



6G-Path

Annex 1.2 Technical Annex

6G-PATH - Open Call #1



Co-funded by
the European Union



6G-PATH project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101139172.

Table of contents

1 Introduction	6
2 6G-PATH Platform	7
2.1 Pilots/ Use Cases.....	7
2.2 Analytics.....	7
2.3 Northbound APIs	9
2.4 Backend	11
2.5 Southbound APIs	12
3 Testbeds	13
3.1 ORO Testbed.....	14
3.2 UWS Testbed	30
3.3 FOKUS Testbed	32
3.4 IT/ALB Testbed.....	37
3.5 UMA Testbed	51
3.6 KAU Testbed	56
3.7 OTE Testbed.....	60
4 Verticals and Use Cases.....	63
4.1 UC-FARM-1 - Water saving	63
4.2 UC-FARM-2 - Smart Vineyards.....	66
4.3 UC-EDU-1- XR rural school.....	68
4.4 UC-EDU-2 - Classroom of Future	75
4.5 UC-EDU-3 - XR health training	76
4.6 UC-HEALTH-1 - 3D hydrogel patches.....	77
4.7 UC-HEALTH-2 - Elderly monitoring	79
4.8 UC-CITIES-1 – Connected and sensing city	80
4.9 UC-CITIES-2 – Automated logistics	82
4.10 UC-CITIES-3 – Security coordination.....	82
5 Extensions and new features.....	84
5.1 ORO Testbed.....	84
5.2 UWS Testbed	84
5.3 FOKUS Testbed	85
5.4 IT/ALB Testbed.....	86
5.5 UMA Testbed	87
5.6 KAU Testbed	87
5.7 OTE Testbed.....	88
6 Data Management.....	89

List of figures

- Figure 1. Portal, Info tab9
- Figure 2. Definition of an Experiment10
- Figure 3. Config.yml, Portal configuration file10
- Figure 4. Test case defined based on current Task availability in the ELCM11
- Figure 5. Southbound Interface - Experiment Lifecycle Manager (ELCM)12
- Figure 6. 6G-PATH Testbed Experimentation13
- Figure 7. 5G SA Testbed Architecture, General view and Key component and capabilities16
- Figure 8. Cloud RAN Deployment in ORO's Testbed17
- Figure 9. A representation of the 5G Control plane17
- Figure 10. Virtualisation Layers available in ORO Testbed19
- Figure 11. Orange 5G Lab Slicing Architecture20
- Figure 12. ORO's Testbed Monitoring Systems21
- Figure 13. Remote access architecture for ORO's Testbed23
- Figure 14. Slicing Capabilities in ORO Testbed25
- Figure 15. 3GPP 5G Slicing Model available in ORO Testbed26
- Figure 16. ORO Testbed Bucharest 5G Lab private 5G network elements26
- Figure 17. ORO Testbed Iasi 5G Lab private 5G network elements26
- Figure 18. ORO Testbed Bucharest 5G Lab networking elements27
- Figure 19. ORO Testbed Iasi 5G Lab networking elements27
- Figure 20. ORO Testbed Bucharest 5G Lab computing servers27
- Figure 21. ORO Testbed Iasi 5G Lab computing servers27
- Figure 22. ORO Testbed Bucharest 5G Lab datacentre infrastructure27
- Figure 23. ORO Testbed Iasi 5G Lab datacentre infrastructure28
- Figure 24. ORO Testbed Bucharest 5G Lab devices29
- Figure 25. ORO Testbed Iasi 5G Lab devices list30
- Figure 26. Testbed description31
- Figure 27. 5G Fraunhofer FOKUS Testbed Infrastructure32
- Figure 28. Open5GCore 5G SA Core Network33
- Figure 29. Infrastructure Capabilities34
- Figure 30. Command-line Interface35
- Figure 31. Fraunhofer FOKUS Testbed36
- Figure 32. NTN Integration36
- Figure 33. ATCLL Testbed Architecture - General view and Key component and capabilities38
- Figure 34. Video CDN Website40
- Figure 35. IPFS and CN configuration40
- Figure 36. Overall ATCLL 5G and Edge Architecture42
- Figure 37. 5G Edge-enabled deployment43
- Figure 38. 5G RAN and Core metrics collection46
- Figure 39. 5G Private Network at the University Campus (Málaga)51
- Figure 40. 5G Private Network at La Mayora (Algarrobo)52
- Figure 41. Site 1 at La Mayora52
- Figure 42. Site 2 at La Mayora53
- Figure 43. HPE 5GC architecture54
- Figure 44. Hyper-converged architecture of the main data centre55
- Figure 45. KAU testbed layout57

Figure 46. View of parts of the KAU engineering building covered by the testbed (1)	57
Figure 47. View of some parts of the KAU engineering building covered by the testbed (2)	57
Figure 48. Sample view from part of the live visualisation of monitoring data	59
Figure 49. OTE testbed high level architecture	60
Figure 50. 5G SA architecture	61
Figure 51. Athonet Architecture	61
Figure 52. Global diagram of the components for the Use Case Farm	164
Figure 53. High-level topology of the Use Case Farm	165
Figure 54. High Level Diagram of UC-EDU	168
Figure 55. Orange 5G/6G Experimentation Platform	72
Figure 56. High-Level Architecture and Topology Diagram for UC-EDU	174
Figure 57. Scenario to detect potential collisions (top left); ATCLL smartlamp post (top right); Autonomous vehicle development platform (bottom left); and ATCLL digital twin application (bottom right)	81
Figure 58. UWS B5GHub Testbed Envisioned with Advance 6G-Ready Features Deployed	88
Figure 59. ATCLL map of the current infrastructure	86
Figure 60. Map of the planned expansion	87
Figure 61. Map providing a close look at the expansion of the ATCLL, featuring new smart lamp post locations and the optical fiber network	87

List of tables

Table 1. Summary of 5G Infrastructure in ORO Testbed	14
Table 2. ORO Testbed Resources	18
Table 3. Available metrics in the monitoring systems	21
Table 4. 5G Lab onboarding platform interfaces	22
Table 5. Services available in the ORO Testbed	24
Table 6. 5G RAN Configuration in ORO Testbed	24
Table 7. 5G/6G Feature Set of ORO Testbed	25
Table 8. Slices definition examples in ORO Testbed	26
Table 9. Slice Availability in ORO Testbed	26
Table 10. Open5GCore Features and their Description	33
Table 11. Summary of the ATCLL 5G Infrastructure	37
Table 12. Services available in the ATCLL Testbed	39
Table 13. Available RAN equipment	60
Table 14. Functional requirements	65
Table 15. Performance Requirements	66
Table 17. Scenarios with objectives	67
Table 18. Use Case functional requirements	74
Table 19. Use Case performance requirements	75
Table 20. Use Case functional requirements	76
Table 21. Use Case performance requirements	76
Table 22. 6G Requirements	78
Table 23. 6G Requirements	80
Table 24. Timeline for the implementation of Upgrades and Extensions to ORO's testbed	84
Table 25. Timeline for the implementation of Upgrades and Extensions to UWS's testbed	84

1 Introduction

The Technical Annex for the 6G-PATH – Open Call #1 provides applicants with an understanding of the main technical components and infrastructure that they may be required to use as part of their applications. This annex is designed to help applicants understand and align their projects with the technical environment of the 6G-PATH initiative.

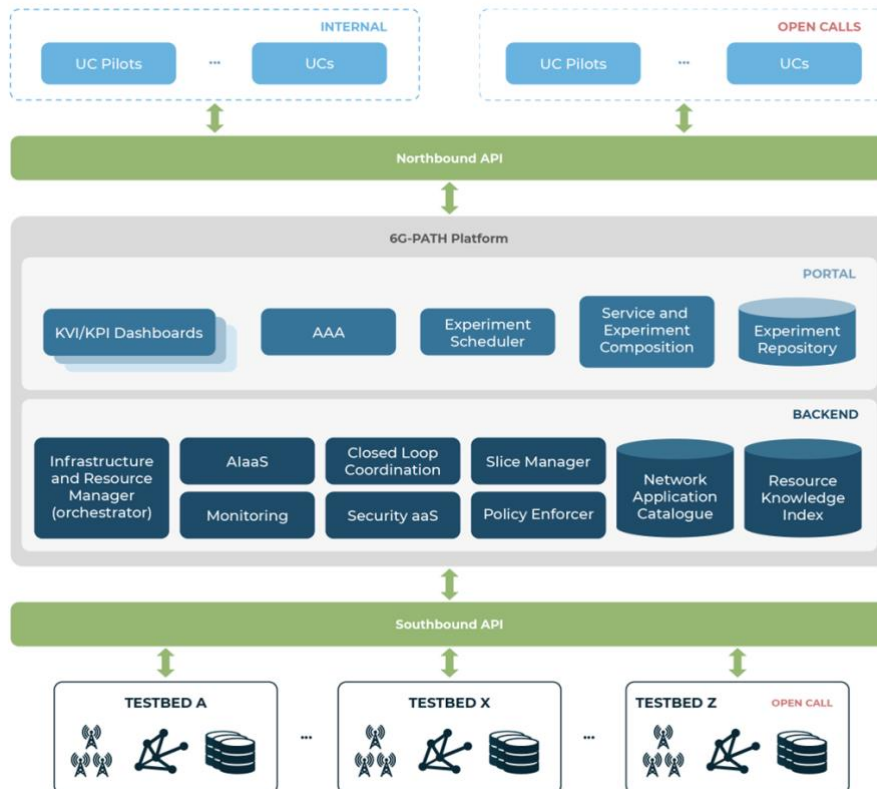
The Technical Annex is structured into six (-6-) main sections:

- The first section is the present introduction section.
- The second section focuses on the 6G-PATH Platform and provides detailed information on the platform, including pilots/use cases, analytics, northbound APIs, backend and southbound APIs.
- The third section describes various testbeds available for the projects, covering current infrastructure, services offered, virtualisation, management, orchestration, monitoring, security services and key features and assets.
- The fourth section delves into Verticals and Use Cases, presenting examples of specific applications and scenarios relevant to the 6G-PATH project.
- The fifth section addresses Extensions and New Features, offering information on potential enhancements and new capabilities that can be integrated into the projects.
- The sixth section covers Data Management, outlining guidelines and protocols for handling and managing data within the project framework.

By providing this detailed technical context, this annex aims to ensure that applicants have the necessary information to develop robust and innovative project proposals well-aligned with the 6G-PATH technical landscape.

2 6G-PATH Platform

The overall architecture of the 6G-PATH platform is illustrated in the diagram below. The main components are briefly introduced in the subsequent subsections.



2.1 Pilots/ Use Cases

The Pilots and Use Cases layer in the 6G-PATH platform layer aims to represent the users and entities responsible for defining their services' compositions, following a set of guidelines specified by the project. They control when experiments run, where they will be deployed and for how long, and collected metrics and other relevant details from past/current experiments' executions.

2.2 Analytics

The Analytics Dashboard is a sophisticated analytics platform designed to integrate seamlessly with existing third-party experimentation systems. This dashboard provides comprehensive visualisation and processing of Key Performance Indicators (KPIs) and Key Value Indicators (KVIs), allowing users to compare performance metrics against target and baseline values to track incremental improvements. With support for multi-domain scenarios, closed-loop systems and robust security enhancements, the dashboard will offer real-time data monitoring, advanced filtering and interactive visualisations.

High-level GUI (Graphics User Interface) requirements are listed below:

The Analytics dashboard is a powerful tool that helps organisations visualise, analyse and interpret data to make informed decisions. Here is a list of features:

- **Data Integration:**
 - Ability to connect and integrate data from multiple sources (databases, APIs (Application Programming Interfaces), cloud services, etc.).
- **Customisable Interface:**
 - Drag-and-drop widgets and customisable layouts.
 - Personalisation options for users to “tailor” the dashboard to their needs.
- **Interactive Visualisations:**
 - Various chart types (bar, line, pie, scatter plots, etc.).
 - Interactive elements (hover effects, drill-down capabilities, clickable areas).
- **Real-Time Data Updates:**
 - Live data feeds and auto-refresh capabilities to keep information current.
- **Filters and Segmentation:**
 - Advanced filtering options to segment data by different criteria (time, geography, demographics, etc.).
 - Dynamic filtering to adjust views based on user input.
- **Performance Metrics and KPIs:**
 - Display of key performance indicators (KPIs) and other relevant metrics.
 - Benchmarking against targets and historical data.
- **Data Exporting:**
 - Options to export data and visualisations in various formats (PDF, Excel, CSV, images).
- **Reporting Tools:**
 - Automated report generation and scheduling.
 - Custom report creation with the ability to save and share reports.
- **User Management and Permissions:**
 - Role-based access control to manage who can view or edit specific data and dashboards.
 - User authentication and security features.
- **Alerts and Notifications:**
 - Set up alerts and notifications based on specific data thresholds or conditions.
- **Trend Analysis and Forecasting:**
 - Tools for trend analysis to identify patterns over time.
 - Predictive analytics and forecasting capabilities.
- **Mobile Accessibility:**
 - Mobile-friendly design for access on smartphones and tablets.
 - Responsive layout to adapt to different screen sizes.

2.3 Northbound APIs

Each platform has deployed its instance of the Experimentation Portal. The Portal provides the Experimentation Northbound Interface to be used by the experimenters to define, execute and consult the experiment results.

The Info tab in the upper part of the Portal offers information about the available testbed devices and network scenarios.



Figure 1. Portal, Info tab

The “Create Experiment” tab allows the users to define the experiment. The experiment definition is based on test cases. A test case defines the KPIs to be measured, with specific preconditions of the test and the calculation methods to obtain the KPI. By default, the Experimenter will have a list of standard test cases that cover technological KPIs such as throughput and round-trip time, and custom test cases that can be defined using the tasks available at the following [link](#).

The experimenter will deploy the solution in the platform and produce new test cases to cover the experimentation features needed by the use case under test. The experimenter can define and implement a new task, as described in the following [link](#).

Once the test case is chosen, a UE (User Equipment) or list of UEs is selected to run the test cases on. Finally, the scenario will enable you to specify a specific scenario that is translated to some specific configurations of the network.

CREATE EXPERIMENT

Name

Type

Standard ▾

Test Cases

☐ TESTBEDVALIDATION

☐ REMOTEPINGSSH

☐ EXOPLAYERTEST

☐ REMOTEPINGSSHTOCSVRETURNANDUPLOAD

☐ PING

☐ FULLTEST

☐ DEPLOYMENT LA MAYORA

☐ DEPLOYMENT ADA BYRON

UEs

☐ UE_S0_IN

☐ UE_S0_OUT

☐ UE_local

Scenarios

☐ Scenario1 ▾

Add Experiment

Figure 2. Definition of an Experiment

The definition of the test cases that appear in the Portal is done by editing the configuration YAML (Yet Another Markup Language¹) file available in C:\portal\config.yml.

```

TestCases:
  - TESTBEDVALIDATION
  - REMOTEPINGSSH
  - EXOPLAYERTEST
  - REMOTEPINGSSHTOCSVRETURNANDUPLOAD
  - PING
  - FULLTEST
  - DEPLOYMENT LA MAYORA
  - DEPLOYMENT ADA BYRON

Slices:
  - Scenario1
  - Scenario2

UEs:
  UE_S0_IN:
    OS: Android
  UE_S0_OUT:
    OS: Android
  UE_local:
    OS: Android

Grafana URL:
  http://localhost:3000/dashboards

Platform:
  Málaga [UMA]

PlatformDescriptionPage: platform.html

```

Figure 3. Config.yml, Portal configuration file

Each test case listed in the Portal has an associated YAML file with the implementation of the test case.

¹ For further information also see, inter-alia: <https://yaml.org/>

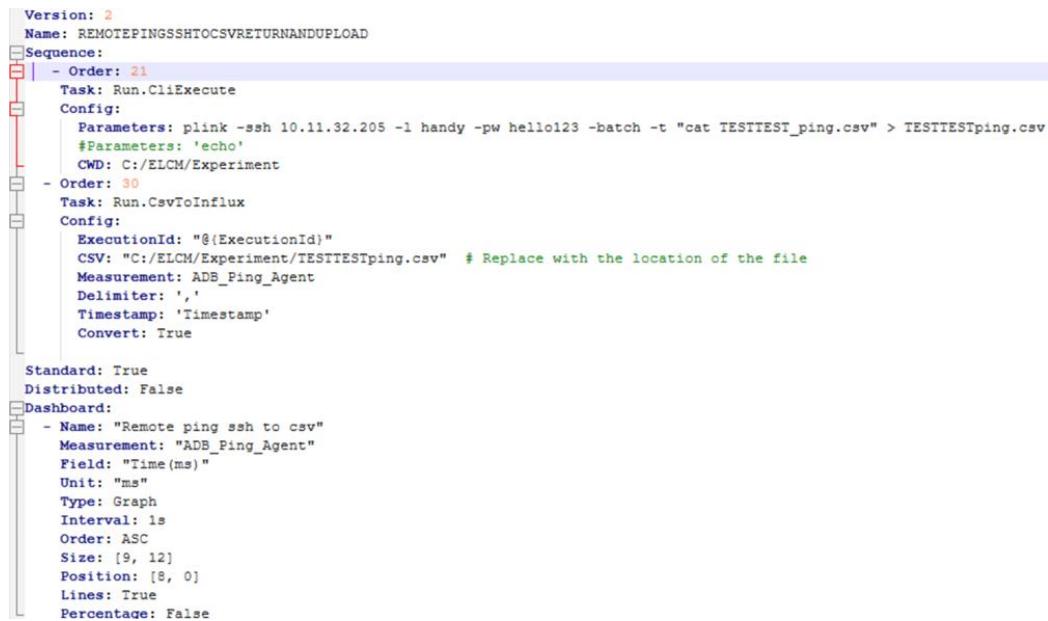


Figure 4. Test case defined based on current Task availability in the ELCM

This comprehensive categorisation ensures that data is organised and utilised effectively throughout the project, maximising its value for research, development and decision-making. This illustrates a test case that uses a task of the type "Run.CliExecute" to connect to a PC (Personal Computer) via SSH (Secure Shell) and execute a ping command.

The output of this test is a CSV file, retrieved by the task "Run.CsvToInflux", which is then injected into the InfluxDB² available on each platform to store the results. The final part of the test case defines a dashboard in Grafana to display the results.

For more detailed information please visit the following [link](#).

2.4 Backend

The backend components layer will facilitate communication between testbeds and the southbound and northbound APIs. Components in this layer can provide various types of data to higher layer components such as Grafana, Analytics, and ELCM (Experiment Lifecycle Manager) or they can execute actions like orchestration from the higher layer components on the testbed. Different partners will supply components for this layer from current or past projects, as well as components developed specifically for the 6G-PATH project. These tools include both standard tools and custom ones developed by the partners.

The tools are separated into four categories:

- **Monitoring**
 - Monitoring system and software information including core network and other software's running in the testbed
- **Management**
 - Management of the core components using standard and non-standard APIs
- **Orchestration**

² InfluxDB is the most popular open-source database (DB) for developers managing time series data. Also see, *among others*: <https://www.influxdata.com/>

- Management of different core services
- Orchestration of core networks
- **Advanced experimentation features**
 - Security-as-a-Service
 - Slice Manager
 - AI-as-a-Service
 - Close-loop coordinator
 - Policy enforcer

2.5 Southbound APIs

The southbound interface is provided by the Experiment Lifecycle Manager (ELCM). The ELCM is a central component of the experimentation framework, designed to orchestrate and manage the entire lifecycle of 5G experiments. It ensures that experiments are conducted systematically, efficiently and repeatedly. The ELCM handles various tasks, from initial setup to execution, monitoring and final analysis. It includes a list of plugins that configure the underlying technologies and modules to support its operation. Technology providers wishing to integrate their solutions into the platforms must implement the corresponding plugin. This plugin will communicate directly with the new hardware or software component and will expose an API to be used during the implementation of test cases or scenarios. Test cases and scenarios will be defined via YAML files, using the available tasks or implementing new tasks if necessary.

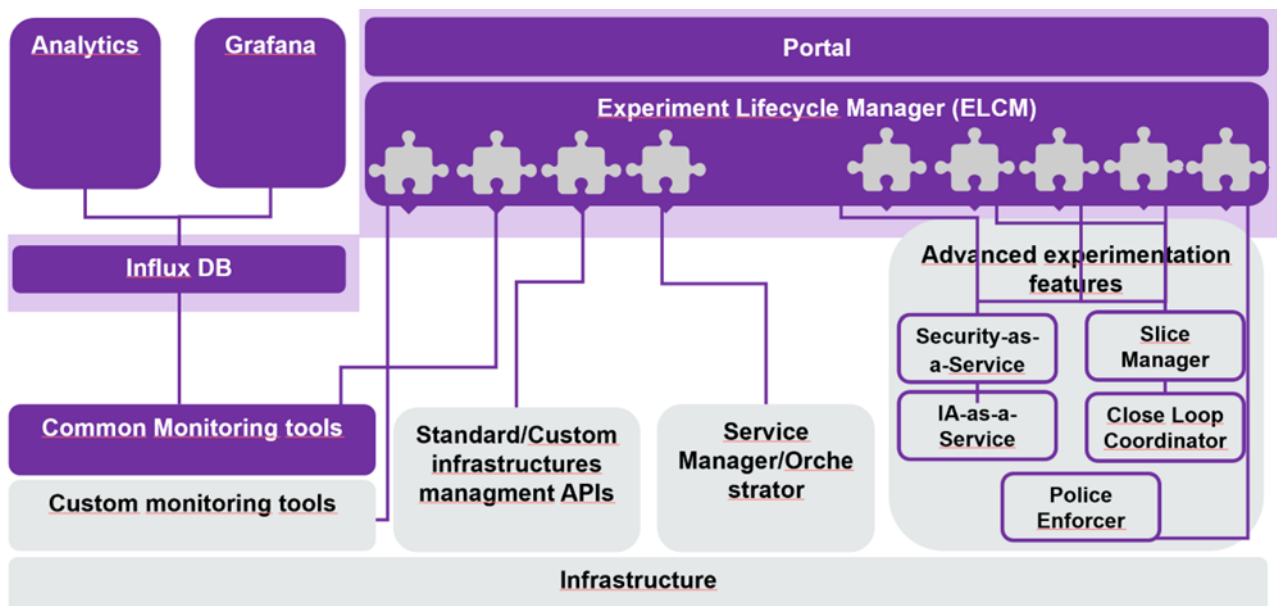


Figure 5. Southbound Interface - Experiment Lifecycle Manager (ELCM)

3 Testbeds

6G-PATH aims to foster the development and integration of new and improved tools and products from EU companies with 5G/6G, while also measuring relevant KPIs and KVIs. To achieve this, seven (-7-) testbeds will be part of the project consortium, utilised by ten (-10-) use cases across four (-4-) key verticals, that is: Health, Education, Smart Cities, and Farming. The testbeds and pilot sites will go beyond 5G and follow 3GPP Releases 18, 19, and 20³. Initially, seven (-7-) testbeds will be made available by the consortium, with the potential for up to two more testbeds or pilot sites to be integrated through Open Calls.

