the impact of assigning different resources to the Kubernetes pod running the edge application. Currently, the edge Virtual Machine from our integrated demonstration setup has 4vCPUs and 4GB RAM. Moreover, no resources were assigned directly to the Kubernetes pod (the pod was competing for these resources with other applications running in the edge such as the UPF).

We plan to test the two following optimizations:

1. Additional CPU resources (8vCPUs, 8GB RAM).
2. GPU resources (4vCPUs, 4GBRAM, 1 GPU with at least 4GB VRAM).

The main rationale behind these two optimizations is that assigning more resources should reduce the edge server processing time. In particular, we expect that the segmentation time would be significantly reduced as U-Nets are highly parallelizable on a GPU.

Additionally, we plan to conduct a more extensive long-term test to evaluate the network availability and network reliability KPIs. This test will run for one month, during which we will have multiple parallel client applications sending HTTPS requests to the edge application at any given time (as indicated in Section 2.2.5 regarding expected connection density). We will monitor whether the network service latency and runtime KPIs are met for all processed HTTPS requests throughout the duration of the test.

4.3 P1 Ubiquitous B5G/6G communication and slice deployment across operators for PPDR AR/VR assisted Control Centers

This section provides a comprehensive overview of the testbed's assessment in the context of PPDR, and work related to the seamless Enabler and service integration. It outlines the deployment and integration of the innovation enablers and network applications to their pre-trial and initial testbed/trial environments. Additionally, it includes some benchmarking results from the testbed and the predefined test cases, ensuring expected testbed functionality and baseline KPIs are in place.

4.3.1 P1 Integration status

4.3.1.1 *Testbed evolution, integration, and enabler deployment*

As discussed in section 2.3, P1 is utilising various testbeds for Scenarios A, B and C, integration and testing, starting with the AMAZING-6G enablers. Precisely, the Patras-5G Autonomous Edge (Figure 55, a & b) has been used for a private 5G (IN-A-BOX) deployment, and the outdoor AW2S radio unit-based site (Figure 55, c) has been configured. Furthermore, WINGS has used wi.breathe (Figure 55, d) for Scenario B pre-trial testing.

(a) Patras-5G Autonomous Edge technologies

(b) Patras-5G Autonomous Edge (IN-A-BOX) deployment, for indoor pre-trial of Scenario A

(c) PNET facility for the outdoor pre-trial testing and trial

(d) WINGS pre-trial testbed

Figure 55 : P1 pre-trial testbeds

AMAZING-6G Enablers integrated

Automated gNB configuration: designed and developed to enable the gNB real-time and dynamic configuration, including the core network connection It has been successfully tested with Amarisoft gNB and AW2S (indoor) for Autonomous Edge (IN-A-BOX). The gNodeBs deployed in Patras-5G lab offer an interface from which real time changes can be made and applied on the running configuration. This functionality is used to modify on demand various parameters of the Autonomous Edge, e.g. using standard Linux tools, the network traffic flow is modified on-the-fly by setting bandwidth limits, introducing time delays and/or introducing corrupted data packets in the network traffic to simulate various network failures or configurations.

Network performance monitoring and control: designed and implemented to provide advanced observability of compute, network, and 5G resources Based on open-source tools for metrics collection, time-series data storage and visualization. Additionally, the facility provides telemetry, data collection, and monitoring services through Prometheus servers, NetData , and custom in house created data collectors tailored for the solutions deployed in Patras testbed, offering extensive metrics related to the infrastructure, transport layer, VNFs, RAN, UEs, and energy consumption sensors. Grafana dashboards enable real-time monitoring, while Elasticsearch and Kibana aid data collection and visualization.

Identification and selection of backhauling: designed and implemented for scanning, checking and selecting a reliable backhaul connectivity option, from a disaster area to Remote Control Centers for example, based on the continuous performance evaluation of the available options. The enabler has been developed and integrated with the Autonomous Edge. It is planned for testing data paths through private 5G & satellite networks, while fine tuning of the selection algorithm is ongoing in the lab environment (details in Scenario C, at subsection 4.3.2).

Compute resource management, intelligent service and resource orchestration in extreme edge/edge/cloud compute continuum: designed to enable the dynamic orchestration of compute workloads (AR/VR), supporting situational awareness in a disrupted environment.

Creation of Kubernetes clusters on demand: designed and implemented for instant, on-demand provisioning of Kubernetes clusters, including services tailored to PPDR service needs.

Open APIs for Network Exposure - TM Forum APIs: implemented as the unified orchestration interface for services inventory, ordering and lifecycle management, across multi-operator communication and compute environments.

Scenario A - testbed description and integration

Patras-5G Autonomous Edge, an ideal solution for on-premises 5G deployments, is used for P1.1 test case. To further help the test execution some mobile phones are connected to the 5G network deployed in Patras5G testbed together with CPE RUTX50. The experiment concerns a short-range indoor 5G deployment operating under clear line-of-sight conditions, with the user equipment positioned within 5 meters of the radio access point. The setup uses a dedicated network slice configured with SST:1, representing a standard enhanced mobile broadband service configuration, while no additional background traffic is introduced in order to isolate and evaluate the baseline network performance. The test environment consists of a Edge-based Open5GS 5G core, an AW2S gNodeB providing radio access connectivity, and a RUTX50 CPE acting as the device under test. The primary metric under investigation is TCP throughput, with the objective of assessing the achievable end-to-end data transfer performance under controlled indoor conditions and minimal interference. However, RTT and reliability are also measured.

The following tests (among others) have been performed. The results of these tests are stored in a Prometheus server, displayed on Grafana dashboards, and can be retrieved for post processing.

Ping: The user can initiate a ping from a device to any target. The ping can be parameterised on duration (fixed or infinite), size (to simulate various protocols), count etc. This tool can be used to estimate network latency, verify network operation, and test the reliability of the network.

Traceroute: Similarly, a traceroute command can be issued to check the various hops and identify possible bottlenecks in the communication.

Iperf: To measure network traffic capabilities, an iperf3 test can be performed between two endpoints in our network.

Speedtest: A typical internet speed test can also be executed. This will try and connect to a public internet or local speedtest server.

4.3.2 P1 test cases and test results

4.3.2.1 *IN-A-BOX Integration and Testing*

The **Throughput test** aims to assess the measurement capabilities of the system employed in future pre-trial and trial activities. For measuring Throughput, a packet stream is emitted from a source and received by a data sink (destination). The amount of data successfully transmitted per unit of time (seconds) as measured by the traffic generator and the probes shall be recorded. A TCP-based traffic stream is created between the source and the destination using the iPerf2 tool. To reduce impacts of TCP slow-start algorithm, the first 20s of a measurement are discarded. The experiment shall include the consecutive execution of several trials (iterations) according to the following properties. Duration of a single trial (iteration) of at least 3min, where the first 20 seconds of the measurements are discarded, records throughput over 5-second intervals within an iteration and number of replicas (iterations) to be at least 25.

RTT is measured between two endpoints. For measuring RTT, a packet stream is emitted from a source and received by a data sink (destination). The data sink shall acknowledge the correct reception of the data packet back to the sink. The time of emitting the packet at the data source and receiving the acknowledgement at the data source are to be captured and the RTT is calculated as the difference between the two events. The test case shall include the consecutive execution of several replica (iteration is at least 2 minutes, number of replica (iterations) to be at least 25). For the execution various UEs have been used, in order to investigate low latency configurations as shown in Figure 56.

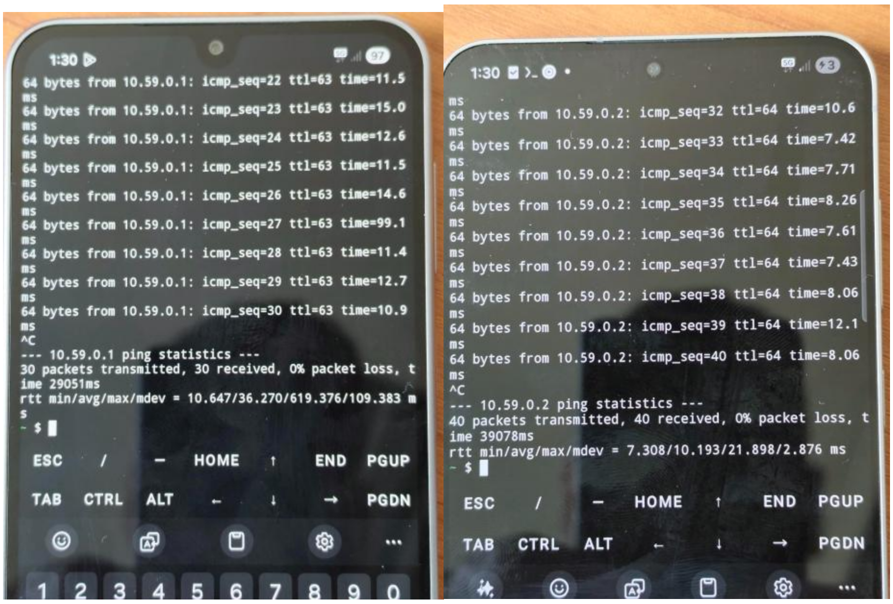


Figure 56 : RTT test results with Samsung A19 and S25pro UEs

Reliability This KPI refers to reliability measured between two endpoints of the network. It measures the number of packets successfully delivered between these two endpoints within the time constraints specified in this test case, divided by the total number of sent packets. In the context of network layer packet transmissions, percentage value of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of sent network layer packets. Note that as underlying system we mean any network components between the source and destination.

For measuring Reliability, a packet stream is emitted from a source and received by a data sink (destination). The data sink shall acknowledge the correct reception of the data packet back to the sink. The time of emitting the packet at the data source and receiving the acknowledgement at the data source are to be captured and the RTT is calculated as the difference between the two events. Several tests have been performed , the default stream of generated ICMP ECHO_REQUESTs shall comply to the traffic profile of the use case so here we assume URLLC = 32 bytes.

These results are noted in Table 67.

Table 67 : P1 pre-trial results

P1.1 / Lab01	Pre-Trial 1 Scenario A Phase A/P1
Facility / Site	Patras-5G
Objective / Description	To test the operation of Private Autonomous Edge operation with local control and user plane, integrating data services with various optimized configurations (line of sight indoor deployment within distance of 5 meters) Measure maximum user data rate available in different scenarios (DL) Measure RTT from one end to the other for latency. Measure Reliability for network layer in specific conditions - URLLC scenario (1 hour, 40 bytes total size, 1 second interval)
Executed By	UPAT and PNET
5G Infrastructure	The pre-trial network environment consists of a cloud-based (Edge) Open5GS 5G core(it is now on NUC130Xi5), an AW2S gNodeB providing radio access connectivity, and a RUTX50 CPE acting as the device under test
Targeted KPIs	Communication service availability ≥ 99.999% End-to-end latency < 100 ms Uplink Bit rate > 100Mbit/s
Measurement Tools	Ping: The user can initiate a ping from a device to any target. The ping can be parameterised on duration (fixed or infinite), size (to simulate various protocols), count etc. This tool can be used to estimate network latency, verify network operation, and test the reliability of the network. Traceroute: Similarly, a traceroute command can be issued to check the various hops and identify possible bottlenecks in the communication. Iperf: To measure network traffic capabilities, an iperf3 test can be performed between two endpoints in our network.
Ethics / Beta Users	Pre-trial Lab test
Technical Enablers	Automated gNB configuration, Network performance monitoring and control, Creation of Kubernetes clusters on demand

Use case KPI measurements are presented in Table 68.

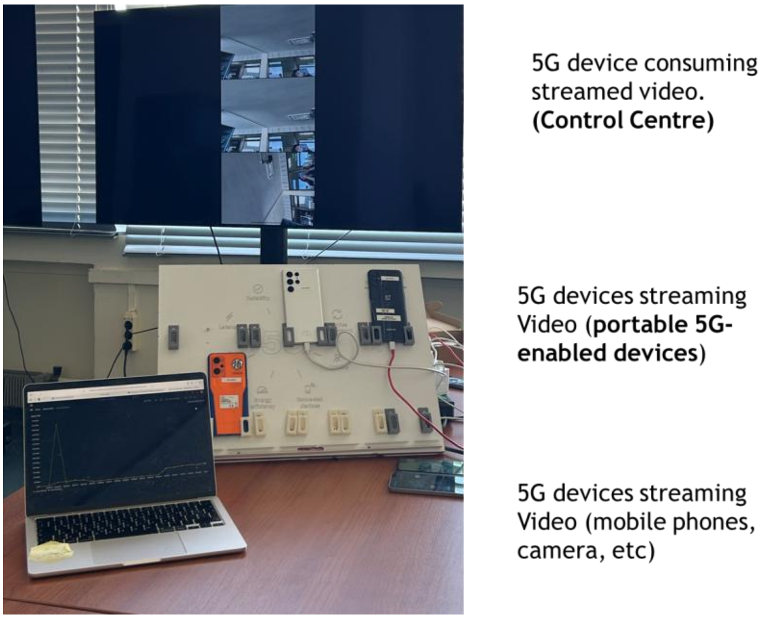
Table 68 : P1 KPI measurements.

Test Case ID	Target KPIs / Requirements	KPI measurements	Evaluation / Notes [Network or Application Related]
P1.1	Mean Throughput >100 Mbps Mean RTT <100 msec % of successful packets received for RTT < 50 ms: 100 %. % of successful packets received for RTT < 100 ms: 99.99 %	Mean Throughput: 429.31 +/- 2.87 Mbps Mean RTT: 14.58 ± 0.29 msec % of successful packets received for RTT < 50 ms: 94.71 %. % of successful packets received for RTT < 100 ms: 97.11 %	This is without Internet cloud connectivity Results are also taken with CPE

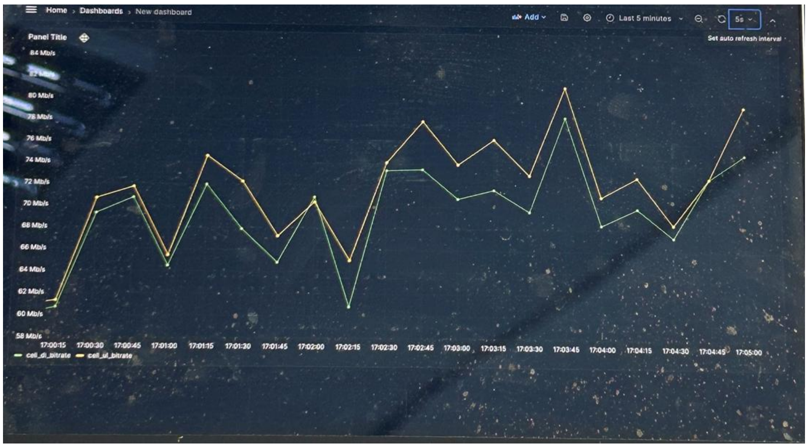
4.3.2.2 *Scenario A - Autonomous Edge (5G IN-A-BOX) benchmarking and application integration*

The concept of this use case is based on a PPDR scenario designed to support and enhance first responder operations through advanced connectivity and edge computing. A private 5G network is deployed, complemented by MEC capabilities to enable low-latency processing and local service delivery. Once first responders arrive on site, they utilize portable 5G-enabled devices, which may be carried on their person or deployed in the field, including cameras, IoT sensors, drones, and other mission-critical equipment for real-time data collection. All information gathered by these devices must be made accessible to Control Centers, whether located directly in the field or at centralized command locations, to ensure effective coordination and situational awareness. However, since the system operates within a private network, public Internet access may not be available, meaning that conventional communication solutions relying on centralized cloud connectivity cannot be used. To address this limitation, the approach focuses on deploying IP-based solutions that operate independently of public Internet access, ensuring full functionality within isolated network environments. These solutions can include Android applications - whether commercial, open-source, or custom-developed - as well as web-based platforms for Control Centers, ultimately enabling reliable communication and enhanced situational awareness in mission-critical PPDR operations.

The proposed system consists of a secure video communication platform designed for a PPDR control room environment. 6 video sources, at this stage mobile phones (portable 5G-enabled devices), connect through the above mentioned private 5G network (IN-A-BOX) that operates independently from the public internet. Each device transmits compressed video streams. Depending on the operational requirements, the video streams can be directly consumed by other UEs, either through dedicated applications in case of tablets (as in a portable Command Center), or custom-made web applications for laptop based on-the-field command centers (centralized command locations). If needed, video streams can be routed to an edge-based media gateway or streaming server, which performs stream ingestion, session management, transcoding (if required), and distribution to further control room clients either on the field or on remote locations pending backhaul connectivity. The control room subsystem includes operator workstations running the developed application capable of displaying multiple simultaneous streams in a grid layout, supporting low-latency viewing, recording, and optional archival storage on local edge. The entire system operates within an isolated private network environment without reliance on external internet connectivity, ensuring security, low latency, and operational resilience suitable for mission-critical PPDR deployments, while allowing for external consumers to receive this feed for even better situational awareness.



(a)



(b)

Figure 57 : (a) P1 pre-trial deployment of 6 UEs with cameras (b) Network traffic monitoring

This Proof of Concept developed on top of the Autonomous Edge in Patras-5G lab demonstrates a basic end-to-end video streaming scenario running over a 5G network. In this setup, 6 Android mobile phones are used as video capture devices, each running an application that streams live video using RTSP over the 5G connection (Figure 57a). These devices act as the video sources and continuously transmit real-time video traffic through the network. On the receiving side, an Android application is deployed to consume these video streams, functioning as a mobile field control center that allows users in the field to monitor incoming live feeds in real time. In parallel, a network traffic dashboard is used to observe and analyse 5G usage generated by the system, showing both uplink traffic from the streaming devices and downlink traffic to the receiving application (Figure 57b). Furthermore, a web application has been developed at UPAT, allowing users to connect directly (IP-based) to devices within the local network and consume the produced video streams, presenting them as an additional control panel for monitoring and management (Figure 58). The above example demonstrates the use of six mobile phones streaming in a configuration similar to the one described previously, further validating the scalability and functionality of the setup.

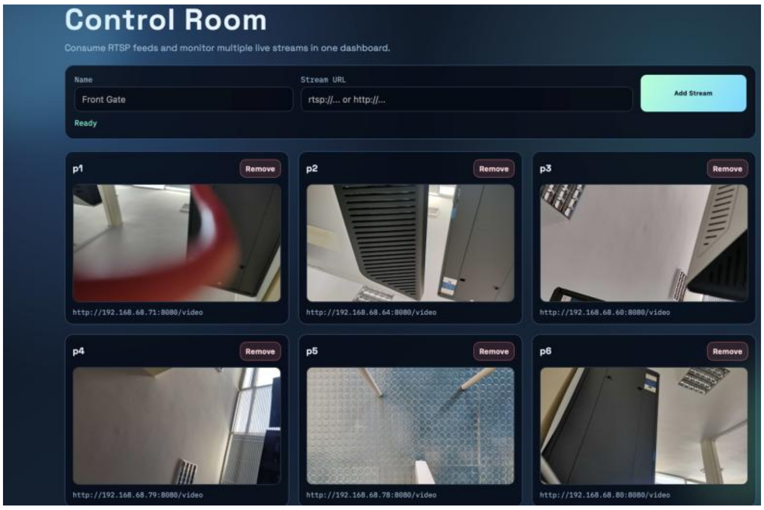


Figure 58 : Streaming from 6 UEs (P1 pre-trial Scenario A)

4.3.2.3 *Scenario B - wi.breathe integration and application testing*

In addition, WINGS has run pre-trial tests in their private testbed. During the tests the management platform (wi.breathe) was used for presenting the data from a camera and sending notifications to users, in cases of measurement fluctuations outside the desired limits or in cases of events (e.g. fire detection). In general, during the pre-trial testing it was possible to (i) Provide remote monitoring in real time and at the desired data measurement/transmission frequency, (ii) Early warning based on multiple data sources and computational intelligence technologies, (iii) Detection of incidents in areas of interest, (v) Sending notifications in case of fluctuations in measurements outside the limit.

Table 69 : P1 WINGS application pre-trial

P1.1 / Lab02	Pre-trial 2/P1
Facility / Site	WINGS 5G/6G Private testbed (Athens)
Objective / Description	Main objective was to test functionality for detection of public safety incidents. During the pre-trial testing it was possible to (i) Provide remote monitoring in real time and at the desired data measurement/ transmission frequency, (ii) Early warning based on multiple data sources and computational intelligence technologies, (iii) Detection of incidents in areas of interest, (v) Sending notifications in case of fluctuations in measurements outside the limit.
Executed By	WINGS
Devices / Components Involved	Camera (optical/thermal)
5G Infrastructure	5G/B5G modem/router
Targeted KPIs	AI model accuracy
Measurement Tools	WINGS platform (wi.breathe)
Ethics / Beta Users	Not applicable as the camera did not capture any people or faces etc. but only environmental aspects (e.g. nature, trees etc.)

Technical Enablers	AI-as-a-Service framework: AI-as-a-Service/ ML models IoT Connectivity and Infrastructure: IoT Gateways/ Devices Data Ingestion and Telemetry - Monitoring Platform IoT Service Platforms and Management - IoT Sensors Orchestration/ Service and Resource Lifecycle Manager/ Message queue fabric/ IoT Exposure Function

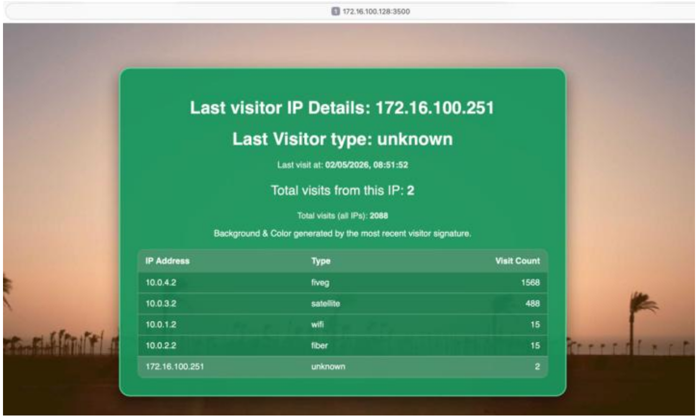
4.3.2.4 *Scenario C - Enablers testing*

For this PPDR scenario, a private 5G network has already been deployed to support mission-critical communications and field operations. Extending this network by connecting it to the public internet would act as a significant force multiplier for first responders, enabling enhanced coordination, access to external services, and improved situational awareness during emergency operations. However, integrating such connectivity introduces a challenge, as multiple potential backhaul options may be available, including Wi-Fi, public 5G, fibre, and NTN, each with different performance characteristics and constraints. To address this, the problem requires an automated and robust backhaul selection mechanism capable of dynamically balancing key metrics such as latency, throughput, reliability, and cost. The proposed solution involves first identifying all available backhaul options, then continuously collecting performance metrics for each candidate link, including parameters like latency, throughput, SNR, and operational cost. Based on a configurable policy, the system selects the most appropriate backhaul to serve as the primary internet gateway, while continuously monitoring the environment for changes. If network conditions shift, the system automatically adapts by re-evaluating and switching the active backhaul to maintain optimal performance and resilience.

The enabler has been developed and integrated to the Patras5G testbed. In a proof-of concept demo, we assume the existence of four candidate backhaul access technologies. Each of these connectivity options exhibits different performance characteristics in terms of latency, jitter, and overall reliability. To evaluate them in real time, we implemented a mechanism that continuously measures latency by calculating the RTT of periodic ping requests. These measurements are then visualized through a monitoring dashboard that displays the current status and performance metrics of each available connection.

At the start of the experiment, the system presents the initial state of all four links, where fibre demonstrates the lowest latency and jitter, followed by 5G and Wi-Fi, while NTN shows the highest latency among the available options. Based on these measurements, our enabler automatically selects the fastest available connection to provide public internet access. To demonstrate this behaviour, we also developed a web application and a client application (Figure 59). The client uses the interface dynamically selected by the enabler to access the web application, which in turn displays information about connected clients visiting the service.

Additionally, we implemented a mechanism that allows manual modification of the characteristics of each connection in order to validate the behaviour of the enabler under controlled conditions. When the enabler detects a change in network performance, such as the emergence of a faster available interface, it automatically switches the active connection, and this change is immediately reflected in the web interface. During the experiment execution, the latency graph shows that initially all interfaces are operating normally, with fibre being selected as the preferred option due to its superior performance. However, at a later stage, a simulated catastrophic event affects the fibre link, demonstrating how the system reacts by reassessing the remaining connections and adapting accordingly to maintain the best available performance.