6G-PATH aims to use these testbeds as a common infrastructure for the systematic integration of B5G/6G innovations developed in other 6G-IA⁴ projects and/or by third parties through Open Calls. This will allow those innovations to be demonstrated and validated across multiple testbeds, use cases and applications.

By enabling the development of a transversal platform for experimentation in beyond-5G networks, 6G-PATH will significantly lower the barriers for innovative use case or application promoters interested in adopting or assessing the suitability of B5G/6G technologies for their services and applications. 6G-PATH will leverage existing 5G Advanced and 6G solutions to set up a unified experimental infrastructure across different trial locations and testbeds.

Moreover, additional technologies will be exploited to directly support the requirements of use cases and verticals in challenging scenarios. These multiple experimental infrastructures will build upon open interfaces, support seamless interoperability and possess the required capabilities to meet the diverse performance requirements posed by its innovative use cases.

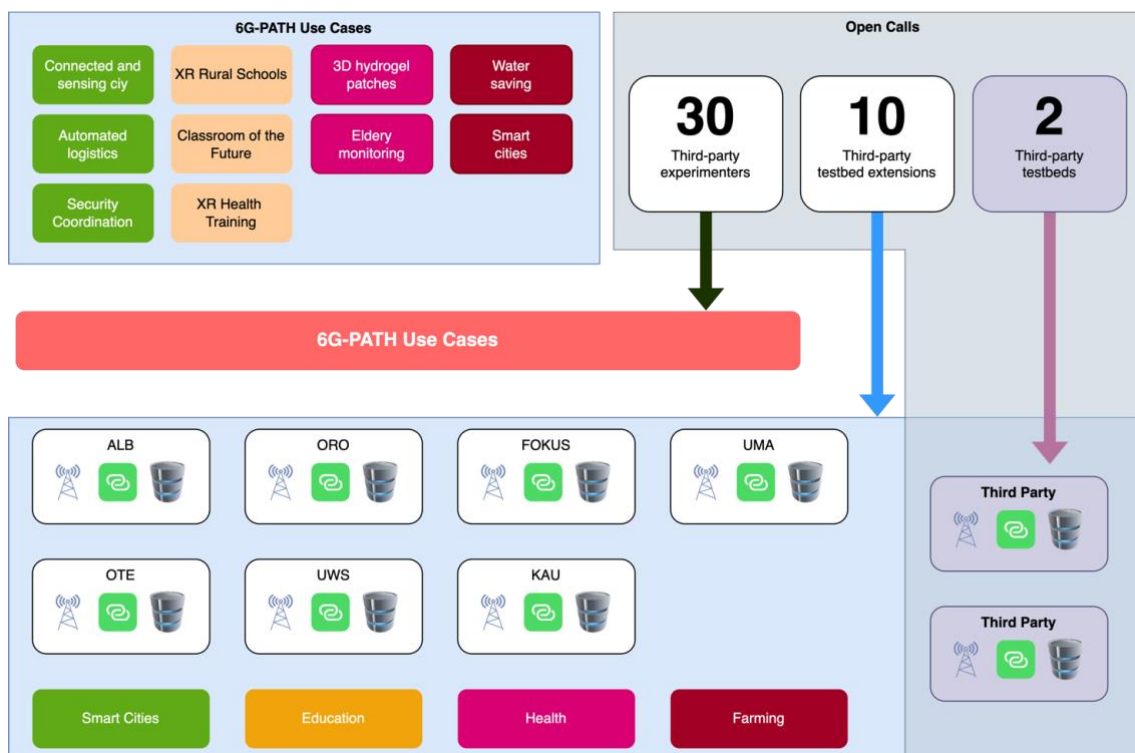


Figure 6. 6G-PATH Testbed Experimentation

³ The Third Generation Partnership Project (3GPP) uses a system of parallel “Releases” which provide developers with a stable platform for the implementation of features at a given point and then allow for the addition of new functionality in subsequent Releases. Also see: <https://www.3gpp.org/specifications-technologies/releases>

⁴ The 6G Smart Networks and Services Industry Association (6G-IA) is the voice of European Industry and Research for next generation networks and services. For further information see: <https://6g-ia.eu/>

6G-PATH will “drive” continuous testbed upgrades and improvements to ensure that the experimentations and derived analyses are highly valuable. To achieve this, the supporting testbeds, encompassing both physical and virtual layers, need to be kept up to date with the latest developments. While the testbeds will initially provide substantial support for B5G/6G technologies, a systematic process of upgrades and improvements is planned to capitalise on developments from other parallel research initiatives towards 6G.

This ongoing process of upgrades and improvements is expected to yield mutual benefits: evaluated use cases may benefit from these advancements and developers of B5G/6G technology will be able to assess the actual impact of their novel or improved technologies. Multiple experiments will be conducted at different stages of the project to determine whether the integrated research advances effectively improve the performance of representative use cases.

3.1 ORO Testbed

ORO’s testbed facility is located at POLITEHNICA Bucharest National University of Science and Technology. ORO and “POLITEHNICA” operate a research, evaluation, testing, and validation environment for next-generation network technologies named the “Orange 5G Lab”. This lab extends remotely to a similar 5G Lab at the “Gheorghe Asachi” Technical University of Iasi in Romania. The two testbeds are interconnected through high-speed broadband (100Gbps) and fully implement a 5G SA (Standalone) 3GPP Release 16⁵ compliant infrastructure.

Table 1. Summary of 5G Infrastructure in ORO Testbed

5G infra \ testbed	RAN NSA/SA	5GCN NSA/SA	IP Transport	IaaS	MANO & Monitoring	Security	MEC	Slicing
Bucharest	Huawei SRAN18 NSA/SA Nokia AirScale OAI / srsRAN	Ericsson 2.15 vEPC Nokia CMU23.10 5GC OAI / Open5GS	CISCO NXOS IPFABRIC	OpenStack Ussuri VMware ESXi K8s	OSM v10 Prometheus Grafana	Fortinet 1000D Arbor DDoS Mitigation	Collocated IaaS w 5G Core	SNSSAI based APN based
Iasi	Ericsson DOTs NSA/SA OAI / srsRAN	Nokia CMU23.10 UPF OAI / Open5GS	CISCO NXOS IPFABRIC	OpenStack Ussuri K8s	Prometheus Grafana	Fortinet 1000D Arbor DDoS Mitigation	Collocated IaaS w 5G UPF	SNSSAI based APN based

3.1.1 Current 5G Infrastructure

Both testbeds are equipped with the latest generation of software and hardware solutions for 5G-NR and 5GC, including open-source tools for monitoring. They feature an advanced programmable network solution based on next-generation Data Centre IPFABRIC⁶ and MANO (Management and Orchestration⁷) functions. The cloud-native infrastructure provides both a Kubernetes and an OpenStack cluster with generous resources and high-speed networks (10/25Gbps).

Both testbeds support dynamic orchestration of network functions, dynamic slice implementation for end-users, intelligent 5G SA network services connection to edge computing nodes, enhanced Mobile Broadband - eMBB (1500Mbps/150Mbps DL (Downlink)/ UL (Uplink)), and URLLC (Ultra-Reliable Low Latency Communications) with less than 3ms one-way delay using a spectrum of up to 100MHz in the N78 band. This

⁵ Also see, among others: <https://www.3gpp.org/specifications-technologies/releases/release-16>

⁶ Also see, among others: <https://ipfabric.io/>

⁷ For further information see, for example:

https://www.etsi.org/images/files/ETSIWhitePapers/ETSI_White_Paper_Network_Transformation_2019_N32.pdf

setup is suitable for intensive and high-capacity services, demanding use cases (XR (Extended Reality)/ VR (Virtual Reality)/ AR (Augmented Reality), Digital Twin, V2X (Vehicle-to-Everything, etc.), as well as indoor and outdoor environments.

ORO's 5G Lab testbed is based on virtualised network infrastructure for both 5G options, NSA (Non Standalone) and SA variants. For the NSA variant, the 5G Labs are connected to the commercial LTE (Long Term Evolution) Core Network. The NSA core architecture is based on Ericsson's vEPC (virtual Evolved Packet Core) solution, deployed in an OpenStack infrastructure – Orange IaaS (Infrastructure as-a-Service). This core architecture supports broadband connectivity with configurable DL/UL throughput values of up to approximately 1Gbps for DL and 100Mbps for UL. For this existing core architecture, the 5G services are manually configured using dedicated QoS (Quality of Service), traffic prioritisation, private APNs (Access Point Names) and network provisioned capabilities in terms of throughput, with eMBB as the primary service that can be supported.

The SA Core architecture employs the 5G SA CMU (Compact Mobility Unit) Core Network solution from Nokia, which operates on a virtualised infrastructure within the Bucharest 5G Lab datacentre. Three main components are integrated: the Cloud Mobile Gateway (CMG), the Cloud Mobility Manager (CMM) and the Authentication and Policy Control (APC).

These components implement the 5G SA 3GPP-defined Network Functions (NFs) as follows:

- The Authentication and Mobility Management Function (AMF), managed by the CMM, handles user equipment (UE) tracking and authentication within the core.
- The Session Management Function (SMF), managed by the CMG, manages Protocol Data Unit (PDU) sessions, selects the User Plane Function (UPF) for data services based on QoS needs and oversees session authentication via the Unified Data Management (UDM).

The User Plane Function (UPF) handles data session payload, prioritisation of payload, multi-access edge computing integration, and communication with the access domain. It is located within the Bucharest 5G Lab CMG and will also be deployed locally in Iasi using a Local Break-Out (LBO) approach.

The Authentication Server Function (AUSF), managed by the APC, oversees user authorisation, authentication and accounting (AAA) tasks. The Unified Data Management (UDM) unit serves as a subscriber management frontend for 5G SA users, while the Unified Data Repository (UDR) functions as a subscriber profile repository.

Additionally, the testbed facility supports various slices based on 3GPP NSSAI (Network Slice Selection Assistance Information) parameters, providing eMBB with throughput of up to approximately 1.5Gbps for DL and 150Mbps for UL, and URLLC with a one-way delay of less than 4ms.

The figure below illustrates the 5G SA Testbed Architecture, including an overview and key components and capabilities.

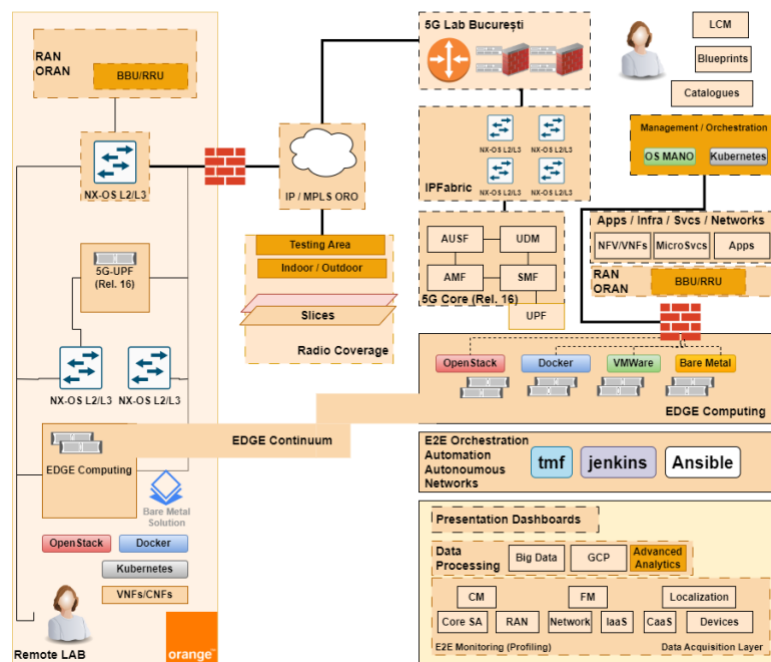


Figure 7. 5G SA Testbed Architecture, General view and Key component and capabilities

3.1.2 Services offered

3.1.2.1 Compute, Storage and Networking Services

RAN: In the 5G SA Option 2 architecture, the RAN consists solely of gNBs connected to the 5G Core (5GC) network. Each gNB connects to the AMF via the NG-C interface for control plane signalling and to the UPF via the NG-U interface for user plane data transfer. The gNBs are interconnected through the Xn interface and provide the NR (New Radio) air interface access to user equipment (UEs).

The RAN includes the Service Data Adaptation Protocol (SDAP) layer and the F1 interface with a Centralised Unit – Distributed Unit split, as detailed. This innovative architecture offers Small Cell coverage to multiple operators “as-a-Service” and utilises virtualisation techniques for data isolation, latency reduction, and resource efficiency. By orchestrating lightweight virtual resources, it enables efficient placement and live

migration of Virtualised Network Functions (VNFs), supporting both small cell capacity and enhanced edge cloud services. The network infrastructure is enriched with edge cloud capabilities.

5G RAN prioritises network slicing through management of 5G QoS Flow inputs, UE TCP (Transmission Control Protocol) sessions and 5G QoS Flow to DRB (Data Radio Bearer) mapping. The network first maps different IP (Internet Protocol) flows with identical QoS requirements into the same QoS Flow.

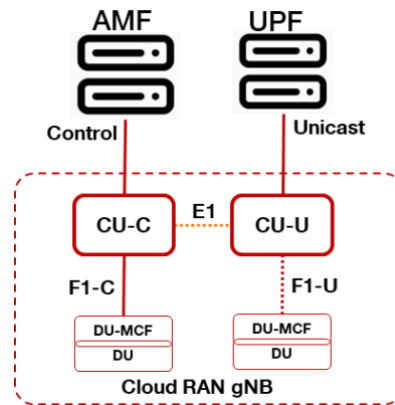


Figure 8. Cloud RAN Deployment in ORO's Testbed

5G Core: The 5G architecture represents an evolution from the 4G framework, introducing significant changes such as the Service-Based Architecture (SBA). As defined by 3GPP, SBA highlights services as the primary architectural components, which execute various functions and authorise access to one another's services. These interconnected Network Functions (NFs) manage the control plane functionality and common data repositories within a 5G network.

The transition to SBA differentiates end-user services from the underlying network infrastructure. Key components in this architecture include:

- AMF (Access and Mobility Management Function): Manages access and mobility.
- SMF (Session Management Function): Oversees session management.
- UPF (User Plane Function): Handles user plane data.
- UDM (Unified Data Management): Acts as the subscriber management frontend.
- AUSF (Authentication Server Function): Manages authentication and authorisation tasks.

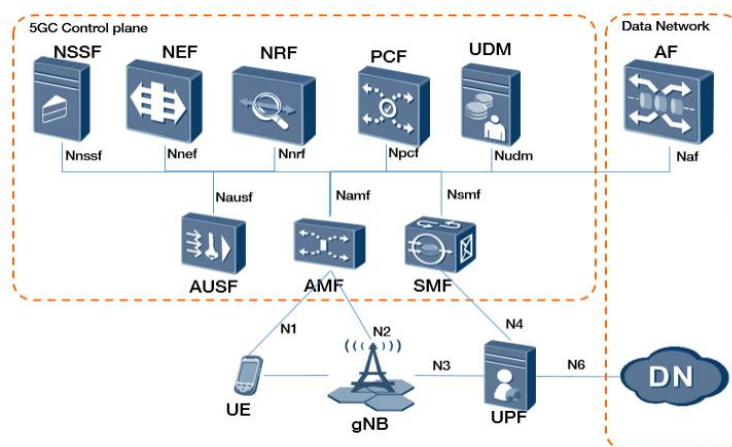


Figure 9. A representation of the 5G Control plane

MEC (Multi-Access Edge Computing): The MEC system reference architecture is deployed within a Network Function Virtualisation (NFV) environment as Virtual Network Functions (VNFs). The virtualised infrastructure

is implemented as Network Function Virtualisation Infrastructure (NFVI) and managed through Virtualisation Infrastructure Managers (VIMs) and Cloud Nodes (CNs). The lifecycle management of the VNFs is overseen by the platform management and platform orchestrator components.

When an application demands additional resources, the cloud infrastructure automatically deploys an additional instance of the application. Conversely, when the load decreases, it removes the extra instances to optimise resource utilisation.

5G Transport: The transport architecture for 5G SBA services incorporates ring or mesh deployments for access front-haul, aggregation middle-haul, and core backhaul. This architecture supports network resource differentiation to cater to various industries. Connectivity is provided through a range of technologies, including radio microwaves, optical (Wavelength Division Multiplexing, WDMs), and Layer 2/Layer 3 (advanced routing, Segment Routing MPLS, VXLAN, Ethernet Provider Virtual Network, EPVN) communication networks.

Proactive congestion management is a key feature, enabling transport-aware RAN (Radio Access Network) load balancing to enhance user Quality of Experience (QoE). This approach facilitates the separation of control and user plane entities, as well as the disaggregation of RAN functionalities. Additionally, automatic provisioning of end-user services, optimisation, and assurance of service Key Performance Indicators (KPIs) are integral to this architecture.

ORO Testbed resources: resources of the testbeds are defined in terms of virtualisation capabilities, VNFs available resources, service automation, monitoring and dashboards visualisation, capabilities to expose the available resources to external partners and available resources to be consumed.

Table 2. ORO Testbed Resources

Capability	Per VNF (up to)			Total no VMs/CNs	Total Infrastructure Resources			MANO / ETSI	Services	Monitoring Capabilities
	Cores /VNF	RAM /VNF	Store /VNF	Concurrent VMs / CNs	vCPUs	RAM (GB)	Store (GB)			
5G Lab Bucharest	16	32	40	200	3200	6400	8000	OSM, Rel. 12, K8s	Automation, NS	Prometheu, StableNet, Graphana

3.1.3 Virtualisation, Management and Orchestration Services

Virtualisation: Virtualisation introduces modularised services that are flexible and adaptable, supporting on-demand networks with fast deployment cycles. This approach allows for dynamic services to be launched within the network, enabling functions to be instantiated, terminated, configured, scaled in or out, and updated more rapidly than traditional physical implementations. It supports on-demand communication service instantiation and includes network slicing, enhancing the network's ability to adapt to varying requirements and optimise resource utilisation.

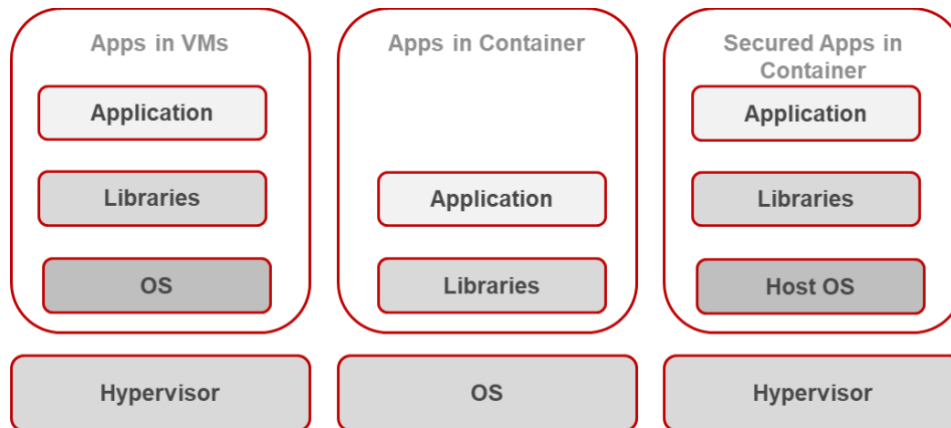


Figure 10. Virtualisation Layers available in ORO Testbed

Management Services and Orchestration: This involves dynamically deploying network functions and automatically programming the connectivity network paths between various components. This approach replaces traditional network configuration methods, which involved manually configuring individual devices and layers, by using industry management and orchestration tools in a coordinated manner.

ETSI NFV MANO: Management & Orchestration (MANO) chains Virtualised Network Functions (VNFs) with other VNFs and/or Physical Network Functions (PNFs) to create a Network Service (NS), which is then mapped into Network Slices.

Cloud Native Orchestration: Containers represent an evolution in virtualisation technology, running underlying microservices on top of the operating system. The benefits of a container-based microservices architecture include efficient resource consumption, faster service creation and deployment, reduced application boot times, lower costs, scalability, resiliency, portability and OS (Open-Source) independence. Kubernetes (K8s) is one of the container orchestration tools, an open-source system that automates containerised application deployment, scaling, and management.

Transport Network Orchestration: Network configuration and end-to-end (E2E) service slice deployment for the transport network should be programmable, elastic, and flexible, allowing for dynamic configuration changes, traffic flows, and QoS service assurance for applications requiring eMBB, URLCC or mMTC (massive Machine-Type Communications). Transport network orchestration addresses various types of transport network implementations.

Resources, Slices, and Services Orchestration: The orchestration layer manages the initial deployment of services across different network domains, such as RAN, Core, or Transport Network (TN), in a coordinated resource allocation method. It includes VNFs or CNF deployment, service chaining, dynamic resource allocation, service composition and onboarding, and slice creation. Facility resources orchestration can be

compliant with 3GPP MANO standards for VNFs in virtual machines (VMs) or with Cloud Native standards for microservices architectures.