(a)

(b)

(c)

Figure 59 : (a) Enabler application interface (b) Monitoring of backhaul options (c) Enabler restoring connectivity after a fiber cut, to other option

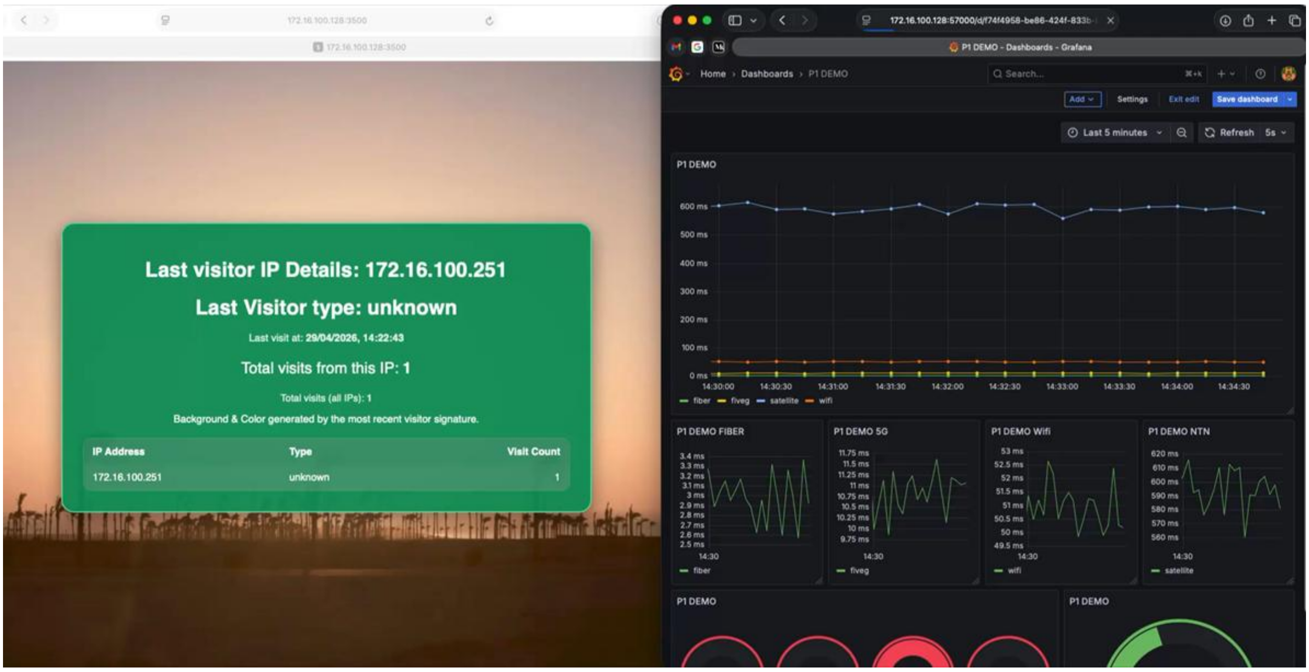


Figure 60 : Enabler demo application dashboard

4.3.3 P1 Next steps

Scenario A: The next phase of testing will take place in June 2026 with integration of MC-PTT application. Additional services will be tested (Phase 2) and KPIs will be measured.

Scenario B: The testing will be transferred to Patras-5G testbed in October 2026. In the meantime, VR-enabled control centre and L4S will be tested in the lab, so that all services to be simultaneously tested in October 2026.

Scenario C: The use case will be evaluated using multi-network connectivity, with 5G, Wi-Fi, and satellite links, to assess enablers and test connectivity.

4.4 P2 Mission critical services interoperability with other systems

4.4.1 P2 Integration status

P2 use case has been integrated and validated in a lab-based “vehicle” setup built on a mini-PC running Ubuntu 24.04. The system combines heterogeneous network connectivity (5G router, Wi-Fi 6, and Starlink) with multiple sensing sources, including two webcams and one thermal camera. A modified FFmpeg pipeline is used to encode and live-stream video feeds from the vehicle towards the CCC.

At the edge, MediaMTX operates as the video server, while Qosium monitors network traffic and performance across access technologies. Network and application metrics are collected into InfluxDB and visualized using Grafana, enabling real-time monitoring and post-analysis. The CCC backend is implemented using Nginx to host the CCC web UI and encoder control functions. At the CCC side, standard web browsers are used for video playback, completing the end-to-end interoperability chain from vehicle to control center. The setup is depicted in Figure 61.

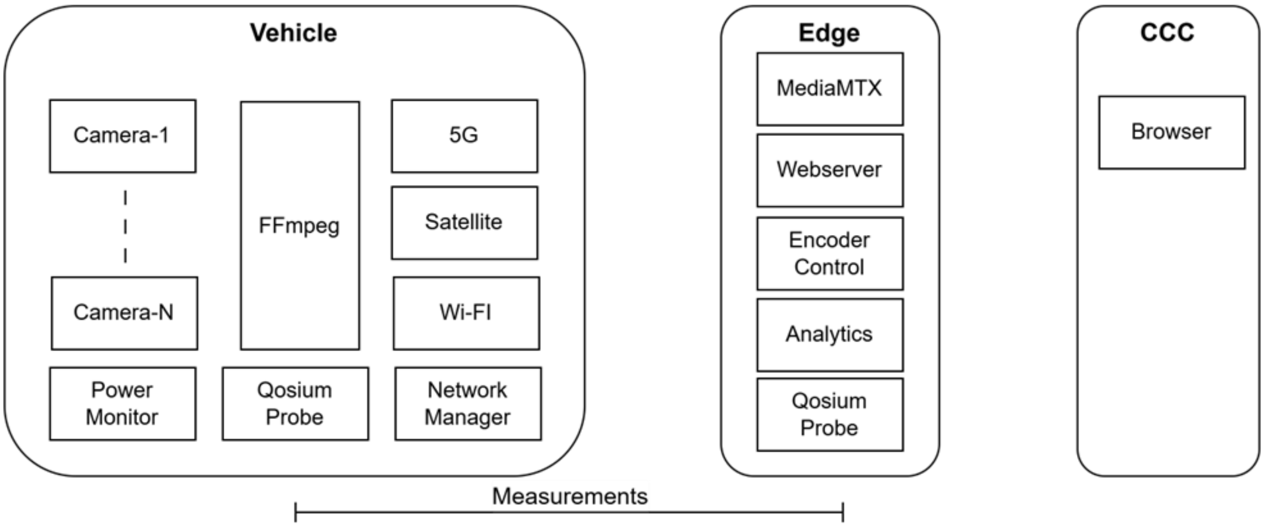


Figure 61 : Test setup for P2 pre-trial tests

4.4.2 P2 test cases and test results

P2 first tests were performed in 5GTN test network at Oulu. All tests were done in laboratory inside. The Starlink dish located in the roof of VTT's building, and it was connected via Ethernet to the laboratory. Table 70 describes the overview of the tests.

Table 70 : Overview of P2 tests

P2.1 / Lab01	Trial 1/P2
Facility / Site	5GTN test network Oulu Finland (Indoor)
Objective / Description	Verify basic functionality and 5G and Satellite network KPIs in RTMP (TCP) and SRT (UDP) video transmission protocols
Executed By	VTT
Devices / Components Involved	Teltonika Altos 5G modem, Starlink Performance (Gen1), FFmpeg, MediaMTX
5G Infrastructure	Commercial carrier-grade n78
Targeted KPIs	User-Experienced uplink data rate >20Mbps, Network latency: <30ms
Measurement Tools	Qosium
Ethics / Beta Users	-
Technical Enablers	Network performance monitoring and control

The test cases are listed in the Table 71. These tests verify low latency RTMP and SRT video streaming from vehicle to CCC. We test a single video by increasing the bitrate every 30 seconds and multiple 5 Mbit/s videos by increasing a new video stream every 30 seconds. We test RTMP protocol which uses TCP and SRT protocol that uses UDP. We measure uplink throughput and latency.

Table 71 : Test cases in P2 pre-trial in laboratory environment

Test case	Description	Bitrate(s) Mbit/s	Network	Protocol	Measurements / KPIs
001	Static location, 1. Start video encoder with 2 Mbit/s, wait 30s 2. Increase bitrate 2 Mbit/s wait 30s 3. if UL delay < 50 ms go to step 2	2, 4, 6, … 20	5G	RTMP	UL throughput, UL delay
002	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Start new video encoder with 5 Mbit/s, wait 30s 3. if UL delay < 50 ms go to step 2	5	5G	RTMP	UL throughput, UL delay for 1st video, Total UL throughput
011	Static location, 1. Start video encoder with 2 Mbit/s, wait 30s 2. Increase bitrate 2 Mbit/s wait 30s 3. if UL delay < 50 ms go to step 2	2, 4, 6, … 20	5G	SRT	UL throughput, UL delay
012	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Start new video encoder with 5 Mbit/s, wait 30s 3. if UL delay < 50 ms go to step 2	5	5G	SRT	UL throughput and UL delay for 1st video, Total UL throughput
101	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Increase bitrate 5 Mbit/s wait 30s 3. if UL delay < 100 ms go to step 2	2, 4, 6, …16	Starlink	RTMP	UL throughput, UL delay
102	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Start new video encoder with 5 Mbit/s, wait 30s 3. if UL delay < 100 ms go to step 2	5	Starlink	RTMP	UL throughput and UL delay for 1st video, Total UL throughput
111	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Increase bitrate 5 Mbit/s wait	2, 4, 6, …16	Starlink	SRT	UL throughput, UL delay

	30s 3. if UL delay < 100 ms go to step 2				
112	Static location, 1. Start video encoder with 5 Mbit/s, wait 30s 2. Start new video encoder with 5 Mbit/s, wait 30s 3. if UL delay < 100 ms go to step 2	5	Starlink	SRT	UL throughput and UL delay for 1st video, Total UL throughput

In tests 001 and 011 The FFmpeg is used to encode test video in RTMP and SRT format to the MediaMTX server (in separate tests) over 5G test network. Video bitrate starts from 2 Mbit/s and bitrate is increased 2 Mbit/s every 30s when final bitrate is 20 Mbit/s. As Figure 62 shows both cases video transfer is successful at the highest tested bitrate (20Mbit/s). We did not test higher bitrate in these test cases. In SRT the average transmitted bit rate is higher than in RTMP in the same encoder target bitrate.

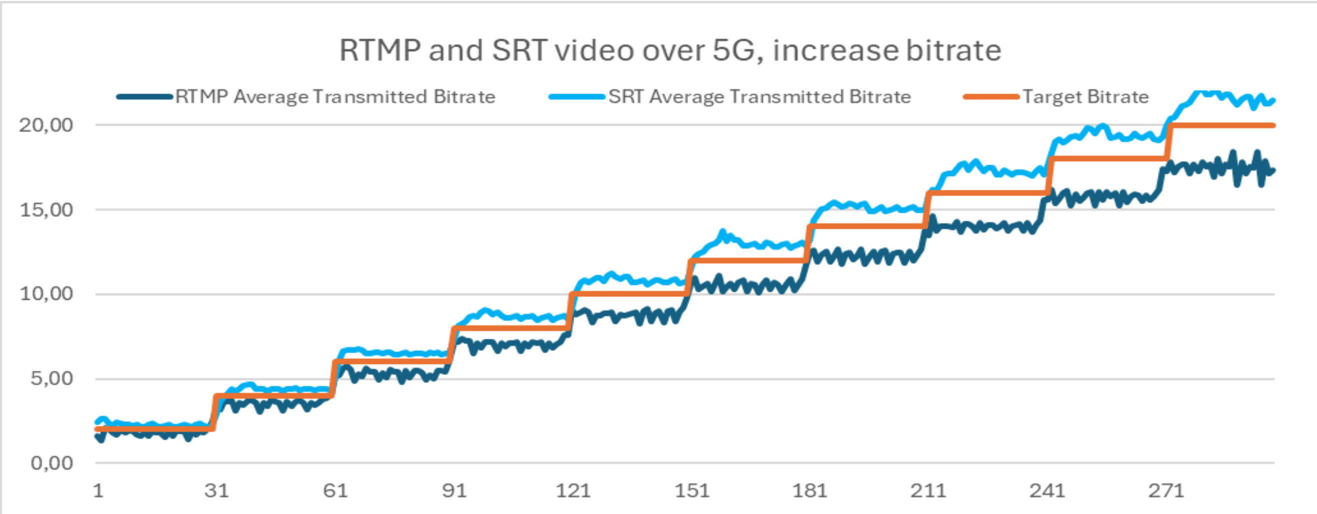


Figure 62 : Results of the test cases 001 and 011

In Test 101 and 111 Starlink (gen1) in VTT's roof static location was used in the tests. The FFmpeg is used to encode test video in RTMP and SRT format to the MediaMTX server (in separate tests). Video bitrate starting from 2 Mbit/s and bitrate is increased 2 Mbit/s every 30s when final bitrate is 16 Mbit/s. We can see from Figure 63 that over 6 Mbit/s video in RTMP format does not go through Starlink connection. We can also see that over 16 Mbit/s video in SRT format does go through Starlink connection. We did not test higher bitrates in these test cases.