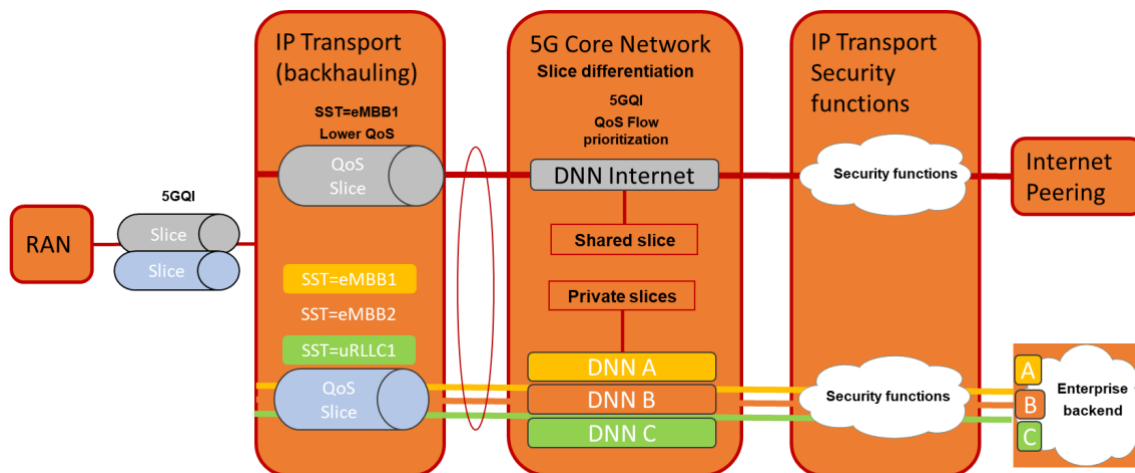


Figure 11. Orange 5G Lab Slicing Architecture

Development and Deployment Tools and Software:

- **CI/CD (Continuous Integration and Continuous Delivery):** This framework facilitates the creation of builds, running automated software application tests and extending integrations to deploy all code changes to testing and production environments.
- **OpenStack:** OpenStack is a cloud operating system that manages large pools of compute, storage, and networking resources across a datacentre. It provides standard Infrastructure as a Service (IaaS) functionality, orchestration, service management, and deployment of user applications, including Cloud Infrastructure for Virtual Machines and Containers.
- **Docker:** Docker is an open platform for developing, shipping, and running applications by isolating them from the underlying infrastructure. This allows for rapid and consistent software delivery. Applications run in a loosely isolated environment known as a container, which supports fast and consistent deployment.
- **Kubernetes:** Kubernetes is an open-source system for automating the deployment, scaling, and management of containerised applications. It serves as the orchestrator for cloud-native applications.
- **OSM (Open-Source MANO):** OSM is an open-source ETSI NFV Management and Orchestration (MANO) stack for end-to-end network service orchestration, particularly for telecommunications services. Key features of OSM include its Information Model, which aligns with ETSI NFV SOL006, unified Northbound Interfaces (NBIs) based on SOL005, network service extensions across multiple domains, and lifecycle management of network slices.
- **Prometheus:** Prometheus is an open-source monitoring and alerting system that collects metrics as time series data. The data is stored on a single server node, with collection methods including both pulling and pushing, and it supports multiple graph modes. It is well-suited for machine-centric monitoring or monitoring highly dynamic service-oriented architectures.
- **Grafana:** Grafana is an open-source, multi-platform analytics and interactive visualisation web application. It enables the creation of dynamic dashboards for centralised data analysis, visualisation, and alerting.

3.1.4 Monitoring Services

Network and Services Monitoring: Network and services monitoring encompasses the capabilities for collecting data on various metrics, utilising different open-source software tools (e.g., Prometheus) for monitoring, and presenting data through dashboards. The monitoring process is centred on two primary streams:

- **Infrastructure Monitoring:** This involves collecting data from infrastructure components such as User Equipment (UE), Radio Access Network (RAN), Core Network, Transport, virtualised infrastructure, and Multi-Access Edge Computing (MEC).
- **Network and Service Performance Monitoring:** This evaluates the performance of network resources, the status of services and user experiences.

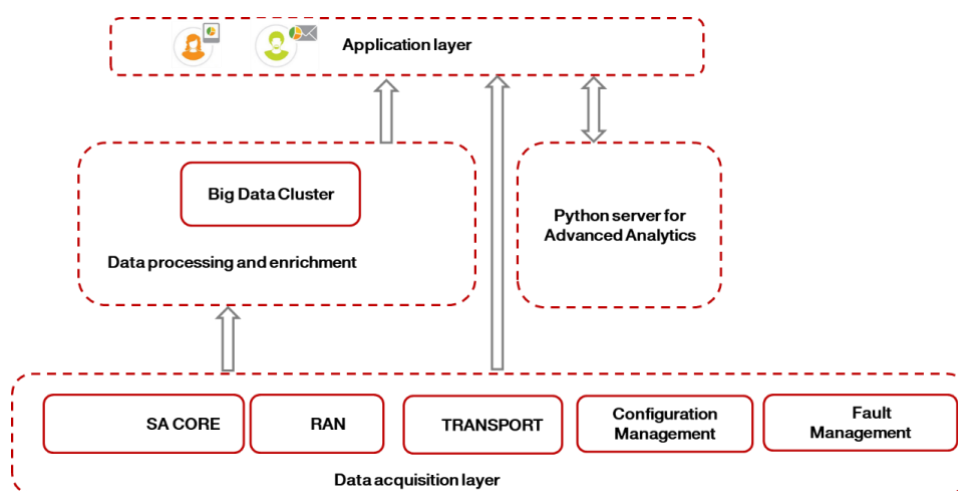


Figure 12. ORO's Testbed Monitoring Systems

The following table lists the various metrics and key data which can be exposed through the monitoring systems of ORO's Testbeds:

Table 3. Available metrics in the monitoring systems

Radio	Core	Transport	Monitoring
5G SA traffic volumes 5G SA Call Setup 5G SA Drop Call - Average reported CQI - Average number of Users - Physical resource Blocks Load 5G SA average user throughput	5G SA Core REST service - List of alarms - Root cause and Impacts - Tree causes and impact for a specific alarm - Network performance monitor in real-time or periodically	- Troubleshooting - Ports, Interfaces, LSPs - Link utilisation - Latency optimisation - TCEs on errors, discards, utilisation - IP traffic usage	- Grafana monitoring tool - Internal tools

The main functionalities exposed by the 5G Lab testbed, and their corresponding abstract interfaces are summarised as follows:

- **Network Slice Management:** This function supports the creation, selection, and configuration of network slices within the 5G infrastructure deployed in the testbed. This is managed through the Slice_conf interface.
- **Onboarding:** This involves the deployment of 5G-enabled applications, Virtual Network Function (VNF) packages, and network service descriptors for vertical services. This process is facilitated

through the orchestration platform connected to the edge/cloud computing infrastructure of the testbed, using the Nfvo_cat interface.

- **Lifecycle Management:** This function provides network services provisioning for the instantiation of vertical services composed of 5G-enabled applications. It is managed through the Nfvo_lcm interface.
- **Monitoring:** This encompasses the configuration of monitoring parameters via the Mon_conf interface and the retrieval of monitoring data through a publish/subscribe mechanism using the Mon_pub interface. Monitoring covers both service and infrastructure Key Performance Indicators (KPIs), including 5G network KPIs and metrics related to computing resource consumption.

Table 4. 5G Lab onboarding platform interfaces

5G Lab testbed	Interface	Reference standards	Implementation
NFV MANO system	Nfvo_cat: management of VNF packages and Network Service Descriptors	ETSI NFV SOL 006 for NFV descriptors ETSI NFV SOL 005 for REST API on management of VNF packages and NSDs	OSM 10 NBI API for: • VNFD Details • NSD Details • PDU Details
	Nfvo_lcm: Management of the lifecycle of NFV Network Services and configuration of their virtual functions	ETSI NFV SOL 005 for REST API on lifecycle management of NFV network services Non-standard extensions for configuration of VNFs, adopting the ETSI OSM mechanisms for VNF configuration.	OSM 10 NBI API, for: • NSLCM Details OSM based Day-1 and Day-2 operations for VNF configuration.
5G slice management system	Slice_conf	3GPP TS 28.531 for REST API to create Network Slice Instances 3GPP TS 28.541 [4] for the information model on network slices	Implementation in progress.
Monitoring system	Mon_conf Mon_pub	-- --	• REST APIs for monitoring configuration (implementation in progress). • Publish/subscribe mechanism for publication of monitoring data, based on a Kafka bus, adopting specific information models.

3.1.5 Security Services

The cybersecurity threat detection and response capabilities encompass several key functions. These include signature-based network intrusion detection and prevention, which identifies and mitigates threats based on known signatures. Distributed Denial of Service (DDoS) attacks are detected and mitigated to safeguard network resources. Network-based malware detection and prevention address threats at the network level, while behaviour-based detection identifies intrusion attempts through unusual patterns, such as ‘beaconing’ attempts (Victim-to-C2C and C2C-to-Victim) and port scanning (reconnaissance).

Additionally, various host-based agents can be deployed on the “compute” components to achieve more granular and enhanced detection and response capabilities.

Available Services

Automation and Orchestration:

The testbed features advanced automation and orchestration software tools, which streamline the deployment, scaling, and management of applications. It employs an Infrastructure as Code approach, facilitating network and application software development, as well as supporting building, testing and deployment through continuous integration and continuous delivery using tools such as Jenkins and Ansible. Orchestration is managed using OSMv12/13 open-source tools, with IaaS/CaaS managers overseeing the instantiation of Virtual Network Functions (VNFs) and Cloud Native Functions (CNFs), as well as network function healing for virtual machines (VMs) or container nodes (CNs).

Monitoring and AI Capabilities:

The testbed implements a sophisticated monitoring and data collection system, capable of acquiring data from the entire network, including devices, in-slice performance, power consumption, and computing performance. This system, developed in ICT-41 projects (such as VITAL-5G and 5GASP) and applied in research actions like 6G ADROIT6G and 6GREEN, leverages innovative data processing and enrichment within a Big Data Cluster. The collected data are presented in an application layer and further analysed by advanced analytics functions using Machine Learning (ML) and Artificial Intelligence (AI) algorithms. These algorithms can trigger network actions through automation, paving the way for 6G autonomous networks, including configuration and fault management.

AI-Driven Network:

The testbed supports 5G services and orchestration for slicing, incorporating conflict resolution based on 5G Quality Index (5QI) and Quality of Service (QoS) mapping across the end-to-end (E2E) network. It ensures effective network orchestration, automation and the proper instantiation and placement of cloud services within distributed and decentralised computing environments, thus preparing for compute continuum readiness.

The system dynamically instantiates services by placing compute resources at the optimal location for processing within the distributed 5G LAB system, directing them to the appropriate EDGE computing node. This process is supported through TMF (Tele-Management Forum) APIs and interface implementations, such as those used in the 5G Lab implementations in Bucharest and Iasi.

Secure access to ORO’s testbed is provided via IPsec and/or VPN over Internet connectivity. This access is available to third parties involved in the 6G-PATH project, including those participating through Open Calls.

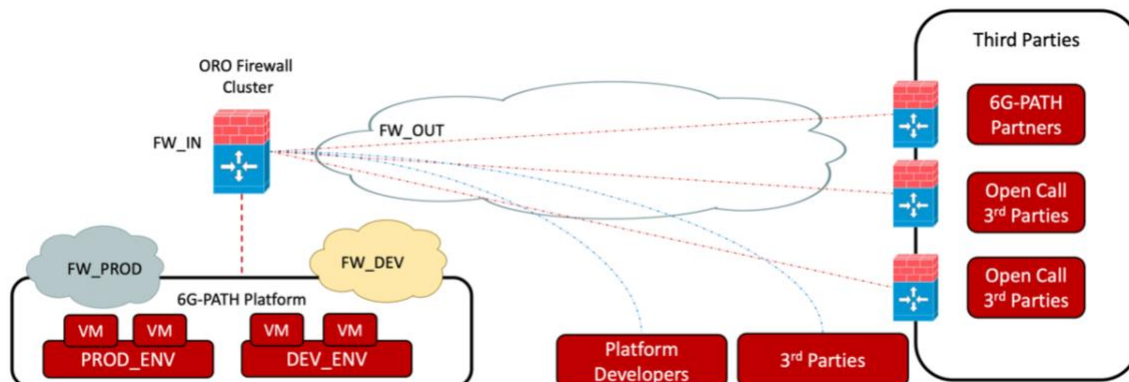


Figure 13. Remote access architecture for ORO's Testbed

3.1.6 Key features and assets

The following table lists the current instances and status of the various network services and “scenarios” that can be used for 6G-PATH experimentation.

Table 5. Services available in the ORO Testbed

Type	Description	Version	Features
Virtualised Infrastructure IaaS/CaaS	• OpensStack • USSURI • K8S • 48TB Shared Storage • 320vCPU 3TB RAM • HPE DL360 GEN10	USSURI K8s 2.3.x dockerv20	High Availability
Orchestration	• OSM	v12	High Availability
5G RAN	• 5G SA gNB • 5G OAI	SRAN18	3GPP Rel.16 High Availability
5G CORE	• 5G Core NOKIA	5GSA CMU23.10	3GPP Rel.16 High Availability
5G Network Transport	• Cisco • High broadband connectivity	IOS XR IP FABRIC	IP FABRIC High Availability
5G SA validated devices	• Huawei PRO2 • Motorola UE • Huawei P40 PRO • XIAOMI 12 PRO • Cradlepoint R1900 • Siemens MUM856 • Quectel RM500Q-GL • Inhand ER805 • Nokia FastMile 5G • (multi-slice capable)	SA option 2	N/A
5G network monitoring	• Network KPI Collection	ORO 5G Probes	Internal
5G network slicing	• 5G SA network E2E Network slicing(3GPP)	eMBB Slice URLLC Slice Multi-slice/same subscriber	SST=1 SST=2 Combined SST1&SST2

5G RAN configuration: 3GPP Rel.16 5G SA option2.

Table 6. 5G RAN Configuration in ORO Testbed

SITE NAME	gNB ID	NR CELL NAME	NRDUCELL ID	PCI	CI	TX and RX Mode	BAND	BW
gNodeB_10_UPB	300103	gNBLAB10_UPB_indoor_NR37_1	1	110	1	4 TX and 4 RX	N78	100 MHz
gNodeB_10_UPB	300103	gNBLAB10_UPB_box_NR37_2	2	210	2	4 TX and 4 RX	N78	100 MHz

ORO Testbed Features Set and Functionalities:

Table 7. 5G/6G Feature Set of ORO Testbed

5G NF	RAN	Core	Transport	MEC
Features	NSA/SA	NSA/SA	Layer Architecture	Apps Platform
3GPP Rel15/Rel16	eNB/gNB Physical/VMs	vEPC/5GCN Virtualised	QoS/QoE Service Flow	System management
Slicing	APN NSSAI/SST	APN NSSAI/SST	QoS DSCP MPLS	E2E slicing
Security	Security Architecture and Procedures ENISA Security reports			
Orchestration	OSS/BSS	OSS/BSS OSM	Network Orchestrator	OSM

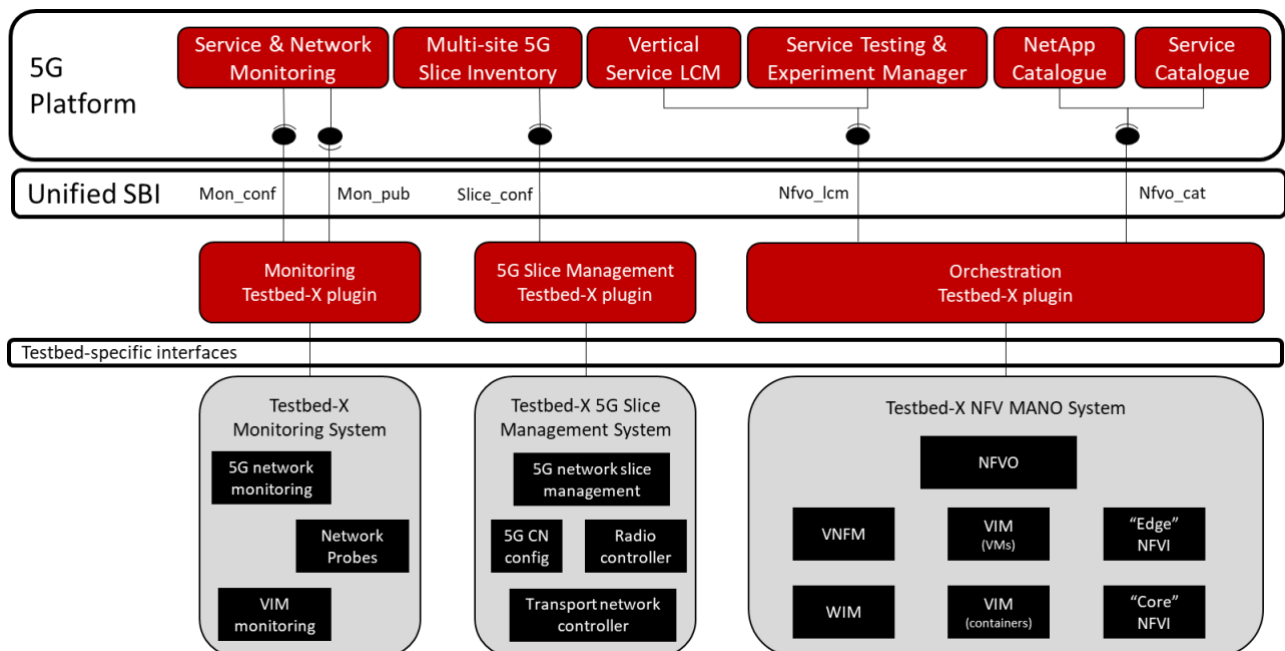


Figure 14. Slicing Capabilities in ORO Testbed

Slicing approach: The slicing is implemented based on the 5G slice parameters, the S-NSSAI identifies network slices in NG-RAN and 5GC and is composed of a Slice Service Type (SST) and Slice Differentiator (SD), SST identifying a type of network slice with specific capabilities and characteristics and SD pointing out different network slices belonging to the same type, examples provided:

Table 8. Slices definition examples in ORO Testbed

Slice Name	Slice/Service Type	Slice Differentiator
NSSAI-1	1	abcdef
NSSAI-2	2	abcdea

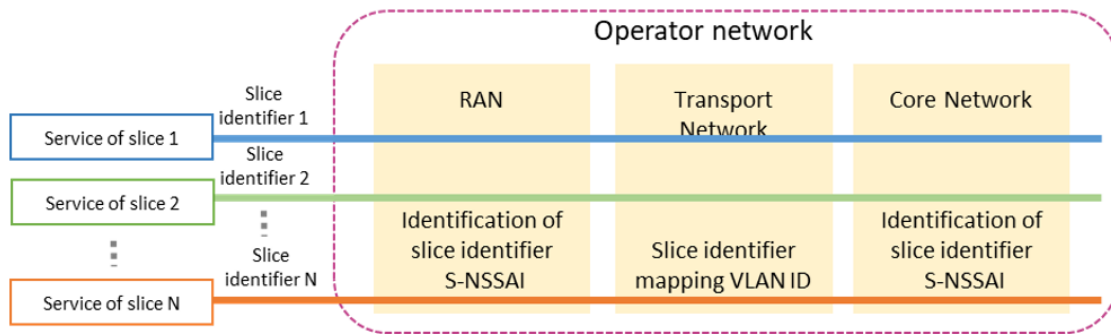


Figure 15. 3GPP 5G Slicing Model available in ORO Testbed

ORO testbed slice availability:

Table 9. Slice Availability in ORO Testbed

Type	Slice	No. of slices in UE	Slice availability	Location access
Shared Slices	eMBBs	Mono slice	UE connects only to the mono slice	Everywhere or Restricted to enterprise
	eMBBs or uRLLC	Dual slice/Mono slice UE	UE can connect to either only one of the slices	
	eMBBs and uRLLC	Dual slice	UE can connect to both slices at the same time	
Dedicated slices	eMBBs or uRLLC	Mono slice	UE can connect to either only one of the slices	Restricted to enterprise

ORO Testbed offers a wide range of assets and equipment for experimentation in Bucharest and Iași. The two facilities operate under the “Orange 5G Lab” brand.

Bucharest				
Private 5G network elements				
No.	Type	Quantity	Comments	
1	Nokia CMU+ 5GC	1	2 servers for load-balancing/reliability	
2	Nokia indoor 5G SA RAN	1	1 BBU, 1 radio aggregator, 2 active antennas	
3	Huawei 5G SA/NSA RAN	1	1 BBU, 2 RUs, 1 passive antenna	
4	Octoscope octobox box-18	1	Semi-anechoic cage	

Figure 16. ORO Testbed Bucharest 5G Lab private 5G network elements

Iași				
Private 5G network elements				
No.	Type	Quantity	Comments	
1	Nokia CMU+ UPF	1	2 servers for load-balancing/reliability	
2	Ericsson indoor 5G SA RAN	1	1 BBU, 1 radio aggregator, 2 active antennas	

Figure 17. ORO Testbed Iași 5G Lab private 5G network elements

Bucharest			
Networking elements			
No.	Type	Quantity	Comments
1	CISCO ASR920	2	Aggregation routers
2	CISCO NXOS N9K-C93180YC-FX	16	IP FABRIC routers
3	CISCO C2960-X	2	Workspace routers
4	F5 Load Balancer	1	Virtualized appliance
5	Fortinet FortiGate-1000D	2	Load-balancing/reliability

Figure 18. ORO Testbed Bucharest 5G Lab networking elements

Iasi			
Networking elements			
No.	Type	Quantity	Comments
1	CISCO NXOS N9K-C93180YC-FX	2	Aggregation routers

Figure 19. ORO Testbed Iasi 5G Lab networking elements

Bucharest			
Computing servers			
No.	Type	Quantity	Comments
1	HPE ProLiant DL360 G10	2	2x10C CPUs, 96GB RAM
2	HPE ProLiant DL380 G10	12	2x12C CPUs, 192GB RAM
3	HPE ProLiant DL380 G10+	2	2x28C CPUs, 960GB RAM, 2x nVidia T4 16GB VRAM GPUs
4	HPE ProLiant DL380 G11	1	2x32C CPUs, 2048GB RAM

Figure 20. ORO Testbed Bucharest 5G Lab computing servers

Iasi			
Computing servers			
No.	Type	Quantity	Comments
1	HPE ProLiant DL380 G10	1	2x12C CPUs, 192GB RAM
2	HPE ProLiant DL380 G11	1	2x32C CPUs, 2048GB RAM

Figure 21. ORO Testbed Iasi 5G Lab computing servers

Bucharest			
5G Lab datacenter			
No.	Type	Quantity	Comments
1	Rack MERX GTN 42HU/ 800x1000	6	Rack
2	Patch Panel 24xSC duplex singlemode and accessories	6	Rack accessories
3	Smart-UPS 5000VA 230V Rackmount SUA5000RMI5U	3	UPS
4	Eaton 9PX11KiRTNBP	1	UPS
5	Daikin AC unit FBA125A/ RZASG125MY1	3	AC
6	Daikin AC accessories and instalation services	1	AC accessories
7	AC Humidity Controller	1	AC accessories

Figure 22. ORO Testbed Bucharest 5G Lab datacentre infrastructure

Iasi			
5G Lab datacenter			
No.	Type	Quantity	Comments
1	Rack MERX GTN 42HU/ 800x1000	4	Rack
2	Patch Panel 24xSC duplex singlemode and accessories	4	Rack accessories
3	NETYS RT 11000VA VFI	4	UPS
4	Mitsubishi AC FDU250VSAWVH	2	AC
5	Mitsubishi AC accessories and instalation services	1	AC accessories
6	HIKVISION DS-K1T805MBFWX	1	Control access and CCTV
7	VIKING 3001-ADVANCE and accessories	1	Fire detection and extinguish system
8	Electric panel and accessories	1	Electronics

Figure 23. ORO Testbed Iasi 5G Lab datacentre infrastructure

Bucharest			
5G Lab devices			
No.	Type	Quantity	Comments
1	Huawei P40 Pro	1	Smartphone
2	Motorola EDGE 30 Pro	1	Smartphone
3	Xiaomi 12 Pro	1	Smartphone
4	Nokia TA-1362	1	Smartphone
5	Zebra ET85	2	Industrial tablet
6	Dell Latitude 7220	1	Industrial tablet
7	Huawei CPE Pro 1	3	CPE
8	Huawei CPE Pro 2	6	CPE
9	Huawei CPE PRO Outdoor N5368X	1	CPE
10	HTC 5G HUB	3	CPE
11	Nokia FastMile 5G Receiver 5G14-B	3	CPE
12	Nokia FastMile 5G Gateway 5G16-12W-A	3	CPE
13	CradlePoint R1900	2	Industrial router
14	SIEMENS MUM856-1	2	Industrial router
15	INHAND ER805	1	Industrial router
16	Sierra Wireless MG90	3	Industrial router
17	ProRoute H685	2	Industrial router
18	Digi TX64	2	Industrial router
19	Milesight 5G dongle UF31	5	Industrial router
20	Nokia Industrial 5G dongle DGRx501e	1	Industrial router
21	Milesight Pro Bullet AI Network Camera	3	Surveillance camera
22	Dahua IPC-HSF7842-Z-5G-LED-0856	2	Surveillance camera
23	Nokia Industrial 5G camera	2	Surveillance camera
24	Quectel RM500Q-GL	30	Modem
25	SIMCOM 8200EA-M2	30	Modem
26	SIMCOM 8202E-M2	12	Modem
27	QUECTEL PCIE CARD EVB KIT	15	Evaluation board
28	QUECTEL 5G M2 EVB KIT	15	Evaluation board
29	SIMCOM SIM8200-M2-EVB-KIT S2-108RE	42	Evaluation board
30	SIMCOM-EVB-KIT S2-106KN	20	Evaluation board
31	SIMCOM SIM7022-EVBKIT S2-109DE	20	Evaluation board
32	SIMCOM Heracles 224G	5	Evaluation board
33	QUECTEL GSM UMTS<E EVB KIT Q1-A2329	9	Evaluation board
34	QUECTEL GSM UMTS<E EVB KIT Q1-A0901	6	Evaluation board
35	QUECTEL GSM BC92-TE-B KIT Q1-A4138	20	Modem
36	QUECTEL GSM BC95-G-TE-B KIT Q1-A6498	21	Modem
37	QUECTEL GSM EVB KIT Q1-A2263	20	Evaluation board
38	SIMCOM SIM8100-EVM S2-108A7	10	Modem
39	SIMCOM SIM7070G-TE-KIT S2-108H9	20	Modem
40	QUECTEL GSM BG77-TE-A Q1-A4742	20	Modem
41	QUECTEL GSM BG95-M3-TE-A Q1-A5440	10	Modem
42	QUECTEL EG91-E-TE-A Q1-A0797	5	Modem
43	QUECTEL EC21-E-TE-A Q1-A1162	5	Modem
44	QUECTEL BG96 MA Q1-A1259	68	Modem
45	QUECTEL EC21-E FA Q1-A1161	49	Modem
46	QUECTEL EG91-E FA Q1-A0795	48	Modem
47	itbrainpower.net xyz-iot	35	Development board
48	Raspberry Pi 3 2GB RAM	2	Development board
49	Raspberry Pi 4 8GB RAM	2	Development board
50	Raspberry Pi 4 4GB RAM	15	Development board
51	Nvidia Jetson Nano 4GB	2	Development board
52	Intel NUC 32GB RAM 4C CPU	2	Development board
53	Arduino Tiny Machine Learning Kit BLE EDGE IMPULSE	10	Development board
54	URAD MONITOR SMOGGIE-CO2 Wi-Fi	2	Sensor
55	URAD MONITOR SMOGGIE-PM25 Wi-Fi	11	Sensor
56	URAD MONITOR ENVIRONMENTAL MOINITOR A3 LoRa	26	Sensor
57	URAD MONITOR ENVIRONMENTAL MOINITOR A3 Wifi	9	Sensor
58	Oculus QUEST 2 256GB	1	XR glasses
59	Meta Quest PRO	1	XR glasses
60	RealWear HMT-1	1	XR glasses
61	Llvision GLXSS ME	1	XR glasses

Figure 24. ORO Testbed Bucharest 5G Lab devices

Iasi			
5G Lab devices			
No.	Type	Quantity	Comments
1	OnePlus 10 Pro	1	Smartphone
2	Huawei CPE Pro 1	1	CPE
3	Huawei CPE Pro 2	2	CPE
4	HTC 5G HUB	1	CPE
5	Nokia FastMile 5G Receiver 5G14-B	3	CPE
6	Nokia FastMile 5G Receiver 5G26-A	2	CPE
7	INHAND ER805	1	Industrial router
8	Nokia Industrial 5G dongle DGRx501e	1	Industrial router
9	Milesight Pro Bullet AI Network Camera	1	Surveillance camera
10	Quectel RM500Q-GL	10	Modem
11	SIMCOM 8200EA-M2	10	Modem
12	QUECTEL PCIE CARD EVB KIT	5	Evaluation board
13	QUECTEL 5G M2 EVB KIT	5	Evaluation board
14	SIMCOM SIM8200-M2-EVB-KIT S2-108RE	10	Evaluation board
15	QUECTEL GSM UMTS<E EVB KIT Q1-A2329	10	Evaluation board
16	QUECTEL GSM BG95-M3-TE-A Q1-A5440	10	Modem
17	itbrainpower.net xyz-iot	10	Development board
18	URAD MONITOR ENVIRONMENTAL MOINITOR A3 LoRa	2	Sensor
19	Oculus QUEST 2 256GB	1	XR glasses
20	Meta Quest PRO	1	XR glasses

Figure 25. ORO Testbed Iasi 5G Lab devices list

3.2 UWS Testbed

The Beyond 5G (B5G) Testbed is located in room E354 at Paisley Campus, University of the West of Scotland, Paisley, Scotland, United Kingdom. It comprises two distinct sets of machines: those dedicated to managing the infrastructure and those used for managing the infrastructure itself. The testbed is owned by the University of the West of Scotland and operated by the Beyond 5G Team.

The testbed features two different 5G software installations: "Open Air Interface 4G RAN" and "Open Air Interface 5G RAN", both at version 2023.w42. At any given time, only one of these can be instantiated, allowing the testbed to operate either a 4G or a 5G network, but not both simultaneously.

In one of the "Core" machines, there are 4 VMs machines.

- 1 VM for the complete 4G Core, using the OpenAir-CN version develop branch.
- 1 VM for the complete 5G Core, using OpenAir-CN version v1.4.0.
- 1 VM for the exposition of RAN network slicing capabilities in 4G networks, using the FlexRAN version developed.
- 1 VM for the exposition of RAN network slicing capabilities in 5G networks, using FlexRIC version 8534bcbb.

When both the LXC (Linux Container) 5G RAN and KVM (Kernel-based Virtual Machine) VM 5G Core are fully operational, the complete 5G infrastructure becomes available. The setup includes prepopulated cryptographic information within five SIM (Subscriber identity Module) cards located on our premises for both 4G and 5G Core networks.

The infrastructure is further supported by two User Equipment (UE) devices:

- 1 UE: OPPO RENO6 5G

- 1 UE: OnePlus 8T

These mobile phones are connected to the Ettus USRP (Universal Software Radio Peripheral) B210 when the RAN and CORE are linked. They receive the necessary configuration to access both any virtual machine (VM) deployed within our infrastructure and the Internet.

All machines in the setup are Dell T5810 models, each equipped with 12 cores (24 hyper-threaded), 2 TB HDD (Hard Disk Drive), and 32 GB of RAM (Random Access Memory).

There are five physical machines designated as Compute (Nova) nodes for deploying services within the infrastructure. Four of these machines use KVM as the hypervisor, while the fifth employs LXC as the hypervisor.

The LXC physical machine is logically assigned to the zone labelled "Edge 1". Another physical machine running KVM is assigned to the zone "Edge 2", and the remaining three machines are assigned to the "Core" zone. These zone assignments are configurable and can be adjusted as needed.

Two machines in the "Core" zone and the machine in the "Edge 2" zone are currently free and available for service deployment.

The LXC Compute machine is connected to an Ettus USRP B210 Software Defined Network Radio Interface via USB (Universal Serial Bus). A live-detection and attachment system for the USB has been built and deployed at our premises to enable USB passthrough to the LXC containers.

All machines are interconnected using a 10 Gb network, serving as the data plane.

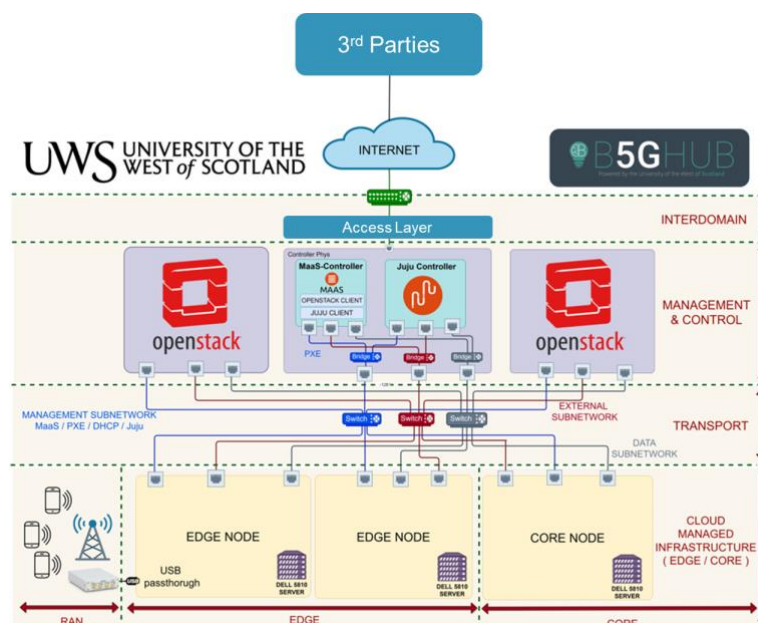


Figure 26. Testbed description

3.2.1 Services offered

The system comprises three physical management machines: "Controller," "David," and "Goliath."

- **Controller:** This machine operates exclusively as a virtualisation layer using KVM, facilitating the creation of multiple virtual machines for management purposes. It hosts four distinct virtual machines:
- **MaaS Controller VM:** Equipped with Ubuntu Metal-as-a-Service (MAAS) version 2.9.3 and its MAAS client, this VM manages the physical infrastructure.

- **Juju Controller VM:** Running Ubuntu Juju Controller version 2.9.43, this VM manages the services within the infrastructure.
- **6G-Path Advance Services:** This VM contains all components necessary to deliver the advanced features available in the 6G-Path.
- **6G-Path Controller:** This VM hosts the components required for the 6G-Path dashboard and provides access to the testbed.
- **David and Goliath:** These machines are configured with all necessary services for operating a high-availability OpenStack infrastructure (Wallaby 5.6.0 release). They support advanced capabilities such as OVN networking, Vault for encryption of the management plane and high availability with RabbitMQ and MySQL quorums. Services on these machines are deployed in LXC containers, ensuring a microservice architecture where each container is isolated and dedicated to a single function.

Our customised monitoring platform has been deployed to collect metrics related to devices, network ports, services, and network flows. Key services are made accessible through VPN (Virtual Private Network) capabilities using WireGuard. For enhanced security, the entire testbed is protected behind a VPN.

3.2.2 Key features and assets

- Metal-as-a-Service
- OpenStack
- Juju
- Device, Device Port and Flow monitoring
- Initial prototype of advance end-to-end network slicing
- Open Air Interface with FlexRIC RAN slicing support

3.3 FOKUS Testbed

The Fraunhofer FOKUS Testbed is a multi-vendor facility designed for the integration and testing of SA (Standalone) 5G Core and RAN (Radio Access Network). This testbed is utilised to showcase various proof-of-concept scenarios, incorporating multiple RAN vendors, diverse user equipment, and different backhaul technologies. The architecture of the Fraunhofer FOKUS testbed is illustrated below. This detailed categorisation ensures that data is organised and used effectively throughout the project, maximising its value for research, development and decision-making.

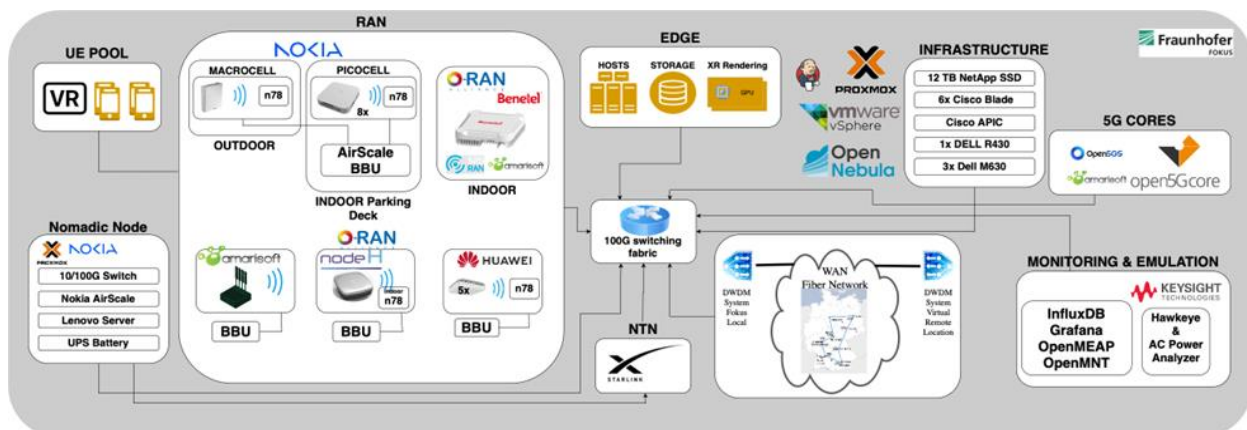


Figure 27. 5G Fraunhofer FOKUS Testbed Infrastructure

The Fraunhofer FOKUS testbed provides the Open5GCore software toolkit developed by Fraunhofer FOKUS. The software core network is built for easy configurability using different configuration file sets. It allows testing different scenarios and use-cases by switching between different configuration sets. The Open5GCore comprises multiple Network Functions (NFs) developed as per the 3GPP specified specifications. It includes the following components:

AMF, AUSF, UDM, NRF, SMF, PCF, UPF, NSSF, N3IWF (Non-3GPP Inter-Working Function), SCP (Service Communication Proxy), LMF (Location Management Function), GMLC (Gateway Mobile Location Centre) and NEF (Network Exposure Function) network functions.

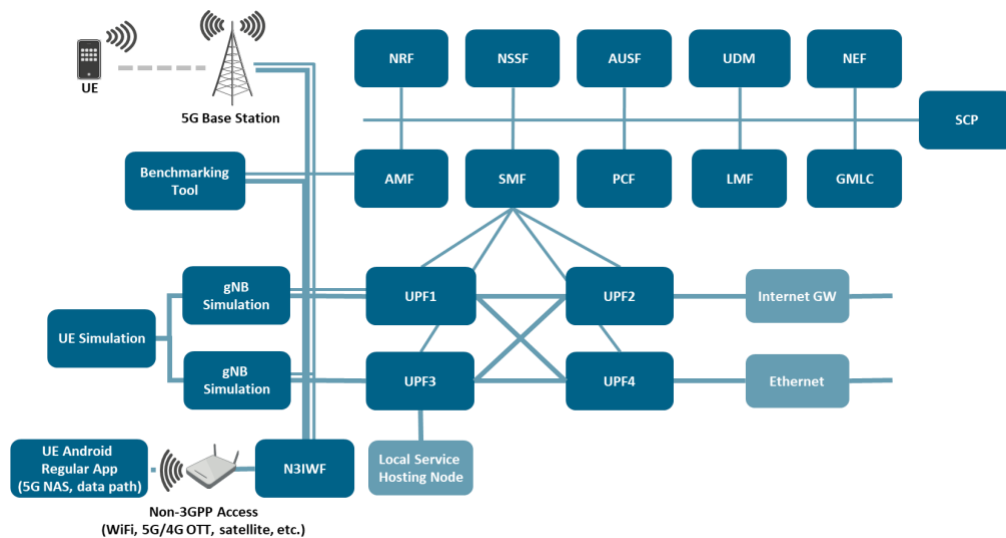


Figure 28. Open5GCore 5G SA Core Network

The Open5GCore core network has support for multiple features from the 3GPP specifications. The Fraunhofer FOKUS testbed runs one or more features for different tests/projects.

Table 10. Open5GCore Features and their Description

Feature	Description
Basic 5G Core (AMF, AUSF, UDM, NRF, SMF, UPF)	5G Core setup with a minimal set of components to provide Authentication and Internet access to the users
Slicing	Support slices on all protocol layers and NAS-based rerouted slicing at N2 interface.
Application Function	Support for 3rdParty API control via NEF for Traffic Influence API
Non-3GPP Access	Authentication and handover of UEs between 3GPP and non-3GPP access technologies
Roaming	Support for Home-routed roaming for authentication and data path via SCP
Location Services	Support for LPP and NRPPa- based location services from UE and gNB.

3.3.1 Services offered

3.3.1.1 Compute, Storage and Networking Capabilities

The Fraunhofer FOKUS testbed comprises six Cisco UCSB-B200-M5 servers, each equipped with 192 CPU (Central Processing Unit) cores (403 GHz), 1.5 TB of RAM and 10 TB of storage capacity. These servers run a VMware ESXi cluster, providing multiple tenants for each project. Each project has its own network layer, managed by Cisco switches and routers. The testbed employs 100G fibre backhaul connectivity between the

servers, with similar connectivity extended to the 5G RANs deployed in the environment. Additionally, the testbed includes a satellite backhaul connection via a Starlink dish.

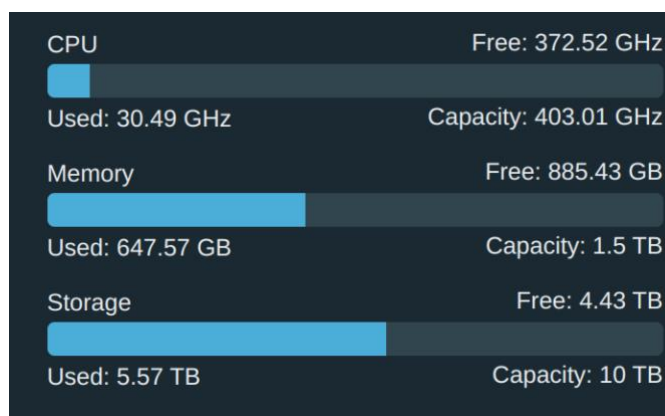


Figure 29. Infrastructure Capabilities

3.3.2 Virtualisation, Management and Orchestration Capabilities

The Open5GCore is a software and vendor-independent toolkit, which means it is not restricted by hardware capabilities. The testbed supports multiple projects running in parallel, so the type of deployment can change based on specific requirements. Typically, Open5GCore network functions are deployed as system services without virtualisation to maximise hardware performance. However, in some cases, core orchestration is handled via Kubernetes or Virtual Machines. For individual projects, a local Kubernetes server is set up as needed; the testbed does not use a common Kubernetes server.

Currently, the Open5GCore is being integrated with the OpenNebula platform for deployment purposes. The testbed supports management of the Open5GCore network and user equipment (UEs) with access limited to management functions only. The 5G core network components expose APIs for network management, mainly using JSON-RPC APIs, which include a web interface. Additionally, Device Farmer software is used for remote access to the UEs. This open-source tool enables remote interaction with the UEs, allowing work on the testbed without physical presence.

3.3.3 Monitoring Capabilities

The FOKUS testbed does not export metrics for the entire testbed due to the infrastructure being shared across different projects. Instead, each deployed core network individually exports its metrics. The Open5GCore exports memory usage and other measurement data via the Prometheus API for each 5G network function. These metrics are collected by a Prometheus server and visualised on a Grafana dashboard.

Open5GCore components natively export memory statistics, which track memory usage over time for various memory pools used in the component architecture. In addition to memory statistics, the User Plane Function (UPF) exports user plane statistics, including packets received, forwarded, dropped, and buffered. This data is collected for each UPF interface and enables the calculation of per-interface throughput, which is displayed in Grafana.

Beyond the Prometheus APIs, the core platform also provides monitoring capabilities via a command-line interface. The Open5GCore platform includes a built-in command-line tool that allows for executing commands to debug and check the status of multiple components. This tool features print commands for displaying monitoring and debugging data.

```

10:19:31>AMF>
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> amf.ng.print_nodes
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> amf.ue.kill
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> amf.ue.print_contexts
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> amf.ue.send_paging
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> exit
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> get_log_cfg
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> help
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> history
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> http_client.curl_verbose.disable
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> http_client.curl_verbose.enable
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> httpd_h2o.logger
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> httpd_h2o.registered_paths
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> list_exec_unit
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> mem_stat
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> nrf_client.nf_table_print
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> set_log_level
139997923493632/2421529 14:14:31 NOTICE:command:list_matching_commands():787> version
10:17:02>AMF>amf.ng.print_nodes
139997923493632/2421529 14:17:02 INFO:command:execute_module_cmd():215> cmd reply:
amf_cmd_reply
-----
[logran_node_ht]
Number of entries: 1 empty slots: 31 out of 32
Hash 23, entries: 1
-----
gNB
-----
gNB ID: 1001
RAN Node Name: gnb1
NG-C addr: 192.168.12.50:38412
SCTP Assoc ID: 76
-----
[logran_node_ht] end
-----
10:19:30>AMF>

```

Figure 30. Command-line Interface

3.3.4 Security Capabilities

Access to the FOKUS testbed is facilitated through a dedicated VPN server, which employs the WireGuard protocol to create secure tunnels into the testbed network. For each project, the VPN server provides an isolated instance, ensuring complete separation of traffic between different projects. This VPN server is hosted as a Linux-based virtual machine within the VMware infrastructure of the testbed.

The use of Linux for the VPN server provides a high degree of flexibility, allowing for adaptations if experimenters require special settings or different VPN protocols. Additionally, the VPN server is utilised to integrate external testbeds or components from Open Call participants into the FOKUS testbed infrastructure.

3.3.5 Key features and assets

The FOKUS testbed features 5G base stations from multiple vendors, reflecting a range of ongoing projects and integrations aimed at ensuring RAN-Core compatibility. The base stations integrated with the Open5GCore include offerings from ADAPTIT, Amarisoft, ASOCS Cyrus, Ericsson, Huawei, NodeH, Nokia, and Sercom, as well as open-source solutions like Open Air Interface and SRS 5G. Additionally, Open5GCore has been tested using the Keysight IxLoad tool, commonly employed by commercial core network developers, and the Defensics fuzzifier for security testing.

The 5G base stations in the testbed operate within the 3.7 - 3.8 GHz campus network band. Coverage extends across the test laboratory, outdoors around the FOKUS premises, with radios installed on the building's rooftop, and indoors in the parking garage. This setup allows for the execution of various proof-of-concept scenarios in both large and small coverage zones.