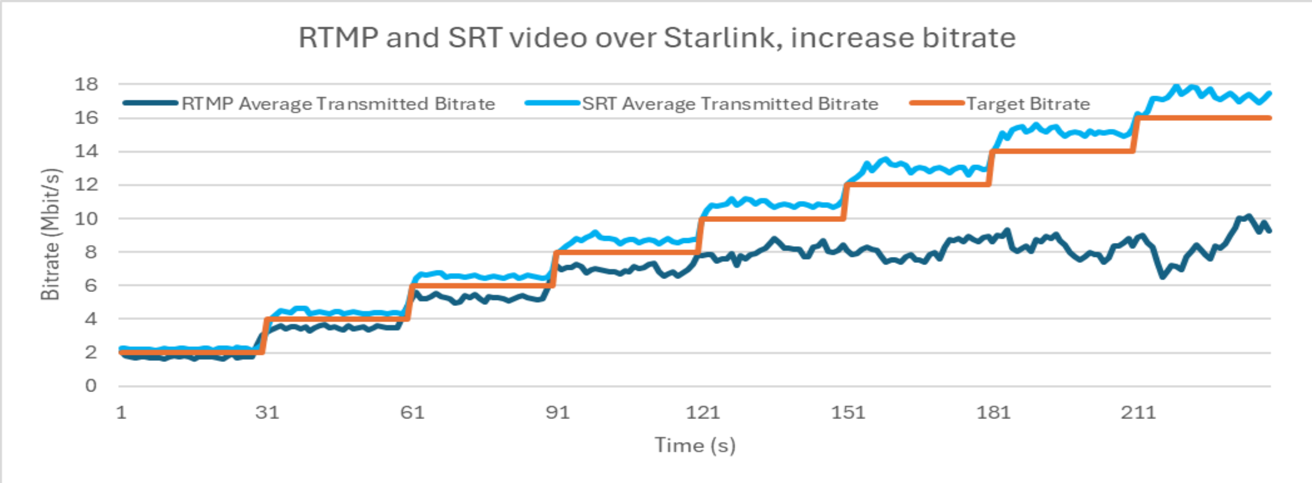


Figure 63 : Results of the test cases 101 and 111

Figure 64 presents the measured uplink (UL) delay performance in single-encoding test cases 001 (RTMP) and 011 (SRT) in 5G test network. The results indicate that SRT outperforms RTMP in terms of latency-related KPIs, achieving a lower average UL delay (16.9 ms vs. 24.3 ms) and reduced UL jitter (0.8 ms vs. 1.9 ms).

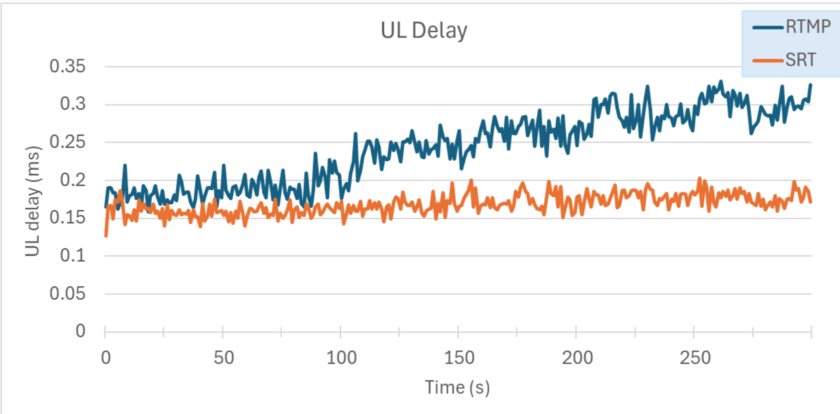


Figure 64 : Measured sent 5G network UL delay for RTMP and SRT in single-encoding scenario for test cases 001 and 011

Figure 65 presents the measured uplink (UL) throughput and delay for single video in the multi-encoding scenario for test cases 002 (RTMP) and 012 (SRT) in 5G test network. The results show that RTMP achieves lower average UL delay than SRT (17.9 ms vs. 21.3 ms). The UL jitter remains low for both protocols, with comparable values of 0.9 ms (RTMP) and 0.8 ms (SRT). The total UL throughput was also measured in both cases. RTMP achieves a higher maximum total UL data rate (160.9 Mbit/s) compared to SRT (132.6 Mbit/s).

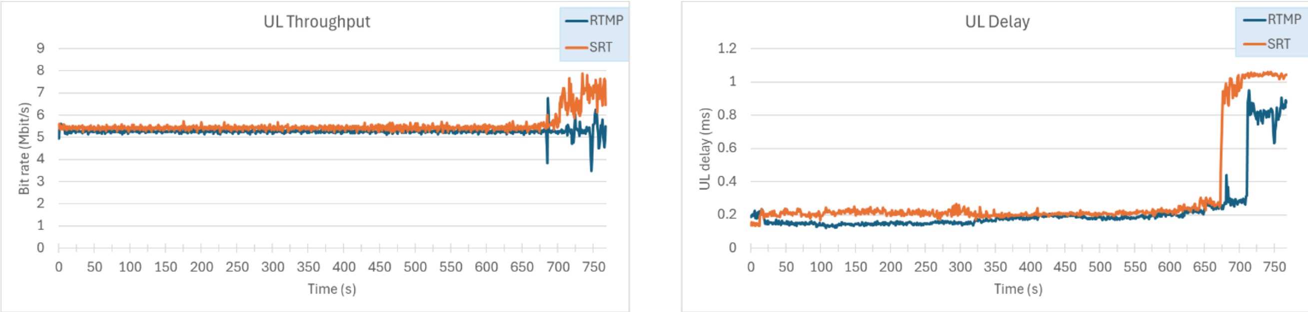


Figure 65 : Measured (received) 5G network UL throughput (left) and delay for RTMP and SRT in multi-encoding scenario for test cases 002 and 012

Figure 66 presents the measured UL throughput and delay performance in an NTN environment for single-encoding scenarios using RTMP (test case 101) and SRT (test case 111). Each test was repeated five times, and the results represent the received network performance. The results show that both protocols experience significantly higher UL delay compared to terrestrial networks. The average UL delay is approximately 52.9 ms for RTMP and 54.8 ms for SRT. In terms of UL throughput, the achieved data rates remain limited in the NTN environment. RTMP achieves an average UL throughput of around 6 Mbit/s, while SRT reaches higher target bitrates (up to 16 Mbit/s, not measured higher bitrate).

Figure 66 : Measured (received) NTN network UL throughput and delay for RTMP and SRT in single-encoding scenario for test cases 101 and 111. Looped 5 times

Table 72 : P2 KPI measurements

Test Case ID	Target KPIs / Requirements	KPI measurements	Evaluation / Notes [Network or Application Related]
001	UL delay: < 30ms	UL throughput: 20 Mbit/s (not tested higher bitrate) UL delay: 24.3ms	Average KPI values for a single RTMP video before 5G network gets congested.
002	UL throughput: > 20 Mbit/s, UL delay: < 30ms	UL throughput: 120 Mbit/s when 1st video delay < 50ms UL delay for 1st video: 17.9 ms	Delay measured for a single RTMP video.
011	UL delay: < 30ms	UL throughput: 20 Mbit/s (not tested higher bitrate) UL delay: 16.9ms	Average KPI values for a single SRT video before 5G network gets congested.

012	UL throughput: > 20 Mbit/s, UL delay: < 30ms	UL throughput: 110 Mbit/s when 1st video delay < 50ms UL delay for 1st video: 21.3 ms	Delay measured for a single SRT video.
101	UL delay: < 30ms	UL throughput: 6 Mbit/s UL delay: 52.9ms	Average KPI values for a single RTMP video in Starlink.
102	UL throughput: > 20 Mbit/s, UL delay: < 30ms	UL throughput: 77.3 Mbit/s when 1st video delay < 100ms UL delay for 1st video: 49.2ms	Delay measured for a single RTMP video. The delay of the 1st video remains below 100ms (max peak 76.5 ms), but after the 6th video the total throughput starts to fluctuate strongly, based on this we can say that five (5 Mbit/s) RTMP videos can be sent simultaneously over Starlink.
111	UL delay: < 30ms	UL throughput: 16 Mbit/s (not tested higher bitrate) UL delay: 54.8ms	Average KPI values for a single SRT video in Starlink.
112	UL throughput: > 20 Mbit/s, UL delay: < 30ms	UL throughput: 77.3 Mbit/s when 1st video delay < 100ms UL delay for 1st video: 49.0 ms	Delay measured for a single SRT video.

4.4.3 P2 Next steps

The next phase of testing will focus on increasing realism and testing interoperability under more demanding conditions. The use case will be evaluated using multi-network connectivity, leveraging 5G, Wi-Fi, and satellite links to assess performance, resilience, and service continuity across heterogeneous access technologies. In addition, outdoor tests will be performed, first using a static vehicle deployment, enabling validation of system integration, power, and operational stability. Using a moving vehicle to perform final tests under more realistic conditions.

4.5 P3 Emergency private B5G/6G communication on-the-move

4.5.1 P3 Integration status

Similar to P2, the P3 use case has been integrated and validated in a static lab-based “vehicle” setup. The current system combines heterogeneous network connectivity (5G router, Wi-Fi 6) with both live and video-on-demand based streaming setups enriched with accurate energy monitoring framework including the whole end-to-end transmission chain. A modified FFmpeg pipeline is used to encode and live-stream video feeds from the vehicle towards the CCC.

At the edge, MediaMTX operates as the video server, while Qosium monitors network traffic and performance across access technologies. Carlo Gavazzi, Shelly Plugs and Otii Ace power measurement devices are integrated as a part of the test network providing 1/s power measurement accuracy. Network, power and application metrics are collected into InfluxDB and visualized using Grafana, enabling real-time monitoring and post-analysis. The CCC backend is implemented using Nginx to host the CCC web UI and encoder control functions. At the CCC side, standard web browsers can be used for the video playback, completing the end-to-end interoperability chain from vehicle to CCC. The setup is depicted in Figure 30.

4.5.2 P3 test cases and test results

In the pre-tests for P3, the focus has been in developing and tailoring the energy measurement framework for P3 purposes, which is used together with P2 energy assessment tests. The first objective in the pre-tests was to validate the system operability for the selected test cases and provide basis towards the final trials where optimized streaming-based algorithms are used to reach the target KPIs. These tests are also aligned with the work performed in P2. The second objective of the pre-tests was to compare RTMP and SRT streaming protocols over Wi-Fi and 5G with altering bitrate/resolution combinations and assess their end-to-end energy efficiency including video client (encoder), 5G/Wi-Fi modem and video server perspectives. The bitrate / resolution combinations are the following. 1 Mbps/HD;5 Mbps/FullHD; 10 Mbps/FullHD; 20 Mbps/4K. The values base on YouTube and 5G XR ETSI recommendations. X264 encoder was used in the experiments. Table 73 shows overview of the P3 tests.

Table 73 : Overview of P3 tests

P3.1 / Lab01	Trial 1/P2
Facility / Site	5GTN test network Oulu Finland (Indoor)
Objective / Description	Verify basic functionality of energy consumption evaluation platform and network KPIs in comparison of RTMP (TCP) and SRT (UDP) video transmission protocols
Executed By	VTT
Devices / Components Involved	Teltonika Altos 5G/WI-FI 6(7) modem, FFmpeg, MediaMTX, PTPd
5G Infrastructure	Commercial carrier-grade n78, Wi-Fi 6
Targeted KPIs	User-Experienced uplink data rate >20Mbps, Network latency: <30ms
Measurement Tools	Shelly Plug S, Carlo Gavazzi, Qosium
Ethics / Beta Users	-
Technical Enablers	Network performance monitoring and control, Network exposure APIs

Table 74 describes the test cases. In these tests we aim at finding average values for uplink energy efficiency for RTMP and SRT. UL delay is used for assessing the streaming reliability in terms of reaching a) the average UL delay KPI target b) the share of target crossings (%). The power consumption is monitored from video encoder (client), 5G/Wi-Fi modem and video server. These values together with UL throughput can assess the energy efficiency of the streaming.