The Open5GCore is integrated and tested with a range of off-the-shelf phones, including models from Apple, Google Pixel, Huawei, Nokia, Samsung, and several CPEs such as Quectel and Huawei. Additional devices are currently undergoing testing. All UEs and CPEs in the lab are accessible remotely, facilitating extensive testing without the need for physical presence in the lab.



Figure 31. Fraunhofer FOKUS Testbed

The FOKUS testbed offers multiple backhaul options to support various use cases. It includes a long-haul fibre connection terminating at FOKUS, which is used to simulate extended distance backhaul scenarios with a long cable. Additionally, the testbed is equipped with satellite backhaul capabilities for NTN (Non-Terrestrial Network) use cases. Specifically, it provides Low Earth Orbit (LEO) connectivity via the Starlink network.

To enhance satellite link availability during experiments, an additional Starlink Terminal has been acquired, complementing the existing Starlink device already available in the testbed. To integrate Starlink connections within the testbed, a VPN tunnel is required to connect back from the SpaceX HUB offloading point. Currently, the management of these VPN tunnels is combined with the general-purpose VPN access used by experimenters.

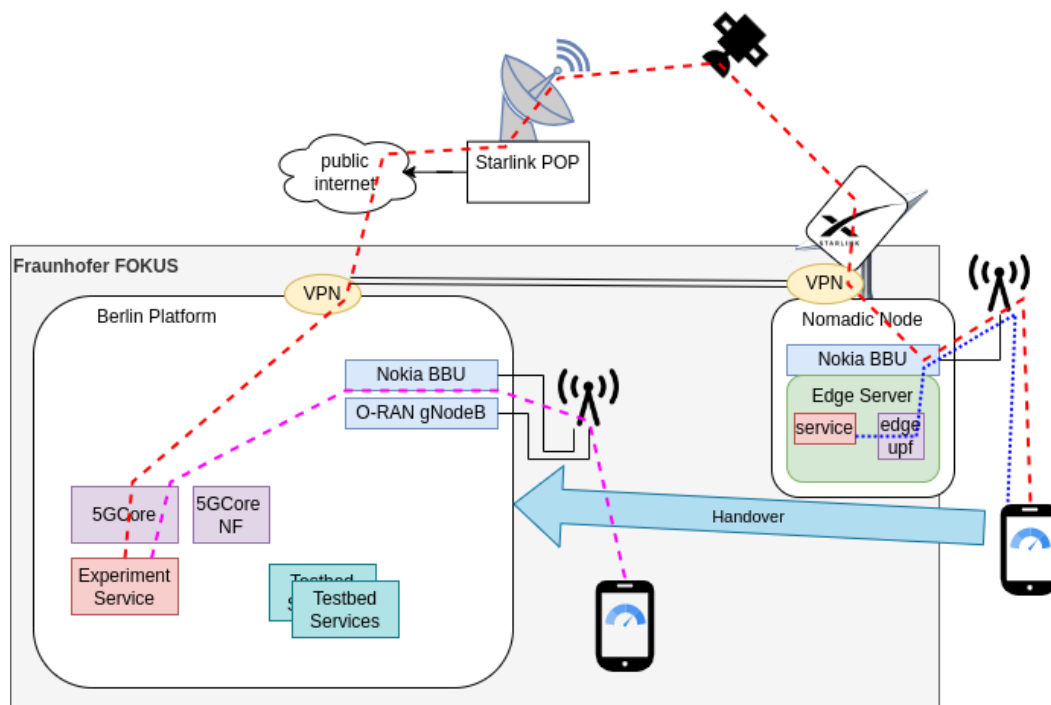


Figure 32. NTN Integration

The NTN integration was tested using the Starlink system to connect a remote nomadic node to a 5G Core running in the FOKUS Testbed. The Nomadic node consisted of an edge server, a Nokia BBU (Base Band Unit) together with power supply and Starlink in a mobile rack mounted in a protective carry-on case. Depending on the location of the mobile node UEs could handover between 5G cells that were connected directly to the 5GCore or via the NTN backhaul link.

3.4 IT/ALB Testbed

The Aveiro Tech City Living Lab (ATCLL) is located in Aveiro, Portugal, and is managed by Instituto de Telecomunicações (IT). This platform is equipped with a variety of Internet of Things (IoT) devices that possess communication, sensing, and computing capabilities. The communication infrastructure is based on fibre and millimetre-wave (mmWave) links, integrating a network with radio terminals for Wi-Fi (Wireless Fidelity), ITS-G5 (Intelligent Transport System – G5⁸), C-V2X (Cellular Vehicle-to-Everything), 5G and LoRaWAN (Long Range Wide Area Network). These terminals are spread across 44 connected access points throughout the city. Additionally, public transportation in Aveiro has been fitted with communication and sensing units.

These components work together to interconnect various sensors, including mobility sensors such as radars, LiDARs and video cameras, as well as environmental sensors. The living lab utilises both edge computing and cloud management to deploy services and manage the platform, while a data platform is employed to gather and process the data. The ATCLL supports a broad array of services and applications, including IoT, intelligent transport systems (ITS), assisted driving, environmental monitoring and emergency and safety services.

Table 11. Summary of the ATCLL 5G Infrastructure

5G infra testbed	RAN NSA/SA	5GCN NSA/SA	L2/L3 Transport	IaaS	MANO & Monitoring	MEC	Slicing
Aveiro	CableFree 4G/5G Small Cell n46/n78 indoor/outdoor	Open5GS	SDN	Kubesphere	Prometheus	Collocated IaaS w 5G Core	SNSSAI based
	OAI		ONOS Controller		Grafana		APN based
	/ srsRAN		Open Hardware Switches (Pica8)	K8s ("FogService")	MongoDB		

3.4.1 Infrastructure

The access network in the Aveiro Tech City Living Lab consists of multiple technologies designed to support various use-case scenarios and verticals throughout the city. The Smart Lamp Post and Wall Box installations across the city integrate several types of equipment for diverse purposes, including sensing devices, communication access points, and Multi-access Edge Computing (MEC) capabilities.

In terms of communication technologies, the network features devices providing wireless access across different technologies and domains. The 5G Radio Access Network (RAN) includes both a commercial solution and a research solution based on a Software Defined Radio (SDR) that is compatible with O-RAN (Open Radio Access Network) network architecture. This setup is supported by a RAN Intelligent Controller (RIC), using

⁸ See, for example: https://www.etsi.org/deliver/etsi_en/302600_302699/302663/01.02.00_20/en_302663v010200a.pdf

either Field Programmable Gate Array- (FPGA-) based units or USRPs. This access infrastructure establishes a complete 5G private network, comprising User Equipment (UEs), Customer Premises Equipment (CPEs) and gNodeBs.

For MEC, each point in the network is equipped with NVIDIA Jetson Orin or Jetson Xavier devices, which feature powerful GPUs for handling graphic-intensive processing tasks. The following figure illustrates the general layout and key components of the testbed, highlighting the 5G private network, MEC, connected vehicles and other technologies.

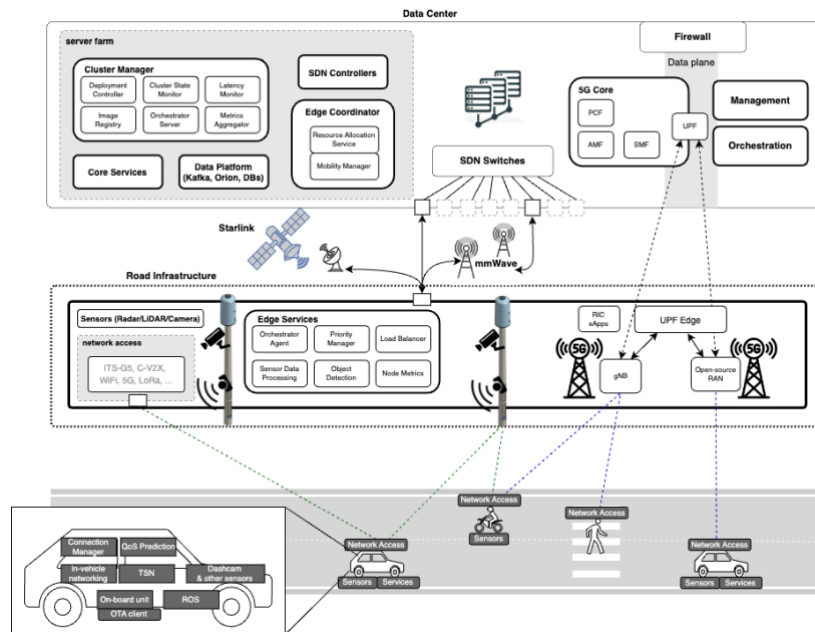


Figure 33. ATCLL Testbed Architecture - General view and Key component and capabilities

The network solution implemented in the Aveiro Tech City Living Lab (ATCLL) integrates various technologies managed through a centralised control system based on Software Defined Networking (SDN). The network is divided into two main domains: the vehicular network and the 5G private network.

From the perspective of the vehicular network, the SDN controller oversees all handovers for On-Board Units (OBUs), relying on data related to connection, position, and heading of the vehicle. This information is gathered through SNMP (Simple Network Management Protocol), LLDP (Link Layer Discovery Protocol) and OpenFlow protocols and is processed by the Ryu/ONOS controller.

In the 5G private network, the core network is disaggregated using Open5GS. Several User Plane Functions (UPFs) are distributed across the city, located on edge devices. This setup facilitates the exit from the 5G domain through the N9 or N6 interfaces, depending on the service, user, or location. The RAN/Core configuration also supports network slicing techniques associated with 5G Quality of Service Indicators (5QI), which are applied to each device, user session or tunnel. This allows for the exploration of the MBRLLC class for future 6G services, particularly for Mixed Reality (MR) and Augmented Reality (AR) applications.

The backhaul connecting all upper-layer networks is composed of Ethernet, millimetre-wave (IEEE 802.11ad), and satellite links (Starlink). These heterogeneous networks are managed by the SDN controller, which employs Quality of Service (QoS) multipath routing. Additionally, the network devices support advanced Time-Sensitive Networking (TSN) technologies.

3.4.2 Services offered

The Aveiro Tech City Living Lab (ATCLL) features mobile sensing services with various devices and geolocation sensors installed on vehicles, such as buses and garbage collection trucks, as well as on lamp posts and

bicycles. The mobile sensing data collected includes GPS (Global Positioning Service) location, speed, heading, temperature, humidity and air pressure, which together create a comprehensive mobility map of the city.

Wi-Fi access points, both stationary and mounted on vehicles, collect data on city occupancy through users' smartphones. For static sensors, the edge nodes in the infrastructure are equipped with traffic radars, LiDARs, video cameras and computing units. These multi-sensing devices, along with edge services, can parse traffic radar data in real-time and perform video object detection using the YOLO (You only look once) framework. The object detection service can apply geo-framing techniques to determine the location and distance of objects.

Data from these sensors are aggregated using data fusion techniques and correlated with information from Intelligent Transportation System (ITS) messages. This integration provides insights into pedestrian flow and supports the development of new solutions for public transportation, safety-critical applications, autonomous driving systems and optimising city mobility. Additionally, a set of Unmanned Aerial Vehicles (UAVs) equipped with 5G base stations, video cameras, and environmental sensors are part of the extended infrastructure. These UAVs gather data from the city and assist with patrolling and traffic management.

Communication equipment is installed in vehicles to transmit mobility and environmental data through static access points, creating a comprehensive live map of these parameters across the city. This setup supports environment sensing, traffic monitoring, and safe driving systems. The mobile equipment comprises a Data-Collection Unit (DCU) that integrates Wi-Fi and LoRa (Long Range) communication technologies. Additionally, each vehicle is equipped with an On-Board Unit (OBU) that features Wi-Fi, ITS-G5 and 5G communication capabilities, allowing for connections with Roadside Units (RSUs) and other vehicles.

Table 12 provides details on the current instances and status of various network services and scenarios available for 6G-PATH experimentation.

Table 12. Services available in the ATCLL Testbed

Type	Description	Version	Features
Virtualised Infrastructure IaaS/CaaS	Proxmox Docker	Virtual environment V8.0.9 dockerv20	N/A
5G RAN	5G SA gNB/srsRAN	Latest	3GPP Rel.17 aligned
5G CORE	5G Core Open5GS	5GSA v2.7.0	3GPP Rel.17
5G SA validated devices	Quectel RM500Q-GL Quectel RM500Q-AE Quectel RM520N-GL SIMCom SIM8262E-M.2	SA	N/A
5G network monitoring	Network metric Collection		Internal
5G network slicing	5G SA network UPF Selection	eMBB DNN URLLC DNN	DNN=internet DNN=internet2

NRF

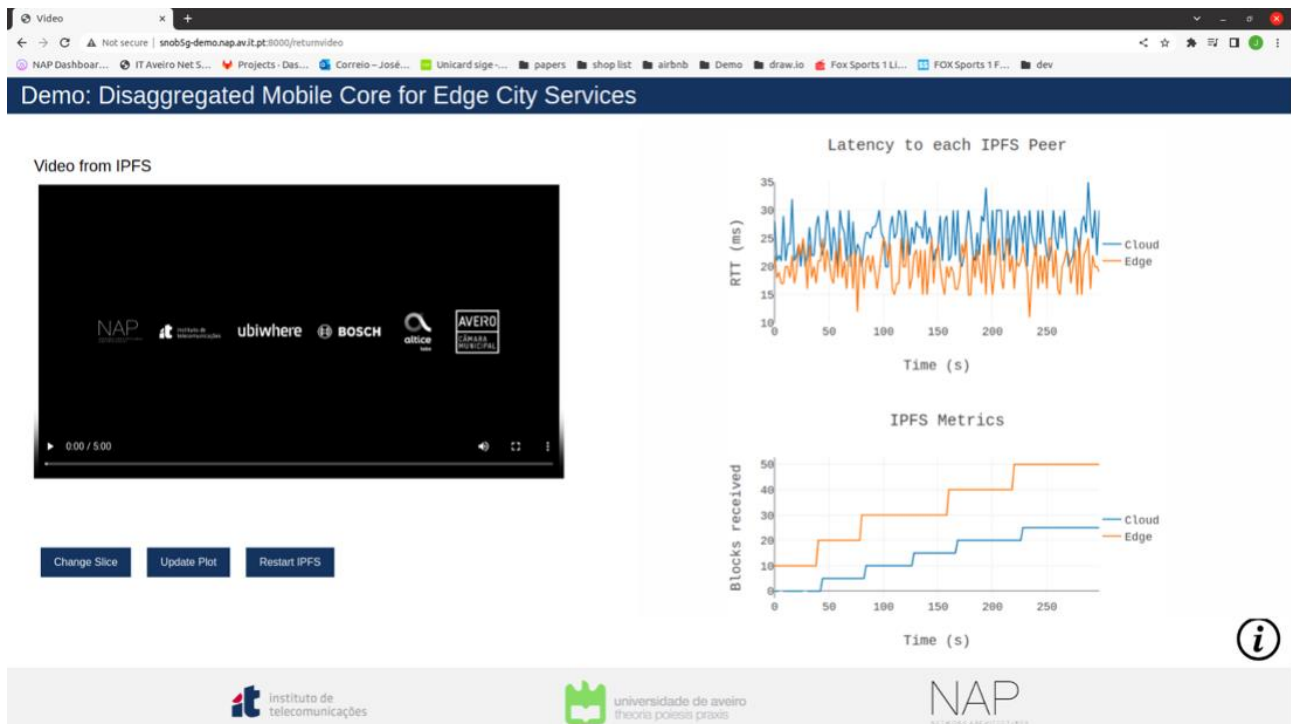


Figure 34. Video CDN Website

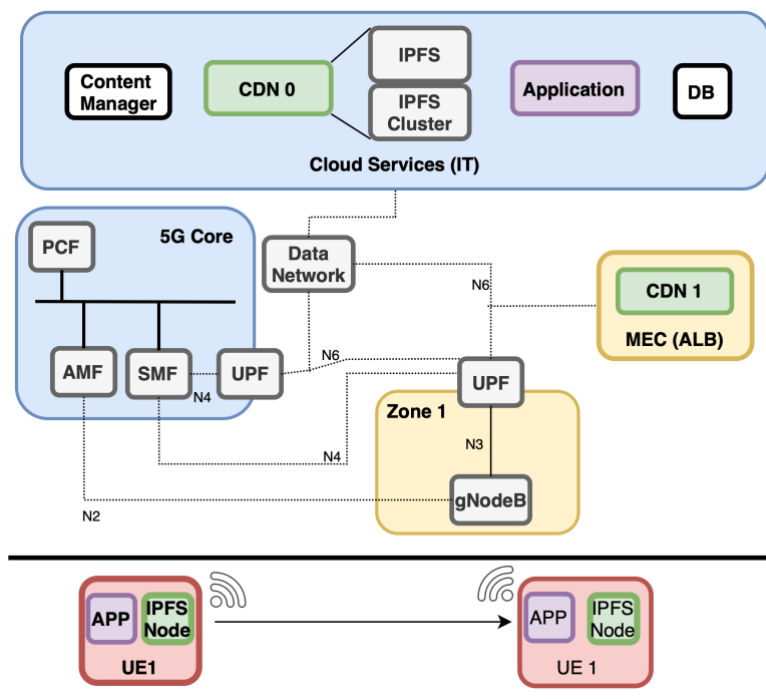


Figure 35. IPFS and CN configuration

3.4.3 Key features and assets

3.4.3.1 Compute, Storage and Networking Capabilities

The backhaul infrastructure is based on Single-Mode Optical Fibre (SMF) link technology (G.652), spanning a length of 16 km. This infrastructure interconnects the 44 edge nodes distributed across the urban area of Aveiro, which are installed on Smart Lamp Posts or wall boxes on building facades. The physical infrastructure of the access network features one-to-one fibre links aggregated by a switch that supports 10 GbE

connections and SDN functionality through Open vSwitch (OVS) or P4. The uplink to the core network is established using 40 GbE ports.

Additional backhaul communication methods include millimetre-wave and satellite communications. The mesh network that forms part of the backhaul includes five millimetre-wave antennas, which link Smart Lamp Posts directly for SDN experiments, covering the University of Aveiro Campus and three nodes in the city centre. The Non-Terrestrial Network (NTN) component of the infrastructure consists of two Starlink business antennas located on the rooftop of IT, providing the network with three Internet connections.

SDN support enables network control via software, employing open-source controllers such as Ryu and ONOS, alongside control plane protocols like OpenFlow and P4 Runtime. These SDN controllers are situated in the network core and dynamically adjust to changes in demand and network conditions. Additionally, network algorithms and Machine Learning (ML) techniques are integrated to monitor and manage the network effectively.

In the vehicular network (V2X), algorithms within the SDN controller manage Internet connectivity and handovers for mobile nodes. The platform supports automated deployment of applications using containerisation technologies, microservices, and Kubernetes for comprehensive end-to-end orchestration. Additionally, services across various nodes can be customised through dynamic allocation and orchestration based on Quality of Service (QoS) and dynamic slicing management.

Time-Sensitive Network (TSN) functions are integrated into the backhaul of the network to support critical services requiring bounded-latency or specific bandwidths. The network is synchronised to nanosecond precision, and network switches can be configured with various types of shapers (e.g., TAS (Time Aware Shaper), CBS (Credit-Based Shaping)) to meet these needs.

At the core, the infrastructure includes a network and data processing centre. This data centre is equipped with multiple servers managed by Proxmox VE, which deploys virtual machines for services, data platforms, applications, and the 5G core (Open5GS). Network functions are operated in the cloud using Kubernetes, Open-Source MANO (OSM), ChirpStack and other related technologies.

RAN: The RAN infrastructure is comprised of various solutions, including OpenAirInterface (OAI) and srsRAN as open-source solutions deployed in Ettus Research USRPs and CableFree 4G/5G Small Cell n46/n78 indoor/outdoor as commercial solutions. Both open-source solutions are O-RAN compliant gNB with CU (Centralised Unit)/ DU (Distributed Unit) split, and interconnect with RAN Intelligent Controllers (RICs) for RAN monitoring. For RIC solutions, ONF's SD-RAN, FlexRIC were attested (soon ORAN SC RIC) and used for metric collection and data processing through ML strategies.

5G Control Plane: The Open5GS Core is a set of software components and network functions that interact with each other. Our Open5GS SA Core has the following functions: NRF, SCP, SEPP AMF, SMF, UPF, AUSF, UDM, UDR, PCF, NSSF and BSF (Binding Support Function). This Core uses a Service Based Architecture (SBA). The NRF is set up to register control plane functions, and the NRF then assists them in finding the other essential functions. Mobility and connection management is handled by the AMF. The UDM, AUSF, and UDR generate SIM authentication vectors and maintain subscriber profiles. The SMF is in charge of session management. The roaming security architecture includes SEPP (Security Edge Protection Proxy), PCF (Policy Control Function) is utilised for charging and enforcing subscriber policies, and the NSSF allows for network slice selection. The SCP allows for indirect communication. With only one function, the 5G SA core user plane is substantially simpler. User data packets are transported by the UPF between the external WAN (Wide-Area Network) and the gNB. It is also connected to the SMF.

This core supports local breakout roaming with the aid of the SEPP module, it enables the Mobile Network Operator to break out internet sessions into the Home Network, to provide inbound roamers with an ability to order data, which is provided directly by the visited network.