Table 74 : Test cases in P3 pre-trial in laboratory environment

Test case	Description	Bitrate(s) Mbit/s	Network	Protocol	Measurements / KPIs
P3_01	Static location, 1. Start video encoder with 1 Mbit/s target bitrate, encapsulate to streaming *Protocol* and send to video server, work 600s 2. Stop encoder and be in idle 60s 3. Repeat steps 1 and 2 with 5, 10, and 20 Mbit/s target bitrates	1, 5, 10, 20	5G	RTMP	UL throughput, UL delay, Energy efficiency
P3_02	Static location, 1. Start video encoder with 1 Mbit/s target bitrate, encapsulate to streaming *Protocol* and send to video server, work 600s 2. Stop encoder and be in idle 60s 3. Repeat steps 1 and 2 with 5, 10, and 20 Mbit/s target bitrates	1, 5, 10, 20	5G	SRT	UL throughput, UL delay, Energy efficiency
P3_03	Static location, 1. Start video encoder with 1 Mbit/s target bitrate, encapsulate to streaming *Protocol* and send to video server, work 600s 2. Stop encoder and be in idle 60s 3. Repeat steps 1 and 2 with 5, 10, and 20 Mbit/s target bitrates	1, 5, 10, 20	Wi-Fi	RTMP	UL throughput, UL delay, Energy efficiency
P3_04	Static location, 1. Start video encoder with 1 Mbit/s target bitrate, encapsulate to streaming *Protocol* and send to video server, work 600s 2. Stop encoder and be in idle 60s 3. Repeat steps 1 and 2 with 5, 10, and 20 Mbit/s target bitrates	1, 5, 10, 20	Wi-Fi	SRT	UL throughput, UL delay, Energy efficiency

Figure 67 presents one example of the conducted measurements illustrating measured power consumption of the video client and server as well as Teltonika modem. It can be seen that real-time encoding is not power-hungry operation even at 4K resolution.

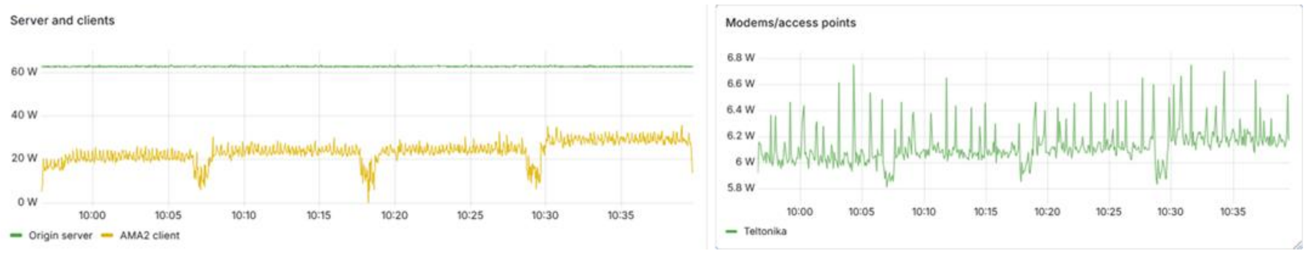


Figure 67 : Energy consumption of the RTMP video client, modem and server using the developed energy measurement framework over Wi-Fi

Figure 68 shows the UL throughput curve measured with Qosium, which is similar for all the test cases as we have enough Wi-Fi and 5G channel capacity to transmit the video successfully.

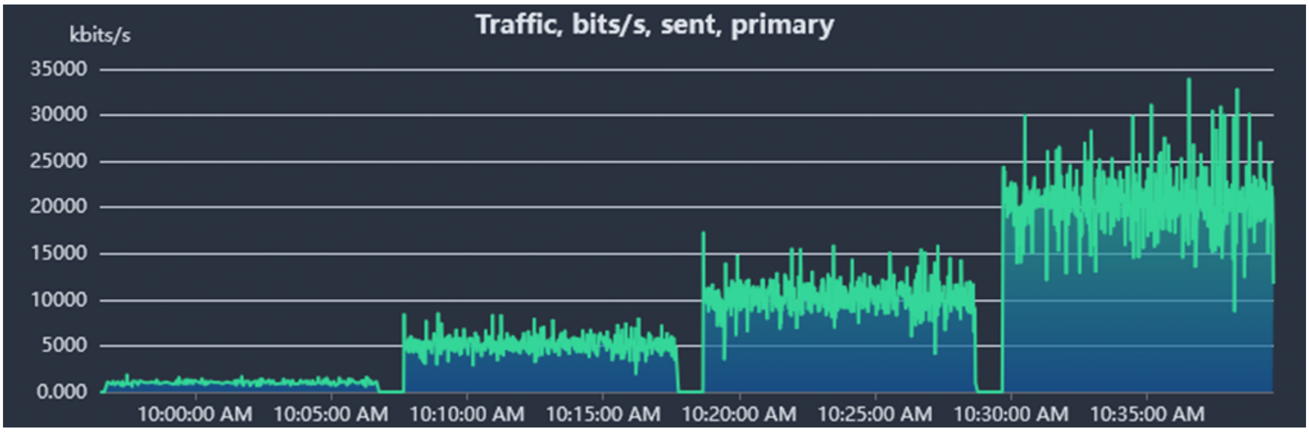


Figure 68 : RTMP throughput

Table 75 illustrates the summary of the measurements from the KPI perspective.

Table 75 : P3 KPI measurements

Test Case ID	Target KPIs / Requirements	KPI measurements	Evaluation / Notes [Network or Application Related]
P3_01	UL throughput >20Mbps UL latency: <30ms Energy efficiency > 20%	UL throughput: 7.4 Mbit/s UL delay:17.7 ms Energy efficiency: 1.3 µJ/bit	Average values for the whole test run. Energy efficiency reduction techniques and improvements will be shown in D2.2.
P3_02	UL throughput >20Mbps UL latency: <30ms Energy efficiency > 20%	UL throughput: 7.6 Mbit/s UL delay: 17.9 ms Energy efficiency: 1.3 µJ/bit	Average values for the whole test run. Energy efficiency reduction techniques and improvements will be shown in D2.2.
P3_03	UL throughput >20Mbps UL latency: <30ms Energy efficiency > 20%	UL throughput: 7.4 Mbit/s UL delay: 7.3 ms	Average values for the whole test run. Energy efficiency reduction techniques and

		Energy efficiency: 1.3 μJ/bit	improvements will be shown in D2.2.
P3_04	UL throughput >20Mbps UL latency: <30ms Energy efficiency > 20%	UL throughput: 7.6 Mbit/s UL delay: 6.1 ms Energy efficiency: 1.2 μJ/bit	Average values for the whole test run. Energy efficiency reduction techniques and improvements will be shown in D2.2.

4.5.3 P3 Next steps

The next steps include pre-testing the network slicing and continuing energy efficiency tests with varying RAN parametrization with the focus on UL optimization. From the video perspective we aim at finding energy-savvy parametrization to be used in final tests and trials.

4.6 P4 Arctic area search and rescue operation

4.6.1 P4 Integration status

The use case is currently under heavy development. Backpack has been built for the first responder and the devices have been installed on it (see Figure 69). Table 76 lists devices in the backpack. First pre-trials have been conducted in Sodankylä. These tests have been done in different days comprising of data gathering, live streaming, testing of the backpack and testing of the different networks. Streaming has been tested between Oulu VTT site and the Sodankylä site, but further tests continue.

Figure 69 : A backpack installation with the eSled driver

Table 76 : Devices in the backpack

Category	Component	Technical Details	Integration situation
Sensor	Camera	pilot helmet camera/360 camera; USB web camera Logitech or Insta360 X5	Web camera streaming tested and done
Vehicle	eSled/Robotic vehicle	Electric snowmobile by Aurora powertrains or Robotic vehicle	eSled has been tested on the test track with equipment.
Hardware	Sensor bac bag	Sensor instrumentation in the backpack, embedded with fixed installation to eSled trunk box.	Currently backpack system viability has been tested on the eSled
Sensor	GPS tracker	Ardusimple GPS RTK Simplertk3b	GNSS have been tested no validation for the accuracy yet.
Sensor	LiDAR	Oyster Os1-128 or Velodyne VLP-16	Velodyne lidar integrated to the backpack
Sensor	Heat camera	Thermal Master P2	Heat camera recording and streaming has been tested.
Sensor	Spectrum analyzer	Aaronia	Not yet integrated and will most likely be a separate system.
Hardware	First responder portable screen	Denver PMO-15601 Windows tablet; Lamina Tablet	Currently tests have been done on a windows laptop. The tablet will be tested in the future.
Hardware	Gimbal	DJI Ronin-SC	It has not yet been necessary, but it has been studied.

Edge integration (CCC) done on the data pipe side, but visualization improvements for demonstrations purposes are ongoing. Command and control center will be demonstrated on the EuCNC'26 demo booth.

Platform integration to the backpack has been physically done and data has been collected and streamed. Improvements for the visualization are ongoing.

4.6.2 P4 test cases and test results

In addition to the backpack integration tests, we tested Sodankylä airport 5G test track KPIs. Table 77 describes basic information about P4 tests.

Table 77 : Overview of P4 tests

P4.1	Trial 1/P1
Facility / Site	Sodankylä airport test track (Sod5G)
Objective / Description	Test first integration, Sod5G test track KPIs by driving the track on a vehicle.
Executed By	FMI, VTT, APT
Devices / Components Involved	Telewell 5G router, FFmpeg, MediaMTX
5G Infrastructure	Sod5G
Targeted KPIs	UL throughput, UL latency (delay)
Measurement Tools	Qosium, Nemo Handy
Ethics / Beta Users	-
Technical Enablers	Network performance monitoring and control

Test setup in Sodankylä is depicted in Figure 70. In the tests, we drove a passenger car around a test track and measured KPIs every single lap. In the vehicle we have Ubuntu 24.04 laptop, Brio camera, FFmpeg video encoder, Telewell 5G modem, Nemo Handy test phone, and Qosium Probe. The edge server is in the 5G core network in Oulu. Video server, OpenSpeedTest server and Qosium Probe were in the edge server. KPI measurements performed between the vehicle and the edge. Table 78 lists the test cases in Sodankylä pre-trial.

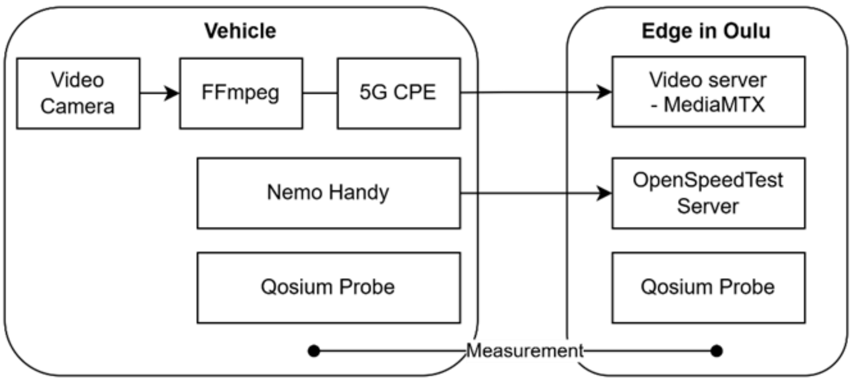


Figure 70 : Test setup in Sodankylä pre-trial in February 2026

Table 78 : Test cases in Sodankylä pre-trial

Test case	Description	Network	Protocol	Measurements
001	The vehicle drives the route about 20 km/h and measuring uplink throughput of the network	5G	TCP	Nemo Handy
002	The vehicle drives the route about 20 km/h and measuring RTT of the network	5G	TCP	Nemo Handy
101	The vehicle drives the route about 20 km/h sending 5 Mbit/s video in RTMP.	5G	RTMP	Qosium (throughput, UL delay), location
102	The vehicle drives the route about 20 km/h sending 10 Mbit/s video in RTMP.	5G	RTMP	Qosium (throughput, UL delay), location

Figure 71 presents the UL throughput performance measured using Nemo Handy against the OpenSpeedTest server in Oulu. The results provide baseline UL capacity measurements of the Sod5G network. A single round around the track took about 4 minutes and 30 seconds. We can see that uplink throughput was over 40 Mbit/s over 95% of the test track. Certain locations (4.55% of the track / 12 second period) the UL throughput decreased under 40 Mbit/s.

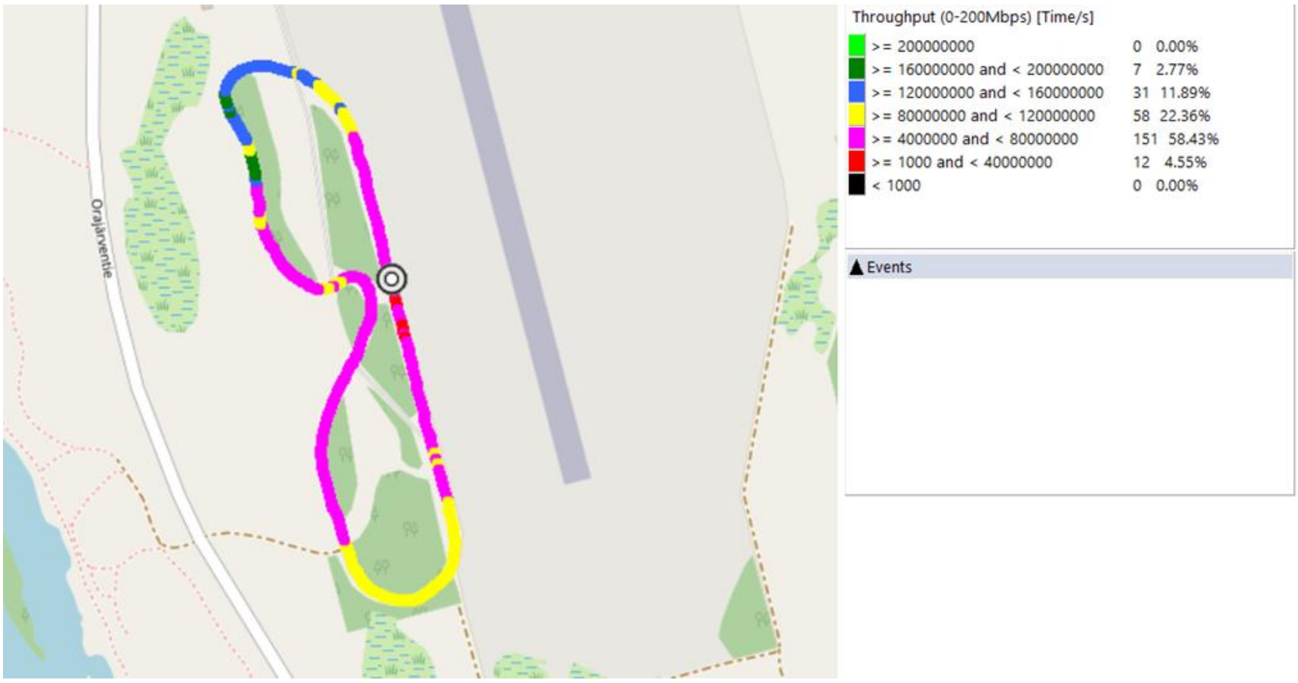


Figure 71 : UL throughput test measured using Nemo Handy (OpenSpeedTest)

Figure 72 presents the measured RTT performance obtained using Nemo Handy. The results provide baseline latency characteristics of the network, expressed in milliseconds. RTT values were below 25 ms except for one over 100 ms peak.

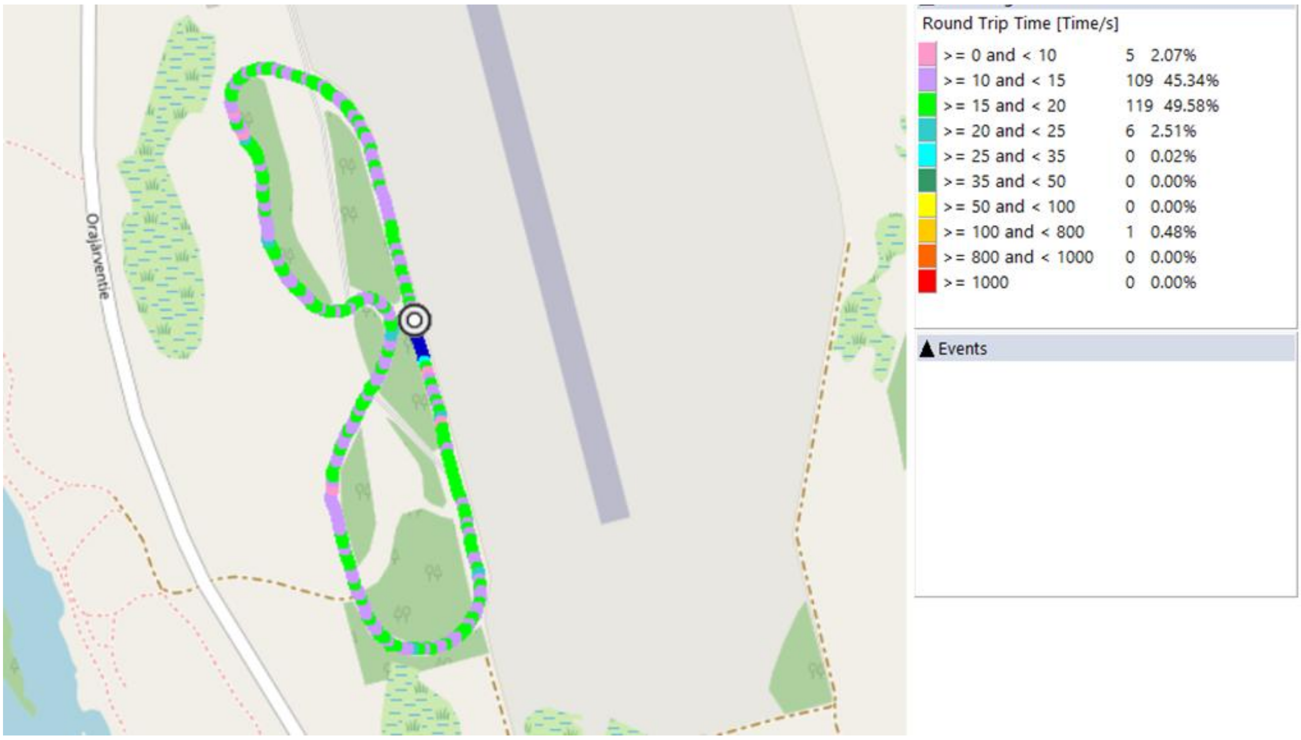


Figure 72 : Basic RTT test measured using Nemo Handy (RTT time in ms)

Figure 73 depicts the UL KPI performance for a 5 Mbit/s RTMP video stream measured using Qosium. The achieved UL throughput remains stable at approximately 5 Mbit/s, indicating consistent application-level performance. The average UL delay is around 18 ms and remains below 30 ms throughout the measurement period, demonstrating stable low-latency behaviour. The UL jitter is low, with an average value of approximately 0.9 ms.

Figure 73 : UL KPIs for 5 Mbit/s RTMP video measured using Qosium

Figure 74 presents the UL KPI performance for a 10 Mbit/s RTMP video stream measured using Qosium. The achieved UL throughput remains stable at approximately 10 Mbit/s. The average UL delay is around 20 ms and remains below 30 ms throughout the measurement period, demonstrating stable low-latency behavior. The UL jitter is low, with an average value of approximately 0.7 ms.

Figure 74 : UL KPIs for 10 Mbit/s RTMP video measured using Qosium

Table 79 summarizes the P4 KPI measurements.

Table 79 : P4 KPI measurements

Test Case ID	Target KPIs / Requirements	KPI measurements	Evaluation / Notes [Network or Application Related]
001	Uplink throughput: >20 Mbit/s	UL throughput: 95 % of the time >40Mbit/s, 5 % of the time 1 – 40 Mbit/s	Uplink throughput measured using Nemo Handy
002	Uplink delay: <30ms	RTT less than 25 ms 99,6 % of the time.	RTT (ping) measured using Nemo Handy
101	Uplink delay: <30ms	Average UL delay 18 ms	Using 5 Mbit/s RTMP video and measure network uplink delay between vehicle and video server.
102	Uplink delay: <30ms	Average UL delay 20 ms	Using 10 Mbit/s RTMP video and measure network uplink delay between vehicle and video server.

4.6.3 P4 Next steps

The next steps include demonstrating the system at EuCNC and continuing energy efficiency tests both in network side and in the eSled. From the video perspective we aim at finding energy-savvy parametrization to be used in final tests and trials.

4.7 P5 Emergency private B5G/6G communication on-the-move

4.7.1 P5 Integration status;

During January–March 2026, the P5 end-to-end system integration was implemented in the Orange 5G Lab, with connectivity across the full chain from radio (gNB) to 5G core to cloud-hosted MCx server services, and finally to UE MCx application. The integrated platform used OAIBOX™ MAX as the portable gNB + CN5G integration point, and National Instruments USRP N310 as the SDR module with a high gain 2x2 MIMO antenna implementing the radio unit. The objective of this phase was to make sure that the combined RAN + SA core configuration could provide stable 5G connectivity and that the MCx service platform could be reached by the UEs in a controlled setup.

In the same lab period, the integration of the MCx application was completed by configuring the Streamwide MCx application, to run in the intended deployment context. The MCx application was treated as a cloud-hosted service for the pre-trial, while for the final trial it will be deployed locally with the network. The end-to-end network behaviour was validated through successful UE attachment, service initiation, and the ability to run MCx service flows over the integrated network chain. Two Crosscall CORE-Z5 smartphones were used as UEs and integrated end-to-end with the lab network and MCx application, enabling validation that MCx client functionality could interact with the cloud-hosted MCx platform through the tactical bubble 5G network.

Beyond baseline connectivity tests, the lab integration also covered connectivity performance and service verification tests needed for P5 operations. In particular, the integrated setup was validated for the ability to support the P5 architectural model, where the tactical gNB provides the access layer and the local SA core functions (AMF/SMF/UPF/PCF/AUSF) provide control-plane and user-plane handling (as seen in Figure 75).

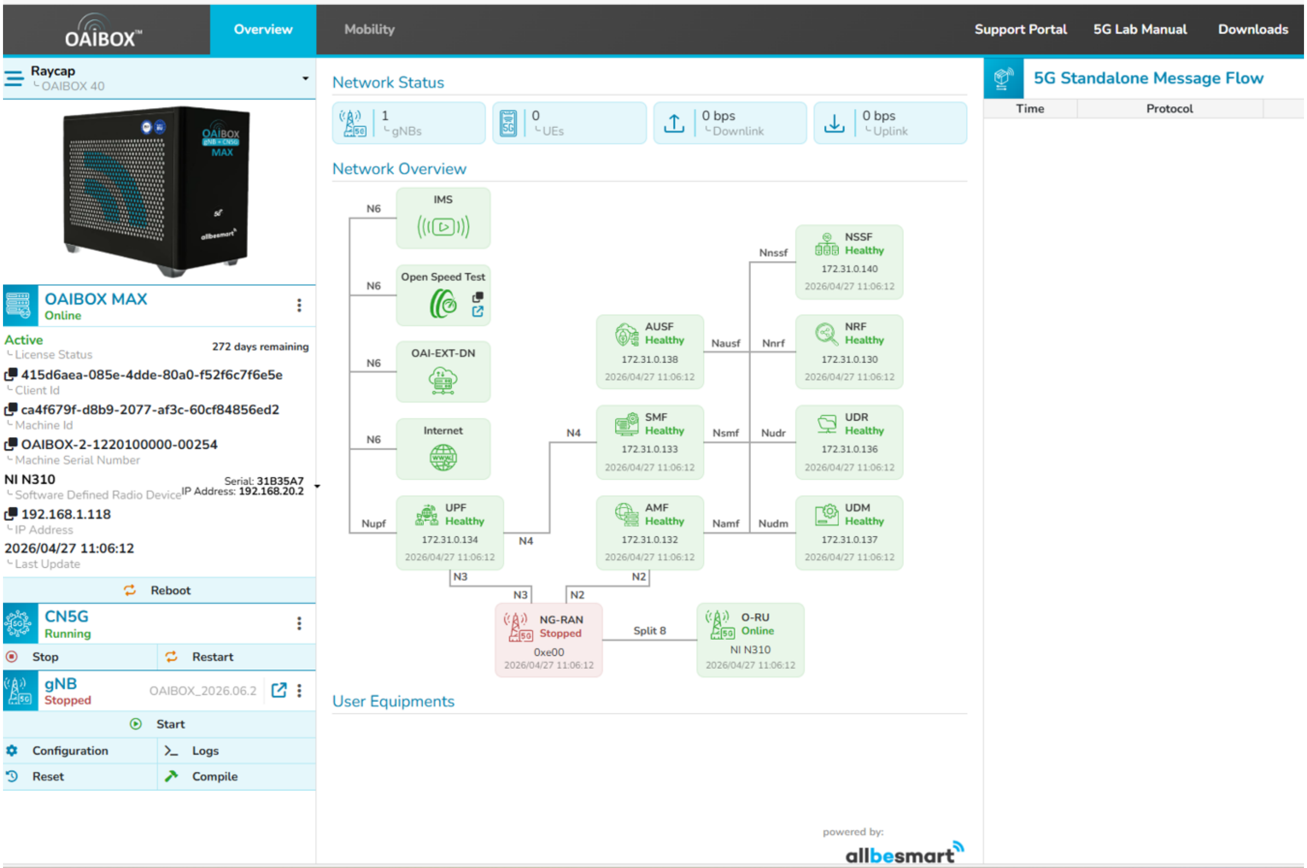


Figure 75 : OAIBOX MAX management and control dashboard

On 27 April 2026, the system was moved from the lab to the field by STS and ORO for the P5 pre-trial execution. The deployment took place in an isolated forest area near Bucharest (Romania), and the full 5G setup was installed on-the-go intervention car in a tactical configuration. In the field deployment, the setup included the portable B5G cell site (gNB) together with the local SA core network hosted as part of the on-vehicle equipment (see Figure 76).