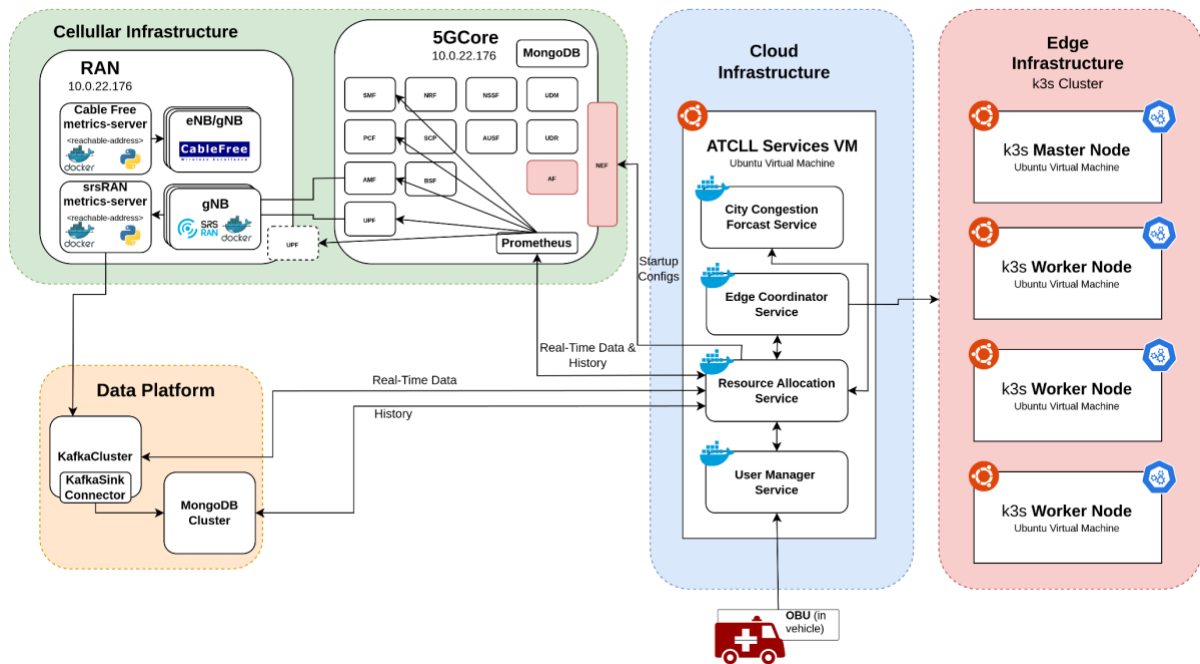


Figure 36. Overall ATCLL 5G and Edge Architecture

It also supports VoNR by adding an NF from the 4G Core, the HSS which is the main subscriber database used within the IP Multimedia Subsystem (IMS), and by using the Kamailio SIP server to provide public telephony service. In collaboration with OneSource, their implementation of the NEF can be integrated with Open5GS for network interaction either directly through the NEF or from an external AF. The services being tested are Traffic Influence and AF (Application Function) Session with Required QoS (“TS 129 522 - V17.6.0”), as these are the ones currently supported by Open5GS.

5G Data/User Plane: Open5GS allows for Control User Plane Separation (CUPS), which disaggregates the User Plane Function (UPF) from the control plane, enabling MEC and reducing backhaul distances. The Packet Forwarding Control Protocol (PFCP) implemented in Open5GS (N4 interface) follows 3GPP standardisation, thus integrating with external UPF implementations, such as UPG-VPP and eUPF. The first project is a user plane gateway implemented as an out-of-tree plugin of VPP (Vector Packet Processor) with DPDK (Data Plane Development Kit) for packet processing acceleration. Which converts the UPF into a programmable router, providing an API for external runtime configuration and VPP network metric collection. The second project uses xBPF (Experimental Beam Profile Fibre) for packet processing and can be configured for various 5G architectures. It also provides an API for user plane monitoring.

UEs: The user equipment possibilities englobe: SIM cards, modems, CPEs and smartphones. The SIM cards used are sysmoSIM-SJA2 and sysmoSIM-SJS1 programmable SIM cards, and CableFree’s non-programmable SIMs. And to program them OMNIKEY 3121 smart card reader together with pySIM. 5G modems from Quectel, SIMCom and SierraWireless are available, with devkits, and are managed by ModemManager. Two indoor CPEs in bands 46 and 78. And finally a wide variety of 5G smartphones, such as Google Pixel, Xiaomi, OPPO and Samsung for compatibility with all types of deployed RAN.

MEC: The MEC system deployment was considered to address smart-city scenarios with edge nodes spread out across various locations with a 5G edge-enabled deployment to address the mobility of the users and the dynamic nature of the edge environment while improving the Quality of Service (QoS). This was accomplished with extensions to base edge architecture through the appropriate plug-ins, custom resources and components, to address the dynamic nature of this environment and the mobility of the users.

The 5G edge-enabled deployment logic involved associating each edge node with the combination of a gNB and an edge UPF. The gNBs serve as a connection point providing radio access to the end-users using 5G-radio technology, while the role of the edge UPF within the context of this architecture is to route the user

traffic to its associated nearest edge node. This deployment ensures that user traffic is routed to the nearest server and additional hops can be avoided, contributing to an optimised QoS in the service consumption.

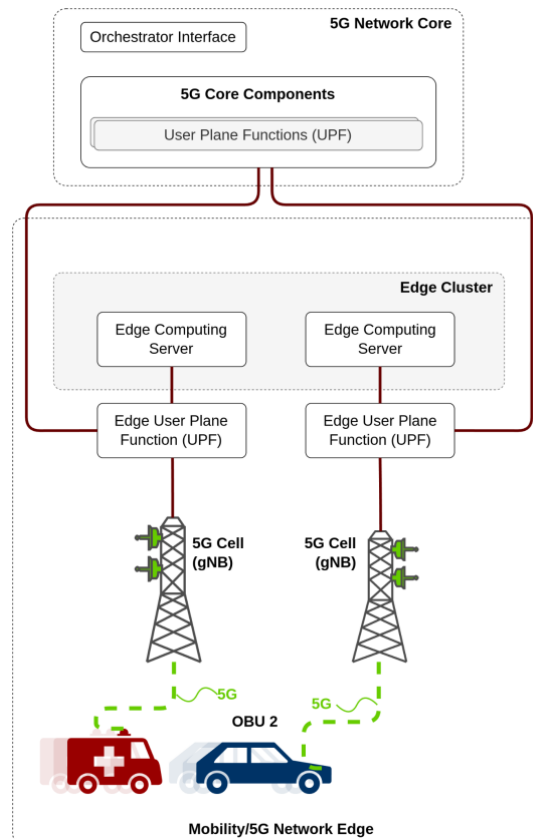


Figure 37. 5G Edge-enabled deployment

3.4.4 Virtualisation, Management and Orchestration Capabilities

The orchestration is performed by Kubernetes. The ATCLL has specific descriptors capable of describing the service requirements (e.g., graphics capabilities, service priority, replication, and proximity). Additionally, load-balancing mechanisms can forward the requests of each service for the best replica, taking into consideration the network and host state. These elements with the above functionalities are available in a [group of repositories](#). The server infrastructure side is also self-provided. At the core, the infrastructure is complemented by a network and data processing centre. The datacentre consists of multiple servers managed by Proxmox VE, deploying all virtual machines with services, data platform, apps, 5G core (Open5GS), and network functions running in the cloud, such as Kubernetes, OSM, ChirpStack, among others. Notice that this infrastructure supports a cloud continuum with a cloud, edge and device continuum. Beyond the server infrastructure in the core, we run the microservices and the detection and actuation algorithms in the edge infrastructure previously described (NVIDIA Jetson Orin and Jetson Xavier with a powerful GPU for graphic-intensive processing) and the access nodes in the vehicles (OBUs, DCUs).

As previously mentioned, edge orchestration mechanisms were implemented using Kubernetes, supplemented with extensions and plugins to enhance its capabilities. The default Kubernetes platform, designed primarily for cloud environments, struggles to address the dynamic needs of smart-city services, particularly in a vehicular context where users are constantly moving. The following extensions have been introduced to address these challenges:

- **FogService:** This new resource type, FogService, enables the deployment of services optimised for edge environments. It allows for defining instantiation locations, the number of replicas, and service-specific metrics to assess the status of replicas and adjust deployment based on node capabilities.
- **Custom Load Balancer:** The default Kubernetes load-balancing algorithm distributes network requests equally among replicas, which is often inadequate in edge-road environments. A custom Load Balancer was developed to adjust the probability of each replica receiving requests based on service-specific metrics and network latency within the cluster.
- **Scheduling Plugins:** New plugins were added to extend Kubernetes' scheduling process. These enhancements aim to create a more flexible and comprehensive scheduling system that considers factors such as service priority, existing applications, service dependencies, and performance.
- **Mobility Management Mechanisms:** New components were developed to gather data from external sources and proactively influence service performance and distribution across the edge platform. This data includes 5G and edge computing platform status, city congestion information, and user mobility details.

Development and deployment tools and software:

Docker: A software platform that builds, tests, and deploys applications by packaging them into standardised units known as containers. Containers provide a lightweight and isolated environment containing all necessary dependencies, libraries, and tools required to run an application.

Kubernetes: An open-source orchestration platform for managing containerised applications. It offers features such as storage orchestration, self-healing capabilities, horizontal scaling, and batch execution. Kubernetes is designed to accommodate extensions without altering its source code.

Prometheus: An open-source monitoring and alerting system that collects and stores metrics as time-series data. It features a flexible query language for a multi-dimensional data model, supports data collection via a pull model over HTTP, and does not rely on distributed storage.

MongoDB: An open-source distributed database system that stores data in a flexible JSON format. It supports ad hoc queries, indexing, and real-time aggregation, providing powerful data access and analysis capabilities. MongoDB also offers high availability and horizontal scaling.

Proxmox: An open-source platform for enterprise virtualisation, featuring a web interface for intuitive management of Virtual Machines (VMs) and containers. It supports software-defined storage and networking and provides high-availability clustering.

Ansible: An open-source automation engine that handles provisioning, configuration management, application deployment, and orchestration. Ansible uses simple, human-readable scripts to automate tasks, minimising repetition and maintenance by avoiding additional software installations.

Grafana: An open-source monitoring platform that allows users to query, visualise, and configure alerts for metrics, independent of their storage location. It enables the creation of dynamic and reusable dashboards.

Portainer: A lightweight container management UI that facilitates the management of various Docker environments, hosts, and Swarms. Portainer supports operations in diverse environments, including data centres, public clouds, network edges, and Industrial IoT devices. It connects all edge nodes, allowing access to Dockerised services running on each node.

3.4.5 Monitoring Capabilities

A dashboard using the ELK (Elasticsearch, Logstash and Kibana) stack is employed to monitor the ATCLL's current state. This dashboard features a map that displays health checks across the city, showing all active services and indicating their operational status. It also tracks the status of containers, highlighting any that are down. All logs are directed to this stack, facilitating the review of logs for warnings or errors. Additionally,

the dashboard monitors the percentage of used file space on each device. Alerts are triggered if a container fails, a health check is unsuccessful, or if the file space usage exceeds a predefined threshold.

Given the diverse nature of the 5G systems, which incorporate a wide range of equipment and technologies, monitoring these systems involves managing various information formats and access methods. In the ATCLL infrastructure, monitoring of 5G systems is divided into two primary sources (see Figure 38):

- **5G Core Monitoring:** The Open5GS core network functions include an HTTP (HyperText Transfer Protocol) server that exposes metrics on their status. These metrics can be scraped and stored in a Prometheus time-series database, using an additional Prometheus server. The stored data can then be accessed for analytics, complex processing, or visualised with other software applications, such as Grafana.
- **RAN Monitoring:** Aveiro's cellular infrastructure incorporates two technologies for implementing gNBs: CableFree and srsRAN. Both technologies provide performance metrics, but these are gathered in different ways. To address this, two metrics servers have been created. These servers collect metrics from both gNB technologies and publish them in the appropriate format to the data platform. The servers are implemented as Docker containers, running simple Python scripts to fetch the metrics.

To ensure data persistence in the ATCLL data platform, two additional approaches are utilised:

- **Kafka Cluster:** RAN data is persisted in a Kafka Cluster, allowing other entities to subscribe to the brokers associated with this cluster. This setup provides real-time updates on the platform's status.
- **MongoDB Cluster:** RAN data is also stored in a MongoDB cluster, enabling services to perform complex analyses on historical data. This is achieved through a Kafka Sink connector, which transfers data from specific Kafka topics into the MongoDB cluster.

Core metrics are aggregated in a dedicated Prometheus server and do not persist in the ATCLL data platform. Applications requiring access to these metrics can directly connect to the Prometheus server end-points.

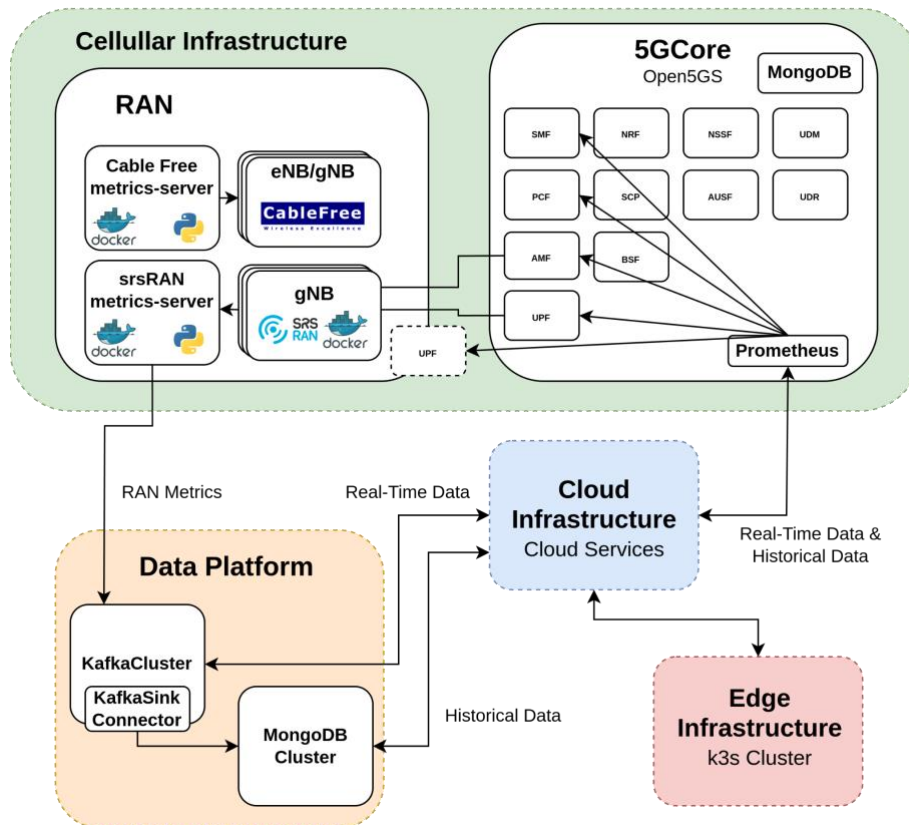


Figure 38. 5G RAN and Core metrics collection

ATCLL provides detailed metrics in the 5G infrastructure from RAN to Core. The list of these metrics is as follows.

RAN Metrics - Common in srsRAN and commercial gNBs

- **ue_count** - number of UEs connected to a gNB
- **cell_id, rnti** (radio network temporary identifier) - gNB identification and UE identification respectively
- **cqi** (channel quality indicator) - that provides insights about the quality of the downlink radio channel (1-15)
- **ri** (rank indicator) - number of independent transmissions and reception channels that can be effectively used in the MIMO systems (dB)
- **dl_mcs, ul_mcs** (downlink and uplink Modulation and Coding schemes) - schemes that determine how the data is transported and protected against errors during transmission
- **dl_bitrate, ul_bitrate** (downlink and uplink bitrate) - data transmission rate between the UE and the base station (bits/sec)
- **pushch_snr** - Signal to Noise ratio of the Physical Uplink shared channel) - indicates the quality of the received signal in the uplink direction as opposed to the noise level

RAN Metrics - srsRAN

- **dl_nof_ok, ul_nof_ok** (number of OKs, downlink and uplink) - Number of packets sent between the UE and the gNB

- dl_nof_nok, ul_nof_nok (number of Not OKs, downlink and uplink) - Number of packets dropped between the UE and the gNB
- bsr (buffer status report) - Send by the UE to the gNB to inform about the amount of data queued in the UE's transmission buffer (bytes)

RAN Metrics – Commercial gNBs

- dl_tx, ul_tx - Number of uplink and downlink transport blocks without errors and retransmissions
- dl_retx, ul_retx - Number of uplink and downlink transport blocks that were retransmitted
- dl_sched_users_min, dl_sched_users_avg, dl_sched_users_max - minimum, average and maximum downlink scheduled users per transmission time interval
- ul_sched_users_min, ul_sched_users_avg, ul_sched_users_max - minimum, average and maximum uplink scheduled users per transmission time interval
- mbms_bitrate - broadcast downlink bitrate (bits/sec)
- dl_use_min, dl_use_avg, dl_use_max - Minimum, average and maximum downlink usage ration
- ul_use_min, ul_use_avg, ul_use_max - Minimum, average and maximum uplink usage ration
- erab_count_min, erab_count_avg, erab_count_max - Minimum, average and maximum number of established radio bearer
- dl_gbr_use_min, dl_gbr_use_avg, dl_gbr_use_max - Minimum, average and maximum downlink GBR usage ratio
- ul_gbr_use_min, ul_gbr_use_avg, ul_gbr_use_max - Minimum, average and maximum uplink GBR usage ratio

Core Metrics - Open5GS

Open5GS exposes a set of Prometheus metrics, but only some of the core functions expose metrics, which include:

AMF

- gnb - number of gNodeBs
- fivegs_amffunction_mm_confudapte - Number of UE configuration update commands requested by the AMF
- fivegs_amffunction_rm_reginitreq - number of initial registration request received by the AMF
- fivegs_amffunction_rm_regemergreq - number of emergency registration request received by the AMF
- fivegs_amffunction_paging5greq - number of 5G paging procedures initiated at the AMF
- fivegs_amffunction_rm_regperiodreq - number of periodic registration update requests received by the AMF
- fivegs_amffunction_mm_confupdatesucc - number of UE Configuration Update complete messages received by the AMF
- fivegs_amffunction_rm_reginitsucc - number of successful initial registrations at the AMF
- fivegs_amffunction_amf_authreject - number of authentication rejections sent by the AMF
- fivegs_amffunction_rm_regmobreq - number of mobility registration update requests received by the AMF

- Amf_session - AMF Sessions
- fivegs_amffunction_rm_regmobsucc - number of successful mobility registration updates at the AMF
- fivegs_amffunction_amf_authreq - number of authentication requests sent by the AMF
- fivegs_amffunction_rm_regemergsucc - number of successful emergency registrations at the AMF
- fivegs_amffunction_mm_paging5gsucc - number of successful 5G paging procedures initiated at the AMF
- ran_ue - RAN UEs
- fivegs_amffunction_rm_regperiodsucc - number of successful periodic registration update requests at the AMF
- fivegs_amffunction_rm_registeredsubnbr - number of registered state subscribers per AMF
- fivegs_amffunction_rm_reginitfail - number of failed initial registrations at the AMF
- fivegs_amffunction_rm_regmobfail - number of failed mobility registration updates at the AMF
- fivegs_amffunction_rm_regperiodfail - number of failed periodic registration update requests at the AMF
- fivegs_amffunction_rm_regemergfail - number of failed emergency registrations at the AMF
- fivegs_amffunction_amf_authfail - number of authentication failure messages received by the AMF

PCF

- fivegs_pcffunction_pa_policyamassoreq - number of Access and Mobility Management (AM) policy association requests
- fivegs_pcffunction_pa_policyamassosucc - number of successful AM policy associations
- fivegs_pcffunction_pa_policysmassoreq - number of Session Management (SM) association requests
- fivegs_pcffunction_pa_policysmassosucc - number of successful SM policy associations
- fivegs_pcffunction_pa_sessionnbr - number of active sessions

SMF

- gn_rx_createpdpcontextreq - received GTPv1C CreatePDPCContextRequest messages
- gn_rx_deletepdpcontextreq - received GTPv1C DeletePDPCContextRequest messages
- gtp1_pdpctxs_active - active GTPv1 PDP (Packet Data Protocol) Contexts (GGSN)
- fivegs_smffunction_sm_n4sessionreport - number of requested N4 session reports evidenced by SMF
- ues_active - active User Equipments
- gtp2_sessions_active - active GTPv2 Sessions (Packet Data Network (PDN) Gateway - PGW)
- gtp_node_gn_rx_parse_failed - received GTPv1C messages discarded due to parsing failure
- s5c_rx_createsession - received GTPv2C CreateSessionRequest messages
- s5c_rx_deletesession - received GTPv2C DeleteSessionRequest messages

- gtp_new_node_failed - unable to allocate new GTP (GPRS Tunnelling Protocol) (peer) Node
- s5c_rx_parse_failed - received GTPv2C messages discarded due to parsing failure
- fivegs_smffunction_sm_n4sessionreportsucc - number of successful N4 session reports evidenced by SMF
- bearers_active - active Bearers
- gn_rx_parse_failed - received GTPv1C messages discarded due to parsing failure
- gtp_peers_active - active GTP peers

UPF

Open5GS's UPF had its network metrics available but ended being removed due to performance loss, by rollbacking to previous versions they can be accessed.

- fivegs_ep_n3_gtp_indatapkt3upf - number of incoming GTP data packets on the N3 interface
- fivegs_ep_n3_gtp_outdatapkt3upf - number of outgoing GTP data packets on the N3 interface
- fivegs_upffunction_sm_n4sessionestabreq - number of requested N4 session establishments
- fivegs_upffunction_sm_n4sessionreport - number of requested N4 session reports
- fivegs_upffunction_sm_n4sessionreportsucc - number of successful N4 session reports
- fivegs_upffunction_upf_sessionnbr Active Sessions
- fivegs_ep_n3_gtp_indatavolumeqosleveln3upf - data volume of incoming GTP data packets per QoS level on the N3 interface
- fivegs_ep_n3_gtp_outdatavolumeqosleveln3upf - data volume of outgoing GTP data packets per QoS level on the N3 interface
- fivegs_upffunction_sm_n4sessionestabfail - number of failed N4 session establishments
- fivegs_upffunction_upf_qosflows Number of QoS flows of UPF

Traveling's UPG-VPP metrics are provided by VPP and not the actual UPF implementation. It integrates with Prometheus and provides network statistics of the interfaces managed by VPP.

- inPackets
- outPackets
- inBytes
- outBytes
- ipv4Packets
- ipv6Packets
- outErrorPackets
- dropPackets
- inMissPackets
- inNobufPackets
- puntPackets

Edgecommllc's eUPF provides an API with PFCP message and session metrics, XDP Action Metrics and Packet metrics.

- upf_pfcpx_rx - The total number of received PFCP messages
- upf_pfcpx_tx -The total number of transmitted PFCP messages
- upf_pfcpx_rx_errors - The total number of received PFCP messages with cause code
- upf_pfcpx_rx_latency - The total number of PFCP messages processing duration
- upf_xdp_aborted - The total number of aborted packets
- upf_xdp_drop - The total number of dropped packets
- upf_xdp_pass - The total number of passed packets
- upf_xdp_tx - The total number of transmitted packets
- upf_xdp_redirect - The total number of redirected packets
- upf_rx_arp - The total number of received ARP (Allocation and Retention Priority) packets
- upf_rx_icmp - The total number of received ICMP (Internet Control Message Protocol) packets
- upf_rx_icmpv6 - The total number of received ICMPv6 Internet Control Message Protocol version 6) packets
- upf_rx_ip4 - The total number of received IPv4 (Internet Protocol version 4) packets
- upf_rx_ip6 - The total number of received IPv6 (Internet Protocol version 6) packets
- upf_rx_tcp - The total number of received TCP packets
- upf_rx_udp - The total number of received UDP packets
- upf_rx_other - The total number of received other packets
- upf_rx_gtp_echo - The total number of received GTP echo packets
- upf_rx_gtp_pdu - The total number of received GTP PDU packets
- upf_rx_gtp_other - The total number of received GTP other packets
- upf_rx_gtp_error - The total number of received GTP error packets
- upf_pfcpx_sessions - Number of currently established sessions
- upf_pfcpx_associations - Number of currently established associations

Metrics Common to all Core Functions

- process_max_fds Maximum - number of open file descriptors
- process_virtual_memory_max_bytes - maximum amount of virtual memory available in bytes
- process_cpu_seconds_total - total user and system CPU time spent in seconds
- process_virtual_memory_bytes - virtual memory size in bytes
- process_resident_memory_bytes - resident memory size in bytes
- process_start_time_seconds - start time of the process since unix epoch in seconds
- process_open_fds - number of open file descriptors.