Figure 76 : Equipment installation on the emergency intervention car

The on-the-move configuration was intended to support the intervention scenario where connectivity must remain available even when the commercial mobile networks unavailable; therefore, the local architecture was installed and operated as a standalone network.

In the same field installation, a LEO satellite backhaul solution - Starlink - was connected to enable satellite-based backhauling for the 5G network. Two terminal devices were tested and deployed, Starlink Mini and Starlink Performance Gen. 2. This dual-backhaul system was intended to maximize the availability of the Internet services in the target remote area. With the satellite terminals installed and configured, the trial team validated that the system could continue to operate end-to-end while backhaul connectivity was active and that Cloud-based MCx services could still be exercised through the full stack without changing the MCx application deployment model to be run on the edge.

The installed configuration also included readiness for slice-based operation in the field, where dedicated slices are used for MCx service categories.

Enablers integrated for P5 during the pre-trial period included communication enablers required for portable gNB operation and real-time monitoring readiness, edge compute enablers to support edge-hosted MCx services, and operational enablers required to support tactical deployment using on-vehicle integration. This also included observability readiness to support KPI collection in the final trial phase, with logging/monitoring at the network/core/edge and the UE/application side.

4.7.2 P5 test cases and test results

On 27 April 2026, STS and ORO representatives executed the P5 pre-trial tests in the field near Bucharest using the on-the-go tactical 5G setup. The setup was configured with local RAN, a local 5G SA core (AMF/SMF/UPF/PCF/AUSF), and cloud-hosted MCx application components, so that the full-service chain could be validated end-to-end.

The execution started with a validation of basic end-to-end service readiness from the user side. The MCx-capable UEs were powered up and used to perform attachment and registration against the local SA core. During this phase, the representants checked that the UE successfully completed the registration process and that the expected MCx service endpoints were reachable through the Internet. Once registration was confirmed, the team validated that subsequent MCx session establishment could be triggered from the UE and that the session state was visible/consistent at the application side.

With the satellite connectivity active, the representants performed the service validation steps starting with MC-PTT in connected mode. The goal of this phase was to confirm that mission-critical voice operation continued to work when the satellite backhaul path was active, and to observe whether any additional instability or noticeable delay behaviour appeared. The representants used the operational workflow (call setup and group communication actions) to keep the test behaviour consistent across modes for later KPI analysis. After the registration validation, the representants tested that PTT call setup completed correctly, that group communication behaviour matched the expected operational workflow, and that the service remained available during repeated call actions within the test window. The focus of this step was to verify that the tactical deployment constraints did not break the MCx control signalling chain and that PTT operation remained stable when traffic was actively generated. Evidence capture for this step included UE-side screenshots/log status and application-side status outputs, as in Figure 77.

Figure 77 : PTT tests during the April 2027 session

The team then validated data connectivity over the standalone 5G network with a local Open Speed Test server. KPIs measurements have been collected as in Figure 78 and Table 81.

Figure 78 : Data connectivity measurements during the April 2027 session

Finally, MC-Video was also tested over the satellite backhaul active. The representants verified that video service behaviour remained operational in connected mode and that the system could sustain video session initiation and continuity for the purpose of this pre-trial.

Table 80 illustrates the pre-trial setup.

Table 80 : P5 pre-trial setup

P5.1 / Lab01	Pre- Trial 1/P5.1
Facility / Site	Orange 5G lab (integration) + field near Bucharest forest area (27 Apr 2026)
Objective / Description	Pre-validate P5 end-to-end operation in standalone and satellite-connected modes, and collect initial KPIs measurements
Executed By	STS and ORO representants
Devices / Components Involved	Portable tactical network (OAIBOX MAX, NI USRP N310), Streamwide MCx server and application, Crosscall CORE-Z5 MCx smartphones, Starlink Mini and Starlink Performance Gen.2 satellite terminals
5G Infrastructure	Local 5G SA core + edge (standalone), Starlink LEO backhaul enabled (connected mode)
Targeted KPIs	UL, DL throughput, latency
Measurement Tools	UE/MCx application logs and monitoring screenshots; KPI snapshot placeholders
Ethics / Beta Users	Trial representants used for validation
Technical Enablers	Cloud-hosted MCx server services, satellite backhaul integration readiness, basic observability for KPI evidence

Table 81 presents the KPIs measured during the KPIs pre-trial.

Table 81 : P5 pre-trial KPI measurements

Test Case ID	Target KPIs / Requirements	KPI measurement	Evaluation / Notes [Network or Application Related]
P5_01	Network service latency: 20 ms Satellite Backhaul Latency: 20 ms Downlink User Throughput: 1Gbps Uplink User Throughput: 100 Mbps Internet Downlink Throughput: 100 Mbps Internet Uplink Throughput: 20 Mbps	17 ms 30ms 750 Mbps 70 Mbps 250 Mbps 40 Mbps	Overall, the results show that latency requirements are partially met, with network service latency within target but satellite backhaul exceeding limits, while user throughput KPIs are underachieved and internet throughput performance exceeds the defined targets.

The collected pre-trial KPI measurements indicate that the target communication performance is feasible within the P5 trial conditions and that the overall end-to-end architecture can achieve connectivity and usable service behaviour in both standalone and satellite-connected operation. In particular, the measured network service latency was 17 ms, which remains close to the P5 target value of 20 ms, and the measured satellite backhaul latency was 30 ms, which confirms that the satellite segment introduces an additional delay but still supports an operationally viable connected mode for mission-critical communications. The measured user-plane throughputs were also consistent with the intended trial expectations, with 750 Mbps downlink and 70 Mbps uplink at the user side, and 250 Mbps downlink and 40 Mbps uplink toward external IP networks, demonstrating that the system can sustain data transfers through the satellite bearer rather than only supporting basic registration and session setup.

However, the measurements may not yet fully reflect worst-case or stress scenarios that will be exercised in 2027, such as higher numbers of simultaneous responders, prolonged on-the-move operation, and dynamic switching between standalone and satellite-connected modes. For the final trial planning, the next gap to close is therefore to refine the measurement methodology so that KPI collection is consistent across multiple runs and scenarios, and to align the service profiles with the final 2027 evaluation plan in order to ensure direct comparability and stronger evidence for performance against the defined targets.

4.7.3 P5 Next steps

During Q2 2027, the final P5 scenario will be implemented in a remote outdoor location in Romania with emergency responders and operational participants involved in realistic on-the-move activity, including tactical vehicle mobility, repeated group call use and manual/dynamic switching between standalone operation and satellite-connected operation using the LEO backhaul when available.

In this phase, the final end-to-end measurements will be collected to confirm the required performance for MC-PTT, MC-Video, MC-Data, with KPI capture synchronized across RAN, SA core, UE/application logs and backhaul-specific checks that track satellite reachability and the additional delay introduced by the satellite segment.

Key KPIs will cover local network service latency toward, one-way satellite backhaul latency, user-plane throughput in downlink and uplink directions for tactical traffic and internet throughput in connected mode, while also documenting how performance changes under higher load profiles and repeated runs.

After completing the technical measurements, KVIs will be collected during and after the live demonstrations using role-based questionnaires with Likert-scale scoring, then aggregated to evaluate operational safety improvement, mission-critical communication availability and continuity (including confidence in standalone mode), perceived energy efficiency versus legacy PPDR solutions, reduction in operational downtime, and perceived reduction in operational and energy-related costs.

4.8 Concluding remarks

Overall, the preliminary integration phase has successfully enabled the initial validation of system interoperability and end-to-end functionality across all Amazing-6G use cases, providing a solid foundation for subsequent testing and optimisation activities. The conducted experiments confirmed the feasibility of integrating diverse technological components, while also revealing specific areas requiring refinement, particularly in relation to network performance tuning, system configuration stability, and cross-domain service orchestration. The collected baseline measurements and qualitative observations form an essential reference point for the upcoming optimisation cycles and full trial executions. In addition, the preliminary results have supported early verification of KPI/KVI measurement methodologies, ensuring consistency and comparability across different scenarios and environments. These outcomes confirm that the project is on track towards achieving its technical objectives, while also reinforcing the robustness of the overall integration strategy and its suitability for complex, real-world 6G deployment conditions.

5 Conclusion and Next Steps

This deliverable (D4.1) serves as the intermediate report and technical progress documentation for Work Package 4 (WP4) within the AMAZING-6G project. WP4 plays a foundational role in the project's mission to revolutionize the health and public safety sectors by deploying large-scale 6G-enabled trials that utilize beyond 6G communications, advanced edge computing, and AI-driven network orchestration. This work package is central to the project's architecture, contributing directly to achieving major project objectives by integrating technology enablers developed in other work packages.

The intermediate results of Work Package 4 within the AMAZING-6G project demonstrate the strong potential of Beyond 5G (B5G) and 6G technologies to support mission-critical applications in the Health and Public Safety domains. The performed activities confirm that 6G is not merely an incremental evolution of current communication systems, but a key technological enabler for highly reliable, low-latency, and intelligent services operating under demanding and unpredictable conditions.

Overall, the findings validate the feasibility of Edge-Centric Healthcare approaches, where computationally intensive Artificial Intelligence (AI) functions can be efficiently offloaded from constrained wearable devices to edge infrastructure. This architecture enables continuous and real-time medical monitoring while addressing the battery and processing limitations of wearable medical equipment. In parallel, the Public Safety and PPDR use cases have demonstrated the critical importance of Hybrid Connectivity, integrating terrestrial 5G networks with Non-Terrestrial Networks (NTN) and satellite systems to ensure resilient and uninterrupted communications in infrastructure-degraded or remote operational environments.

The project has also demonstrated the value of autonomous and rapidly deployable communication infrastructures, including "network-in-a-box" solutions capable of supporting emergency operations in disaster scenarios. Having on board a variety of testbeds and use cases in harsh environment with private and public networks among the use cases, ensures that AMAZING-6G will demonstrate impactful results during the next reporting period (Trials). Furthermore, the adoption of 3GPP-aligned mechanisms and CAMARA APIs ensures interoperability and alignment with evolving global 6G standardization efforts, positioning the project as a significant contributor to the future European 6G ecosystem.

Overall Domain Findings

From a use-case perspective, the health domain developments have confirmed the viability of advanced edge-enabled medical services. The H1 wearable ultrasound patch introduces a first-of-its-kind solution for continuous cardiac monitoring through edge-based AI-assisted imaging analysis. Preliminary evaluations confirm the capability of the system to provide high-quality real-time monitoring while mitigating wearable device energy constraints. Nevertheless, the high volume of ultrasound data and the strict reliability requirements remain major challenges that necessitate further optimization and validation through large-scale trials planned for 2027. Similarly, the H2 use case demonstrates the potential of predictive AI for closed loop and near real-time reprogramming of pacemakers and implantable cardiac devices. The results highlight the importance of ultra-low latency 6G communications for enabling medical interventions "within a heartbeat." While early testing validates the concept, achieving the targeted sub-10 ms service latency remains a significant technical challenge that will require further optimization and extensive validation under realistic operational conditions.