3.5 UMA Testbed

The Malaga platform, represented by Victoria Network, includes several 5G deployments across various locations: the University of Málaga, the city centre of Malaga, the Malaga TechPark, and the experimental farm La Mayora in Algarrobo. For this project, the focus is on demonstrations and trials at the University Campus and the experimental farm La Mayora.

At the University of Málaga campus, the 5G private network serves as the central location, featuring both outdoor and indoor massive communication 5G radio deployments using Nokia equipment. Outdoor coverage is achieved through four microcells in band B7 (eNodeBs), four microcells in band n78 (gNodeBs), and two mmWave NSA cells operating on n257 and n261. Indoor coverage is provided by two FR1 picocells in band n78.



Figure 39. 5G Private Network at the University Campus (Málaga)

The 5G Private Network in La Mayora network includes 2 sites, a local 5G core and an edge computing server.

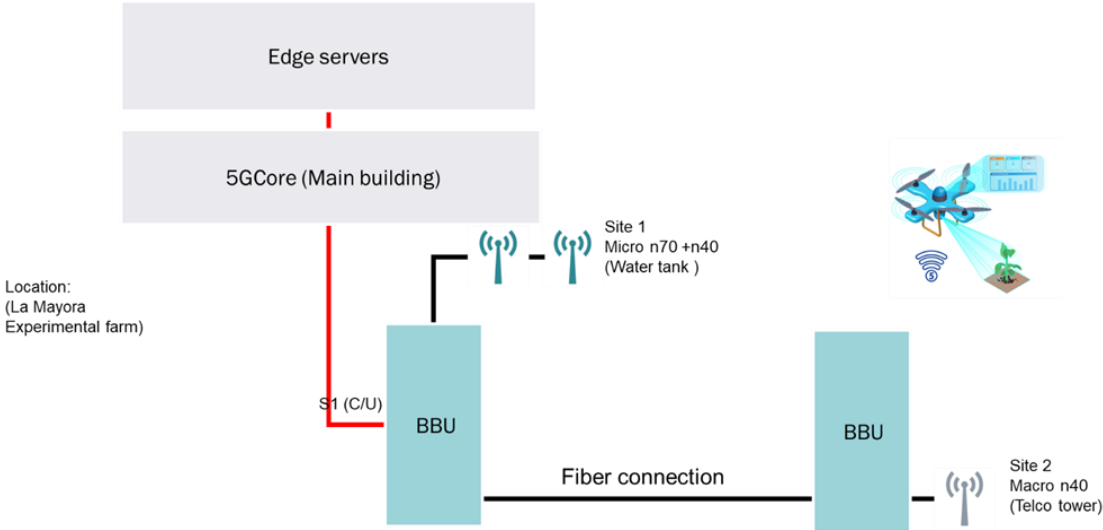


Figure 40. 5G Private Network at La Mayora (Algarrobo)



Figure 41. Site 1 at La Mayora



Figure 42. Site 2 at La Mayora

3.5.1 Services offered

Radio

The latest 5G features available in the radio are the following:

- **Dynamic UL Resource Allocation in FR1 TDD Cells:** This feature increases UL throughput by dynamically allocating unused long physical UL control channel (PUCCH) resources to the physical UL shared channel (PUSCH).
- **Additional Standard Slices Support:** This feature extends the support of slice identifiers from non-standard values and enhanced mobile broadband (eMBB) to all 3GPP standard Slice/Service Type (SST) values. The feature also introduces data radio bearer (DRB) inactivity timers, which users can set and control per slice or DRB profile.
- **Adaptive Re-Transmission:** This feature improves the average cell throughput up to 3% at 10% block error rate (BLER) in UL and DL. The CB008662 feature also improves the spectral efficiency and optimises the handling of the physical resources. Those benefits are achieved with the Hybrid Automatic Repeat Request (HARQ) re-transmission scheme that adapts reserved Modulation and Coding Schemes (MCSs) in FDD (Frequency Division Duplexing) and TDD (Time Division Duplexing) frequency range 1 (FR1).
- **Service-Aware Scheduling Request and HARQ Re-Transmissions:** This feature improves end-user experience. Users can reduce call latency using several settings for Data Radio Bearer (DRB) configuration. The feature also introduces 5QI-80 identifier for non-GBR DRBs in frequency range 1 (FR1), 5G SA mode.

UMA's testbed is endowed with the HPE 5G Core Network (5GC which is the 5G network component that manages functionalities like authentication, control signalling, Quality of Service (QoS) policies, mobility, and data traffic forwarding between the base station and the networks external to the 5G system.

Core network

The HPE (Hewlett-Packard Enterprise) 5GC is a fully virtualised solution that adheres to 3GPP and ETSI standards, offering flexibility and adaptability for a wide range of verticals and use cases. It incorporates several Network Functions (NFs), including the Access and Mobility Management Function (AMF), the Session Management Function (SMF), the User Plane Function (UPF), the Unified Data Management (UDM), the Authentication Server Function (AUSF), the Unified Data Repository (UDR), the Policy Control Function (PCF), the Network Repository Function (NRF), and the Network Slice Selection Function (NSSF). Additionally, the

HPE 5GC features an Equipment Identity Register (EIR), which provides a mechanism to restrict malicious user terminals within the mobile network.

Further, the 5GC system exposes the following 3GPP standard-compliant interfaces:

- N1: Non-Access Stratum (NAS) over N2 between the UEs and the AMF.
- N2: Next-Generation Application Protocol (NG-AP) over Stream Control Transmission Protocols (SCTP) between the gNB(s) and the AMF.
- N3: Next-Generation User Plane (NG.U) interface over User Datagram Protocol (UDP) between the gNB(s) and the UPF(s).
- N4: Interface between SMF and UPF to allow the control and user plane separation.
- N5: Interface between the PCF and the Application Function (AF).
- N6: IP connectivity to external Data Networks (DN).

In particular, the PCF is accessible to trusted third parties (AFs) via the exposed N5. External AFs can configure network parameters and perform end-to-end 5G QoS modification and control to support mission-critical (MC) services.

Furthermore, the HPE 5GC is equipped with a pre-installed instance of Prometheus, capable of exporting 5GC-related KPIs to an external monitoring system or an orchestrator. Such metrics are Central Processing Unit (CPU), memory, and disk usage, information and statistics on processes and 5GC NFs, service usages, etc.

Finally, the HPE 5GC also provides a wide set of northbound RESTful, APIs to allow external Operation, Administration, and Monitoring (OAM) systems to easily integrate and automate configuration, performance, and fault management procedures.

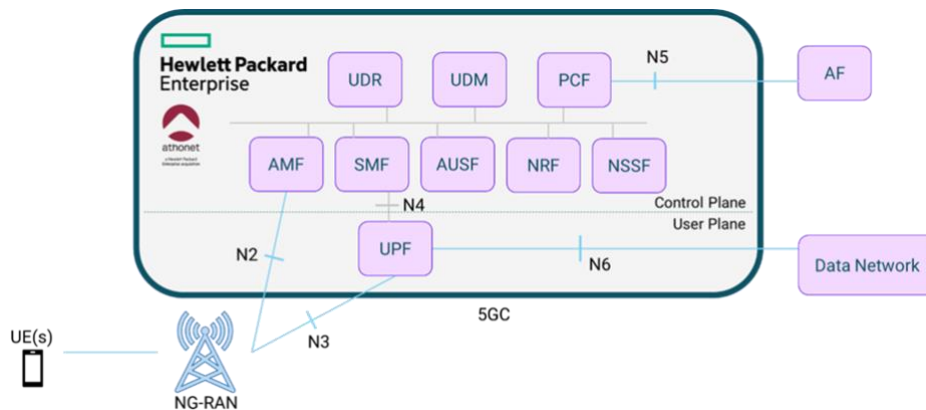


Figure 43. HPE 5GC architecture

Computational resources

The main data centre is located in the Ada Byron building and is based on a hyper-converged architecture as depicted in Figure 44. The computational resources available at the main data centre include:

- Computing: 11 Hosts
- Storage: 12 TB CEPH Storage
- Networking: 1Gb to the Internet. 10Gb and 40Gb Internally (Management, Service, Storage)

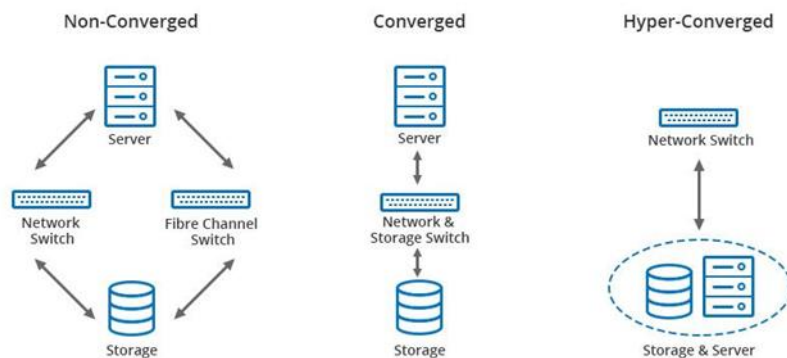


Figure 44. Hyper-converged architecture of the main data centre

There is a second micro data centre located at La Mayora, that will act as an EDGE node. The computational resources available at the edge are the following:

- Computing: 2 Hosts
- Storage: 2TB Local Storage
- Networking: 10Gb and 40Gb Internally (Management, Service, Storage)

The private cloud manager used for both sites is OpenNebula. OpenNebula is an open-source platform designed for building and managing private, public, and hybrid clouds. It offers a robust solution for orchestrating various virtualised data centres and cloud infrastructures. OpenNebula supports multiple hypervisors, including KVM, VMware vCenter, and LXD containers, enabling users to select the most suitable option for their requirements. It also features Multi-Tenancy and User Management based on Role-Based Access Control (RBAC), providing fine-grained control over user permissions and roles to ensure secure multi-tenant environments. Additionally, it includes user quotas, allowing administrators to set limits for users and groups to manage resource utilisation effectively.

3.5.2 Monitoring Capabilities

UMA has developed monitoring agents for Android devices using Test Automation Platform (TAP) plugins. TAP, developed by Keysight Technologies, is a software solution designed to automate testing processes. It is part of Keysight's suite of tools for various electronic testing needs, from simple device functionality checks to complex system validations and certifications.

Iperf Agent: The Iperf Agent for Android is based on Iperf, a network testing tool used to measure bandwidth between two hosts over a network. For Android devices, this agent is an app that can function as either a client or a server in network performance tests. It is useful for assessing network infrastructure performance as experienced by the device.

Ping Agent: The Ping Agent for Android is based on the ping tool, which is used to monitor and analyse network connectivity and performance. It operates by sending ICMP (Internet Control Message Protocol) echo requests to specified network hosts (such as servers or other devices) and measuring the response time. This tool helps in evaluating network latency and detecting packet loss, both of which are crucial for network troubleshooting and performance assessment.

The Resource Monitoring Agent for Android is a tool that tracks various system resources on Android devices, including radio resources, CPU usage, memory, and battery levels.

Prometheus is utilised to monitor the usage of the virtual infrastructure and the 5G Core (5GC). It collects and stores metrics, enabling comprehensive analysis and visualisation of resource utilisation.

Nemo Handy from Keysight is employed to collect radio performance parameters at the user equipment (UE) side. This drive test tool is essential for evaluating and analysing the performance of radio networks.

3.5.3 Key features and assets

For the configuration of the radio, we will use the API exposed by NaC, a tool from Nokia. This tool allows the management and configuration of the following resources:

- IMSIs management
- Slices management
- QoS profile management
- Radio status

The HPE 5GC also provides a wide set of northbound RESTful APIs to allow external Operation, Administration, and Monitoring (OAM) systems to easily integrate and automate configuration, performance, and fault management procedures. These APIs follow the OpenAPI 3.0 specification and can be consumed by any client that can send HTTP requests and interpret HTTP responses, regardless of its programming language. All network function configuration settings are exposed through the 5GC's APIs. This means that one can programmatically adjust settings, deploy new configurations, provision new users, and manage the network behaviour directly through the APIs, without directly interacting with the network elements.

In addition, real-time and historical data about network performance, diagnosis, and troubleshooting issues can be retrieved via APIs, facilitating proactive maintenance and problem resolution. For each network function within the system, metrics are meticulously collected and exposed using Prometheus. These metrics encompass resource consumption data, 3GPP-related metrics for signalling and traffic data, and detailed information regarding the state of the network. Further, the HPE 5GC exposes a set of parameters via API for monitoring the virtual machines. This includes metrics such as CPU utilisation, memory allocation, disk usage, networking data, and more.

3.6 KAU Testbed

The Communication Advanced Research Laboratory Wireless Testbed (CARL-W) is on the Campus of Karlstad University, Karlstad, Sweden, and is part of the Northstar Testbed. The testbed is managed by the Computer Science Department at Karlstad University in cooperation with Telia (operator) and Ericsson (HW supplier). The communication infrastructure, built on standard fiber and 10GbE, integrates a communication network with radio terminals (4G, 5G, Wi-Fi and Starlink). The platform allows several possible end-user equipment and technologies like mobile phones, IoT devices, virtual machines and different container solutions (Kubernetes/docker).

The testbed is equipped with a commercial indoor 5G system (Ericsson Radio Dot), with four radio dots deployed in the engineering building of Karlstad University and one radio dot deployed in the nearby Innovation Park building hosting industry clusters and startups. Outdoor coverage in the geographical area surrounding the Karlstad University campus will be added during fall 2024 and will be available for Open call 1 extensions.

The testbed is configured to provide 5G SA (as well as 5G NSA) and Low Latency edge capabilities, e.g. <5ms one-way delay using a 100MHz spectrum in the N78 band. The performance has been validated with a series of 5G devices and hardware components, such as Cradlepoint R1900, Mikrotik, Huawei CPE, Quectel RM500, and 5G SA enabled mobile phones. The setup is suitable for intensive and capacity services, low latency experiments and other demanding use cases (VR/AR, smart industry etc.). The testbed will host the XR Health.

The current layout of the testbed depicted in Figure 45, Figure 46, and Figure 47 shows some of the areas in the Karlstad University engineering building covered by the 5G testbed. These include a large experimental space where various use cases can be staged.

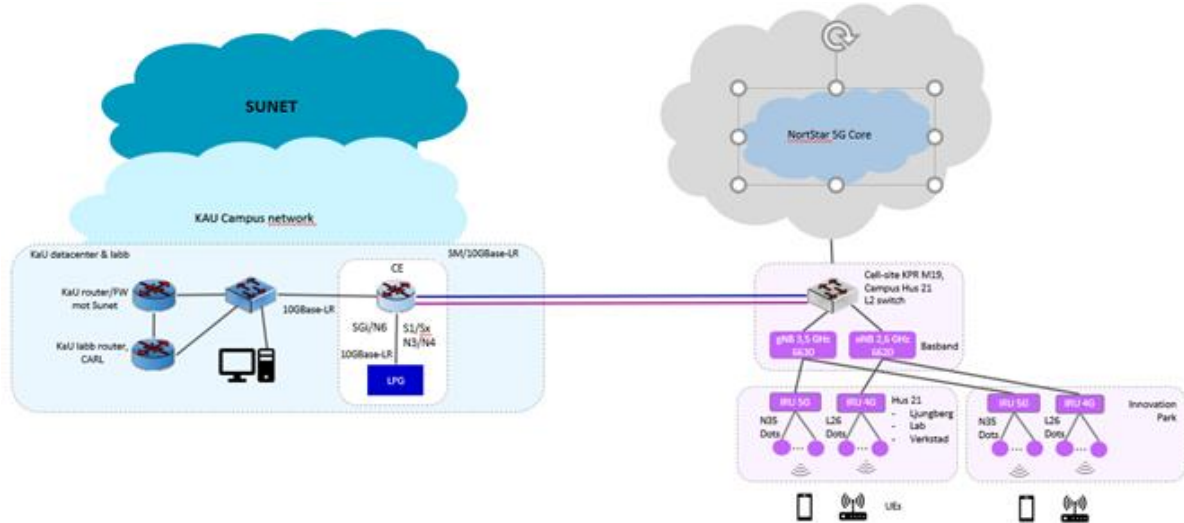


Figure 45. KAU testbed layout



Figure 46. View of parts of the KAU engineering building covered by the testbed (1)



Figure 47. View of some parts of the KAU engineering building covered by the testbed (2)

3.6.1 Services offered

Experiments

Experiments in the CARL-W testbed can be freely setup using one or more of the available network technologies, e.g. 5G - Starlink measurements, 5G - edge (wired) or any other combination of network technologies available in the testbed. New services made available as containers can be easily deployed within the testbed infrastructure. As further detailed in this Section, the testbed provides experimenters with both network and service monitoring capabilities.

One present limitation is that we do not currently support automated experiments where both the client and the server are on the same network technology, i.e. both the client and server are in our 5G network and orchestrated by the testbed. When one of the end-points is external, it is possible to perform the same technology experiments automatically. Alternatively, for local same technology experiments, either the client or server needs to be manually initiated.

The current deployment of the testbed covers an indoor deployment, with mobility limited to the areas of the engineering building covered by the testbed. As mentioned above, the addition of outdoor coverage is planned for the fall of 2024. This will allow us to also experiment with handovers between indoor and outdoor and for experiments in outdoor mobility scenarios within the geographical area covered by the testbed.

Radio

The testbed offers 5G connectivity over preconfigured network slices that can be selected by the experimenter, with currently two slices configured. One standard eMBB like slice and one high priority slice. The slices can be reconfigured, but only on a slow time scale.

The testbed offers RAN support for low latency, low loss scalable throughput (L4S) signalling. L4S traffic is also handled separately by the MAC (Medium Access Control) scheduler. L4S is a recent standard by the IETF (Internet Engineering Task Force) that supports low latency services over the Internet. RAN support for L4S is a 3GPP Release 18 feature. This feature is of particular interest for services that require low latency. The use of L4S is controlled by the configuration of the applications/end-hosts. For TCP-based applications, the use of L4S can be controlled through the selection of the OS configuration of the end-hosts.

The testbed also offers connectivity over satellite, Wi-Fi and 4G.

Core

The selection of different network slices described above also involves the core network. No separate knobs to reconfigure the core network are available.

3.6.2 Remote Access Capabilities

The testbed infrastructure is designed to facilitate the seamless integration of external (third-party) sensors, network devices, or services, in addition to supporting containerised services. This capability is especially relevant for Open Call Track B. For external devices or services to integrate with the testbed management system, they must meet specific requirements: they need to support WireGuard, function as a Docker/Kubernetes host, and have an internet connection.

3.6.3 Key features and assets

Compute, Storage and Networking Capabilities

The 5G radio dots are strategically placed across two buildings on the Karlstad University Campus. Each radio dot connects directly to a Local Radio Unit (LRU) within the building, and both LRUs together form a single cell, served by a baseband unit and covering two floors. The physical infrastructure for the access network includes one-to-one fibre links aggregated by a switch supporting 10 GbE connections. The primary uplink to the internet is established through two 10 GbE ports, which are connected to the University's 100 GbE internet uplink. Additionally, separate networks and gateways for Starlink and other communication types (such as Wi-Fi) are integrated into the testbed network, providing five possible internet connections: Wired, 5G, 4G, Starlink and Wi-Fi.

The platform supports the automated deployment of applications through containerisation technologies, such as microservices. The server infrastructure and data centre are self-hosted and managed by the same team overseeing the CARL-W testbed. The data centre comprises multiple servers managed by VMware vCenter, connected via Cisco 10 GbE switches. These servers deploy all virtual machines and network functions running in the cloud, including Kubernetes and Docker Swarm. In addition, the data centre features bare-metal installations for time-critical workloads, along with edge nodes and user equipment (UEs) such as Raspberry Pi, Nvidia Jetson devices and various commercial mobile phones.

3.6.4 Virtualisation, Management and Orchestration Capabilities

The testbed orchestration is managed by Kubernetes. CARL-W employs specific descriptors to define service requirements, such as network technology and service type. While the testbed's worker nodes are organised according to the network technology they use, the testbed itself remains technology-agnostic, not requiring any particular connection technology.

To be included in the network orchestration, all devices must support WireGuard, Docker/Kubernetes, and have a routable IP address, ensuring they can connect to the Internet.

3.6.5 Monitoring Capabilities

The testbed has both network and service monitoring capabilities:

- We monitor the infrastructure by collecting the data from the different network technology end-points (e.g. 5G, Starlink) as well as status from the compute infrastructure components, e.g. IO (Input/Output), CPU and Memory load. Monitoring of the compute infrastructure is based on the DESK monitoring framework and utilises a set of open-source components.
- Application and service performance monitoring evaluates network resources, services status, etc. The automated performance monitoring includes continuous monitoring of the capacity and latency performance. Some eBPF-based tools for fine grained latency and inter-packet delay monitoring are also available. These tools are currently started manually when fine-grained monitoring is required.

The monitoring information is collected in an Influx database. Part of the monitoring information is also made available live through a [Grafana web interface](#). An example showing part of the live visualisation can be seen in the Figure 48.