Both healthcare use cases – H1 and H2 – propose a small wearable patch designed for capturing patient vital signs and subsequently uploading them for processing on the edge. A common aspect between them, or at least between clinical case H1A and use case H2, is the need for long-term autonomy from a tiny battery i.e., energy-efficient transmission is a key design criterion. However, at the same time they are quite opposed in terms of the KPI space which they address, with H1A focusing on very infrequent upload of a huge amount of data, yet with moderate reliability/availability and latency demands, and H2 focusing on very frequent uploads of tiny amounts of data, but with very stringent demands on both reliability/availability and latency.

Therefore, it is insightful to compare the initial results on device energy efficiency. For H1, which involves transmitting 645 MB per day in a single upload, a 93-day battery life is estimated, albeit under very good coverage conditions and not accounting for data acquisition and preprocessing. However, for H2, which involves transmitting 512 bytes once every second, amounting to 42 MB per day, only 17 hours of battery life is estimated (again, very good coverage and not accounting for data acquisition and preprocessing). In conclusion, the H1 use case transmits 15x as much data, yet uses 130x less energy for doing so or, in other words, H1's daily transmission pattern is 2000x more energy-efficient than H2's once per second transmission pattern. It should be noted that this difference may be less pronounced under less than very favourable coverage conditions. Also, using sleep modes in between transmissions may help optimize H2. Nevertheless, cellular transmission – particularly via 5G-NR RedCap – is much more efficient when transmitting large amounts of data infrequently, compared to transmitting tiny amounts of data very frequently. This can be explained by the fact that maintaining a cellular connection e.g., keeping synchronized with the gNB is quite energy demanding. In particular, the need to keep the receiver active may have a substantial impact on overall energy consumption.

PPDR Domain: The project has validated that Hybrid Connectivity—integrating terrestrial 5G with Non-Terrestrial Networks (NTN) like Starlink—is critical for ensuring 100% service availability. Autonomous "network-in-a-box" solutions have proven capable of rapid deployment, providing essential communications for first responders in disaster zones where traditional infrastructure is compromised.

In the Public Safety domain, the P1 use case demonstrates the feasibility of autonomous edge-based "IN-A-BOX" networks capable of rapidly providing AR/VR-enhanced situational awareness for first responders. The integration of dynamic backhaul selection and multi-operator slicing confirms the capability of the proposed architecture to support highly demanding emergency communications, although maintaining stable Quality of Service (QoS) over heterogeneous and satellite-based backhaul links remains an open challenge.

The P2 use case validates the importance of intelligent network selection and seamless interoperability across terrestrial 5G, Wi-Fi 6, and satellite systems. Preliminary results indicate that uninterrupted mission-critical connectivity for first responders is achievable, though further testing is required to ensure seamless handovers and service continuity in highly mobile and remote environments.

The P3 use case highlights the value of private communication-on-the-move solutions based on integrated network slicing, Multi-access Edge Computing (MEC), and Open RAN technologies. These mechanisms enable traffic prioritization and isolation for mission-critical services even in the absence of public infrastructure. However, the integration of these advanced technologies introduces considerable architectural complexity that must be carefully managed during large-scale deployments.

The P4 Arctic Search and Rescue use case confirms the feasibility of maintaining resilient B5G connectivity under extreme environmental conditions through hybrid terrestrial-satellite communications and sensor-equipped eSled platforms. The conducted evaluations demonstrate the potential of these technologies to provide real-time situational awareness in harsh arctic environments, although signal degradation and synchronization challenges remain important technical considerations.

Finally, the P5 tactical B5G/6G network use case demonstrates the effectiveness of rapidly deployable standalone tactical communication systems integrating local Standalone (SA) cores with opportunistic satellite backhaul. Early field trials have already validated Low Earth Orbit (LEO) satellite integration and confirmed the capability of the system to maintain operational connectivity under challenging conditions. Future large-scale trials will focus on validating performance under worst-case radio environments, high responder density, and dynamic mobility scenarios.

Overall, the current results confirm that the proposed technologies, architectures, and orchestration mechanisms provide a strong foundation for future resilient digital services in healthcare and public safety. The transition from laboratory integration to large-scale field experimentation now represents the critical next step toward validating operational readiness, scalability, interoperability, and compliance with future 6G standards. The planned demonstrations in 2027 will therefore play a decisive role in validating the maturity and societal impact of the developed solutions.

Standardization: Use of 3GPP-aligned mechanisms and CAMARA APIs ensures that all developed enablers remain compatible with evolving global 6G standards, positioning the project as a key contributor to the European 6G ecosystem. In addition, challenging requirements, as in the healthcare use case H1A scenario, push the boundaries for novel 6G technologies and this clinical scenario and the associated KPIs have been contributed to the 3GPP 6G Study [3].

5.1 Large scale trial aspects

The H1 use case introduces a first-of-its-kind wearable ultrasound patch utilizing edge-based AI for real-time cardiac imaging, while addressing the significant challenge of balancing the large data volume generated by ultrasound imaging with the limited energy constraints of battery-powered wearable devices. Due to the very sensitive nature of health use cases and the fact that all of them need high levels of reliability, large scale aspects concern the longevity of the results. For the H1 Wearable ultrasound patch for cardiac function monitoring Use Case, the H1B clinical case has very stringent requirements for availability (>99.9999%) and reliability / Mean Time Between Failure (>1 year) (see Section 2.1.5.2). To address this, testing of 1-month duration is planned around Q2 2027, with system load, such as the number of parallel sessions and simulation parameters to be determined).

Similar to the H1B clinical case described above, the H2 Event-aware real-time reprogramming of pacemaker through wearable patch Use Case has very stringent requirements for availability (>99.9999%) and reliability / Mean Time Between Failure (>1 year) (see Section 2.2.5). Based on the current planning, around Q2 2026, testing of 1-month duration is planned, followed up with another test planned for Q2 2027.

In the AMAZING-6G PPDR domain, large-scale trials we defined as real-world, multi-site, stress-tested field deployments of integrated 6G systems under operationally realistic emergency conditions, rather than controlled lab or small pilot experiments. In the first phase of the project, pre-trials were focusing in making use that all automation and autonomous mechanisms are in place, integrated with the 6G Enablers and 6F infrastructures (both network and compute).

Large scale trials however are planned with focus on end-to-end validation of PPDR services across heterogeneous and geographically distributed environments, including urban, rural, and remote or infrastructure-degraded areas. They test full system stacks (RAN, edge, core, slicing, NTN/satellite, and applications) under high mobility, high load, and mission-critical constraints, involving multiple responder teams, vehicles, and live data streams (e.g., video, AR/VR, camera and sensor feeds). In the end-to-end service delivery however in some cases, the ends are not pre-defined, and during large scale trials mechanisms should be in place that discover the assets (network, digital infra) required to set up the service in an autonomous way while try to resolve issues of damaged infrastructure.

A key defining aspect is that they move beyond technical feasibility to assess operational performance at scale, including:

- Continuous service delivery under harsh and real disaster-like/extreme conditions (P2-P4)
- Interoperability across large number of network technologies P1-P2-P5 (5G, Wi-Fi, satellite/NTN, private tactical networks)
- Dynamic orchestration and network slicing performance under stress P1 and P2
- End-to-end KPIs such as sub-10 ms latency and high reliability (up to 99.999%) with fast recovery times during mobility or failures
- Multiple pilot sites in various countries
- Use of operator-grade (P5) or near-commercial networks (P1) and private testbeds (All use cases)
- Integration of cloud, edge, AI/ML, security, orchestration platforms

In addition, in AMAZING-6G large-scale PPDR trials will showcase:

- Expansion of coverage area through multiple technologies (P1, P5)
- Involve multiple stakeholders and first responders (P1-P5)
- Operate for an extended period (from weeks to months), as in the case of H1
- Include emulated emergency scenarios (search and rescue, disaster response, arctic operations, etc.)(All)
- Validate both technical KPIs and societal/operational impact (All)
- Stress-test systems under worst-case conditions (network outages, satellite dependency, high congestion, mobility extremes) and real-life complexity (weather conditions etc)

In the context of 6G projects like AMAZING-6G, large-scale PPDR trials represent the final validation stage before pre-commercial readiness, ensuring that integrated 6G-enabled systems are robust enough for deployment in real emergency and disaster response operations.

5.2 Conclusions and Strategic Outlook

Based on the intermediate developments in WP4, the following conclusions have been reached:

- Feasibility of Edge-Centric Healthcare: Preliminary tests confirm that offloading AI processing to the 6G edge effectively mitigates the power limitations of medical wearables, enabling clinical-grade monitoring in home and ambulance settings.
- Robustness through Hybrid Connectivity: The integration of satellite as a non-blocking backhaul for tactical networks (P5) and as a redundant link for mobile units (P2) is critical for ensuring high service availability in public safety missions.
- Automatic deployment of the digital infrastructure: end to end service delivery over 6G networks.
- Standardization Alignment: The project's use of 3GPP-aligned mechanisms (and CAMARA APIs ensures that the developed enablers are compatible with evolving global 6G standards.

WP4 has made a strategic contribution to two SNS (Smart Networks and Services) White Papers, reinforcing its role beyond use case development by actively shaping European 6G research direction and standardization priorities. Through its Health and PPDR use cases, WP4 has provided concrete, evidence-based insights on the requirements, feasibility, and societal impact of 6G-enabled services, particularly in ultra-low-latency communications, edge AI, and hybrid terrestrial–non-terrestrial connectivity. These contributions help bridge the gap between experimental system development and high-level 6G vision, ensuring that emerging architectural and technological frameworks remain grounded in validated real-world needs. As a result, WP4 strengthens the project's positioning within the European 6G ecosystem and supports the alignment of research outcomes with future SNS and global standardization efforts.

The project is transitioning from lab-based integration to field trials. Future work will focus on optimizing AI model complexity for lower latency and refining the automated orchestration of network slices in high-mobility scenarios.

These developments position AMAZING-6G as a leading contributor to the European 6G ecosystem, demonstrating tangible benefits for patient outcomes and first-responder safety.

6 References

[1] AMAZING-6G Deliverable D2.1, "Initial Requirements and System Architecture", September 2025

[2] AMAZING-6G Deliverable D3.1, "Technology Enablers – Intermediate Report", October 2025

[3] 3rd Generation Partnership Project (3GPP) - Technical Specification Group TSG SA, "Study on 6G Use Cases and Service Requirements", Stage 1 (Release 20), 3GPP TR 22.870 v2.0.0 (2026-03), https://ftp.3gpp.org//Specs/archive/22_series/22.870/22870-200.zip

[4] WINGS, "wi.BREATHE: WINGS platform for the live monitoring, measurement, and management of air quality and wildfire detection", 2022, wi.breathe - WINGS ICT SOLUTIONS

[5] 3GPP, "Technical Specification Group Services and System Aspects; Mission Critical Services; Stage 1 (Release 17)," 3GPP TS 22.179, 2022.

[6] Smart Networks and Services Joint Undertaking (SNS JU), "Strategic Research and Innovation Agenda (SRIA) for 6G Smart Networks and Services," European Commission, 2023.

[7] 3GPP, "Technical Specification Group Services and System Aspects; Functional Architecture and Information Flows to Support Mission Critical Services (Release 17)," 3GPP TS 23.280, 2022.

[8] Allbesmart LDA, "OAIBOX™ 5G Lab Manual (for OAIBOX™ 40)", 2026.

[9] Ettus Research, "USRP N310 Datasheet (v3)", 2019.

[10] SpaceX, "Performance Setup Guide (Performance Kit)", Starlink™, 2026.

[11] Ericsson, "RedCap - expanding the 5G device ecosystem for consumers and industries", 2023, https://www.ericsson.com/493d70/assets/local/reports-papers/white-papers/redcap-5g-iot-for-wearables-and-industries.pdf

[12] Kalyakulina, Alena, Yusipov, Igor, Moskalenko, Viktor, Nikolskiy, Alexander, Kosonogov, Konstantin, Zolotykh, Nikolai, and Mikhail Ivanchenko. "Lobachevsky University Electrocardiography Database" (version 1.0.1). PhysioNet (2021). RRID:SCR_007345. https://doi.org/10.13026/eegm-h675

[13] A. Goldberger, L. Amaral, L. Glass, J. Hausdorff, P. C. Ivanov, R. Mark, J. E. Mietus, G. B. Moody, C. K. Peng, and H. E. Stanley. "PhysioBank, PhysioToolkit, and PhysioNet: Components of a new research resource for complex physiologic signals. Circulation [Online]. 101 (23), pp. e215–e220." (2000). RRID:SCR_007345.