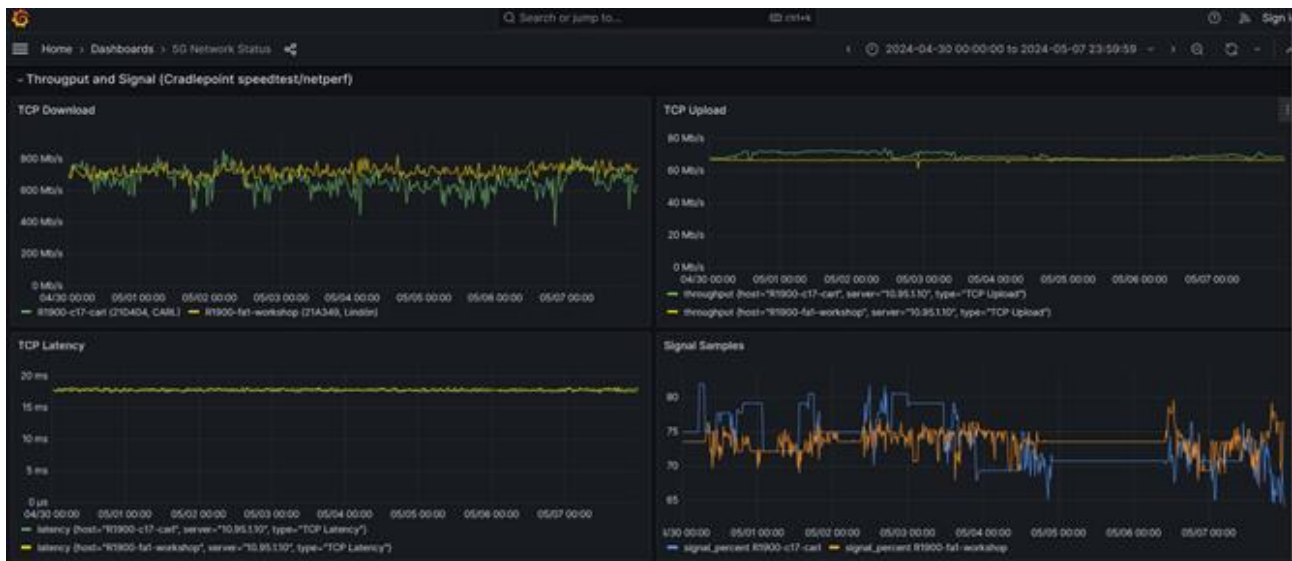


Figure 48. Sample view from part of the live visualisation of monitoring data

3.7 OTE Testbed

OTE testbed will be used in UC-CITIES-2 – Automated logistics, validation. Its current version is based on 5G SA architecture is presented in the following figure.

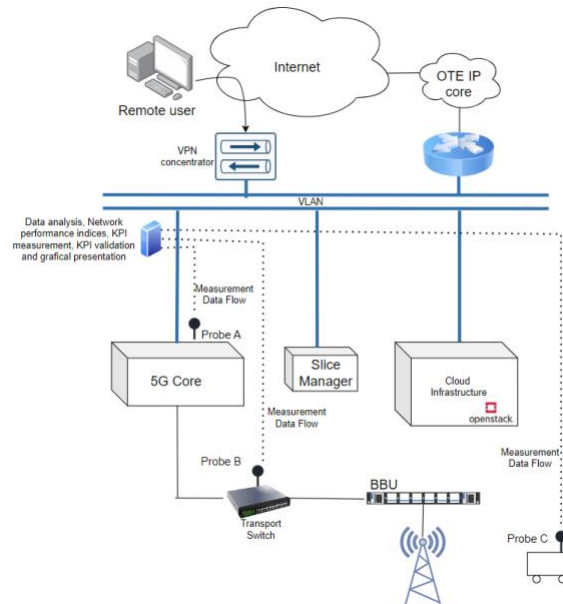


Figure 49. OTE testbed high level architecture

The main parts of the infrastructure are:

RAN: The radio system utilises New Radio (NR) technology and is integrated with the SA Rel. 16 architecture. The currently available equipment is detailed in the following table.

Table 13. Available RAN equipment

Type	Manufacturer	Model	Information
Radio Unit	Ericsson	ERS4408	4x4 MIMO, Carrier Aggregation and 256 QAM
Radio Unit	Ericsson	Radio Dots	4x4 MIMO, Carrier Aggregation and 256 QAM
Network Equipment	Ericsson	6630	Baseband Unit, 15 CPRI/9 eCPRI, LTE+NR with up to 12 CCs LTE and 12 CCs NR in dual mixed mode

Packet Core: In the OTE testbed, a 5G SA Rel. 16 network infrastructure is installed based on the architecture that is presented in Figure 50, using Athonet Packet Core, which is an enhanced implementation of network functions. The packet core is separated into two main parts as can be seen below in Figure 51: the Control Plane Function (CPF) and the User Plane Function (UPF). Both are implemented as OCI (Oracle Cloud Infrastructure) containers. In the CPF component, four Network Functions are installed based on the 3GPP standard:

- **Access and Mobility Management Function (AMF):** The AMF component in the CPF can be accessed by any number of gNBs. Each gNB is assumed to be locally configured to access the AMF.
- **Session Management Function (SMF):** It can be configured to access any number of UPFs, including the co-located UPF. However, a UPF may only be controlled by one SMF. Although a gNB may connect

to multiple AMF instances in different instances, each 5GS configuration containing an AMF is an independent 5GS (5G System).

- Authentication Server Function (AUSF): It enables the authentication of 3GPP access over NR.
- User Data Management (UDM) Function: It supports the Authentication credential Repository and Processing Function (ARPF) function, the SUDF (Subscriber Identity De-concealing Function) function to de-conceal the SUPI (Subscription Permanent Identifier) from the SUCI (Subscription Concealed Identifier), the 5G Authentication Vector Generation, the UE Subscriptions and the ARPF to store the USIM (Universal Subscriber identity Module) long-term keys.

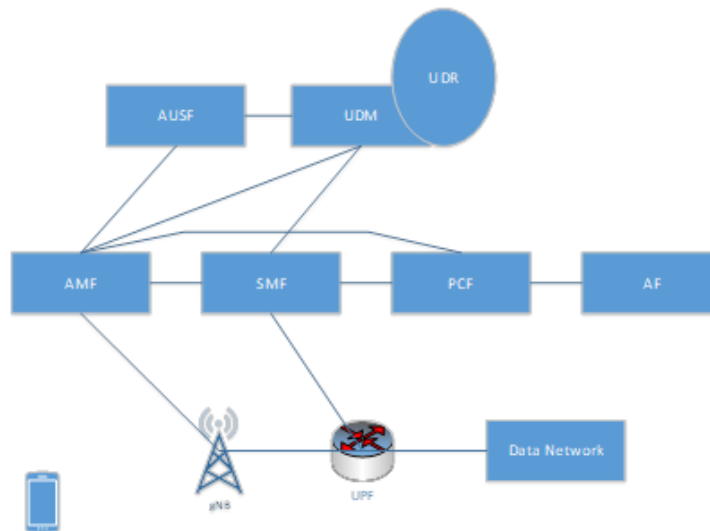


Figure 50. 5G SA architecture

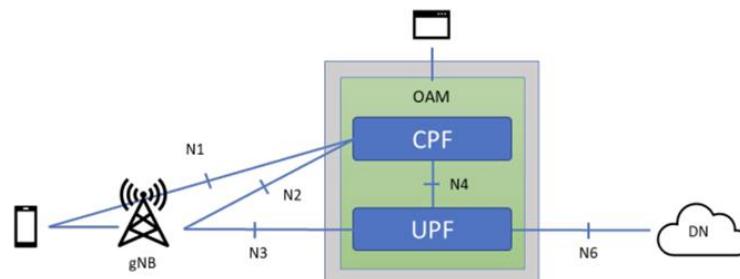


Figure 51. Athonet Architecture

Athonet packet core exposes the following 3GPP interfaces:

- N1: NAS over N2 between the gNBs and the AMF.
- N2: NG-AP over SCTP between the gNBs and the AMF.
- N3: NG-U over UDP between the gNBs and the UPFs.
- N4: PFCP over UDP between the SMF and the UPFs.
- N6: IP connectivity to external Data Networks (DN).

Cloud Infrastructure: Edge computing is supported by providing the available resources on OTE's cloud infrastructure, where an OpenStack Platform is installed. Edge servers allow moving the application hosting from centralised data centres down to the network edge, closer to consumers and the data generated by applications.

For the implementation of the infrastructure the resources that were used were:

- For RAN installation
 - Radio Dot: 4x4 MIMO (Multiple Input Multiple Output), Carrier Aggregation and 256 QAM (Quadrature Amplitude Modulation) (Ericsson)
 - Baseband Unit: 15 CPRI (Common Public Radio Interface) /9 eCPRI (evolved Common Public Radio Interface), LTE+NR with up to 12 CCs (Component Carriers) LTE and 12 CCs NR in dual mixed mode (Ericsson)
- For Packet Core installation
 - Red Hat OpenStack Platform release 16.1.8 (Train): 352 vCPUs, 576 GB RAM and 4TB storage
- For cloud applications support
 - CPU: Intel(R) Xeon(R) Silver 4216 CPU @ 2.10GHz - 32 cores available
 - Memory: 64 GB DDR4 (Double Data Rate Fourth Generation) ECC (Error Correction Code)
 - Storage: 1TB SSD (Solid-State Drive)

3.7.1 Services offered

Increased network KPIs: Since the OTE testbed will be used in UC-Cities-2 – Automated logistics, it is designed to support Industry 4.0 vertical requirements, offering network capabilities such as Network Function Virtualisation Management and Orchestration, network slicing and Slice Management and monitoring of the network KPIs (throughput, latency, packet loss, jitter).

Therefore, it ensures real-time data exchange and optimal performance:

- High network reliability and availability to support uninterrupted connectivity.
- High throughput to support HD (High Definition) video streaming.
- High device density to support many sensors.
- Leveraging heterogeneous data, which is important for moving UEs. This includes real-time information on product location, current UE position, and its designated destination.

Slicing: Slicing is a key feature in 5G networks, allowing the use of different types of services and supporting heterogeneous requirements that could not be fulfilled by one type of service. In OTE testbed multiple slices are available. A slice selection mechanism supports the following operations:

- Slice creation.
- Slice update.
- Slice cancellation.
- Get list of slices.
- Get slice configuration parameters.

3.7.2 Key features and assets

Technologies that are supported by NR allow **RAN** to use new bands and increased bandwidth which allows the future expansion. At the same time, massive MIMO will improve the throughput while beamforming, apart from achieving higher throughput, will increase coverage. Multi-Services transmission could be supported, as well as end-to-end slicing.

The design of the **packet core** supports capabilities that increase flexibility and virtualisation, such as slice selection and Virtual Network Functions.

Finally, a **monitoring system** that is installed collects data using an automated process that runs 24x7, with 1min monitoring granularity and 10 ms sampling granularity. Thresholds can be set to allow for a cockpit view of KPIs, in accordance with the designated performance targets. KPI metrics measured are latency, packet loss, packet delay, frame loss and traffic throughput.

4 Verticals and Use Cases

The 6G-PATH project strategically focuses on four primary verticals and ten use cases (UCs) to test and refine key innovations.

- **Farming:** Two (-2-) use cases (water saving and smart vineyards) will evaluate deployment types, network slicing with various QoS levels and AI-driven Edge-Cloud computing.
- **Education:** Three (-3-) use cases (XR rural schools, classroom of the future, and XR Health Training) will explore XR and holographic education, Edge Computing, location-sensitive processing, and AI-driven video/data processing.
- **Health:** Two (-2-) use cases (3D hydrogel patches and elderly monitoring) will assess micro and nomadic edge nodes, Over-The-Top (OTT) 5G MNO (Mobile Network Operator) and NTN (Non-Terrestrial Network) integration, XR platforms requiring high bandwidth and low latency and security-related KPIs.
- **Smart Cities:** Three (-3-) use cases (connected and sensing city, automated logistics, and security coordination) will focus on large-scale IoT-Edge/Cloud integration, differentiated QoS for MCX (Mission Critical Communication services) communications and high-throughput video/data streaming. They will also evaluate reliable, high-resolution services and the security of next-gen networks for emergency applications.

Throughout this section, the ten (-10-) internal UCs are described, including the details on the architecture, requirements and expected outcomes.

4.1 UC-FARM-1 - Water saving

4.1.1 Description and main objectives

The use case aims to automate the decision making for irrigation through the monitoring and continuous control of the phenology of an open avocado fruit orchard. This is located at the 40Ha experimental station of La Mayora in Algarrobo-Costa Malaga (Spain), using the advantages of 5G/6G technology, which means instantaneous treatment of large volumes of data to automate decision-making and diagnostic processes in real time. Thus, the main objective of the use case is to acquire and store data and monitor and control the plot of fruit trees to create a real-time information database that allows us to make decisions regarding parameters of efficient crop irrigation management. The combination of plant knowledge (CSIC) with data processing (UMA) becomes essential for the success of the project.

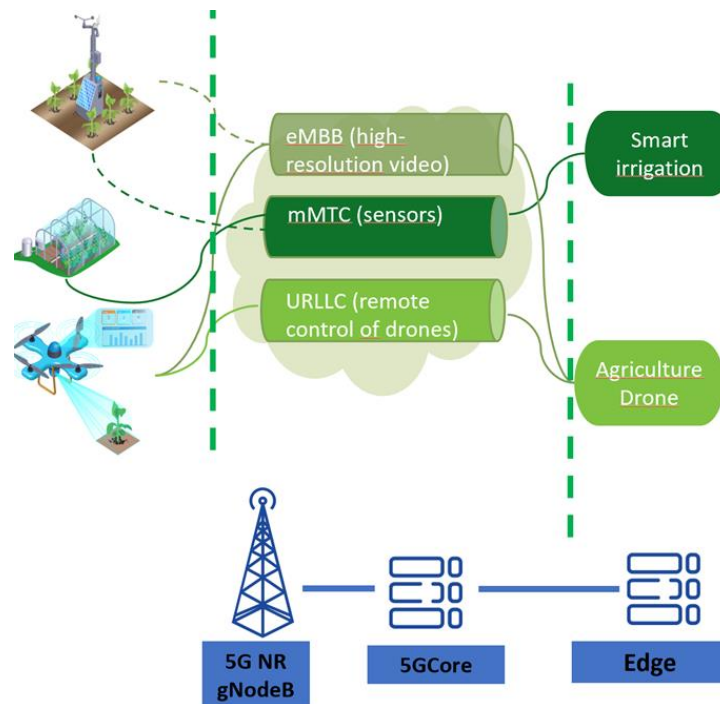


Figure 52. Global diagram of the components for the Use Case Farm-1

The “Water saving” use case pursues three (-3-) major goals:

1. Creating a network of (battery-powered) sensors and actuators to allow the acquisition of the necessary data on the water content of the soil-plant-atmosphere continuum.
2. Test the water demands of avocado crops in situ by comparing stressed and unstressed plants and improve the precision of irrigation.
3. Periodically monitoring the phenological state of the crop through images and videos transmitted in real-time by a drone adapted with different types of artificial vision cameras designed for agriculture.

The use case objective is to focus on the development and provision of guaranteed products and services for the agricultural sector, in this case, ensuring water saving according to the phenological stages of the crop and taking advantage of the pilot facilities to optimise and validate the final product. All this will lead to efficient and intelligent irrigation. Large volumes of video and images in real-time require the use of 6G technology with lower latency and reliability.

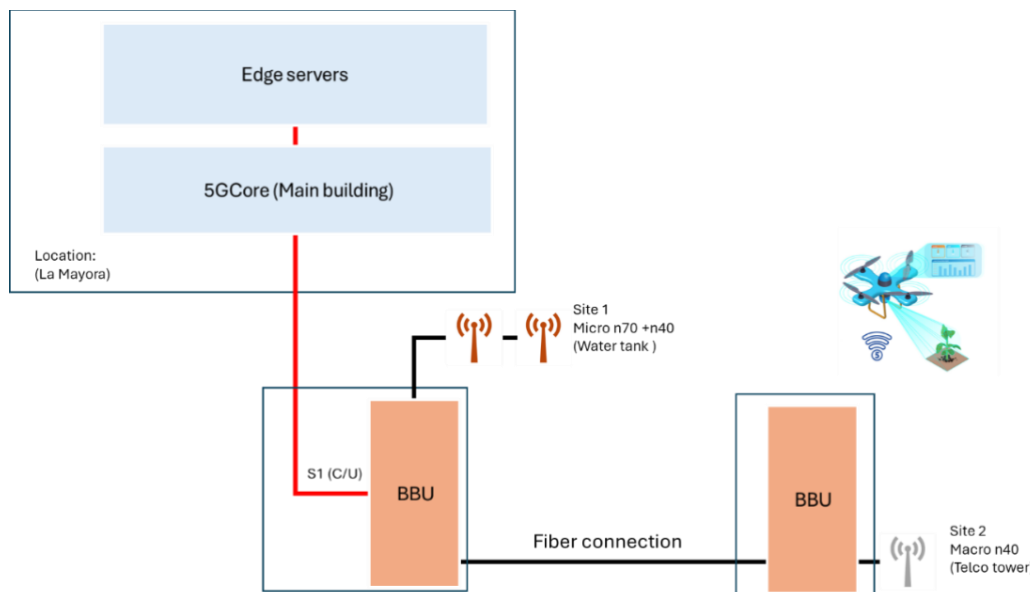


Figure 53. High-level topology of the Use Case Farm-1

4.1.2 Scenario 1. Avocado irrigated

Several sensors powered by solar energy and batteries will be installed to control the physiological parameters of the trees that are related to water consumption. Sensors of water in the soil, sensors of water potential in the tree trunk, sensors of turgor in the leaves and sensors of humidity in the environment are being combined. Information from multiple sensors is uploaded to the UMA server cloud in real-time, and visualised in *Grafana* to generate parameters that serve to understand the hydric status of avocado crops.

4.1.3 Scenario 2. Avocado water scarcity

With the sensors mentioned above, irrigation deficit will be applied to a set of fruits in the orchard to evaluate changes that are associated with the lack of water and identify critical points of water use. All data will be sent through a 5G private network to the UMA repository and the NPN (Non Public Network) of CSIC. Then, using dedicated Python-based software based on decision algorithms (Neural Networks - NNs), a feedback process is expected to provide more efficient irrigation of avocados and ameliorate drought effects in situ.

4.1.4 Scenario 3. Monitoring avocado phenology

Periodically, a drone will send images and videos in real time to the server, which will process automatically these images to obtain parameters to control the hydric status of the plants. The images will be uploaded to the cloud using 5G/6G technologies. From there, using Python-based image processing software, the phenological status will be inferred first, and then the effects of drought will be identified at the tree level. This is a milestone in tree plantations in open plots, enabling detailed diagnoses by tree.

4.1.5 6G requirements

Table 14. Functional Requirements (FRs)

FR	Title	Description
FR1	High density of sensors	Usage of a massive number of IoT sensors to calculate the precise requirements of water.
FR2	Drones	The system must support their remote control and the streaming of high-resolution videos and images for scanning the status of crops.

FR	Title	Description
FR3	Edge deployment	Servers at the edge of the network employ data analytics algorithms to interpret the images and sensor data.
FR4	Real time data collection	The system must be capable of continuously collecting real-time data from various sources, including soil moisture sensors, weather stations and multispectral imaging from drones, to accurately assess the current water needs of crops and the soil's moisture levels.
FR5	High-speed Data Transmission	Utilise the capabilities of 5G networks for high-speed data transmission to ensure that the vast amounts of data collected from sensors and drones are quickly transmitted to the processing servers without significant delays.
FR6	Data Processing and Analytics	The system must efficiently process and analyse the collected data to determine the optimal watering schedules and amounts for each crop type and field section, considering current soil moisture levels, weather forecasts and crop water requirements.

Table 15. Performance Requirements (PRs)

PR	Title	Description
PR1	Smart irrigation	Connection density: > 100/km ² ; Battery life: > 1 year
PR2	Drones	Reliability: > 99,999%; Latency: < 5ms
PR3	Multispectral camera	High uplink capacity for transmitting high resolution images.

4.2 UC-FARM-2 - Smart Vineyards

4.2.1 Description and main objectives

The Smart Vineyards use case aims to elevate vineyard management through the integration of advanced technologies such as edge computing, private 5G/6G networks, and AI/ML algorithms. By leveraging these technologies, the use case seeks to optimise resource usage, improve productivity, and minimise environmental impact.

The Smart Vineyards use case encompasses multiple scenarios tailored to different vineyard conditions and requirements. These scenarios include:

4.2.1.1 *Scenario 1: Off-grid Deployment:*

In an off-grid deployment scenario, the vineyard operates in a completely isolated environment without consistent access to external networks or cloud services. This could occur in remote rural areas where traditional network infrastructure is unavailable or unreliable. In this scenario, all processing and storage occur locally within the vineyard premises. The edge computing nodes (Crates) deployed within the vineyard handle data collection, analysis and storage autonomously. This setup provides vineyard operators with complete privacy and control over their data. It also ensures continuous operation even in the absence of external connectivity. However, it requires robust local infrastructure and may limit access to real-time updates or cloud-based services.

4.2.1.2 *Scenario 2: Intermittent Connectivity:*

In the intermittent connectivity scenario, the vineyard has periodic access to cloud services and external networks for data backup and updates. This scenario is common in partially covered regions where network

connectivity is available but may be unreliable or intermittent. It could also apply to vineyards located in areas with limited network infrastructure or where network connectivity is established temporarily for specific purposes. In this setup, data collected by the edge computing nodes is periodically synchronised with cloud-based storage and processing platforms during periods of connectivity. This allows for the backup of critical data and updates to algorithms or software without requiring constant network connectivity. However, it may result in delays in data processing and analysis during periods of disconnection.

4.2.1.3 Scenario 3: Interconnected Deployment:

In an interconnected deployment scenario, the vineyard has constant backhaul connectivity to both local and cloud-based processing resources. This scenario is suitable for vineyards located in well-connected regions with reliable network infrastructure. It provides continuous access to cloud services for real-time data analysis, updates, and seamless integration with external systems. The edge computing nodes within the vineyard leverage both local processing capabilities and cloud resources to optimise performance and scalability. This setup enables vineyard operators to leverage the full potential of edge computing and cloud services, ensuring high efficiency and optimisation in vineyard operations. However, it may require higher investment in network infrastructure and ongoing maintenance to ensure uninterrupted connectivity.

Table 16. Scenarios with objectives

Aspect	Description	Objective
Performance	Increase in imagery processing time on-site (edge) compared to cloud.	<5%
Performance	Reduction from cloud resources dependency.	10%
Security	No (costumer-sensitive) data transfers from on-site deployments to the cloud (in off-grid, intermittent, and interconnected deployment modes).	Off-grid operations
Performance	Vineyard coverage by using AGVs (Automated Guided Vehicles) and AAVs (Assault Amphibious Vehicles) to automate and minimise the time getting processed.	>99%
Performance	Predictive model Inferencing accuracy improvements by employing on-site sensors, AGVs, AAVs.	5%

4.2.2 6G requirements

The key areas of interest and investigation in this use case are the following:

- **Edge Computing Support:** 6G will natively support edge computing architectures, allowing for distributed data processing and storage, reducing the need to transfer data to centralised cloud servers and thus lowering latency and bandwidth usage.
- **Security and Privacy:** Enhanced security protocols and advanced encryption methods in 6G will provide robust protection for data processing at the edge, addressing privacy concerns, especially in farming, and ensuring secure communication.
- **Enhanced Energy Efficiency:** 6G networks are designed to be highly energy-efficient, which is essential for battery-operated or lower constrained edge devices and sustainable deployment of extensive IoT networks.
- **Ultra-low Latency:** 6G aims to achieve latencies as low as 1 millisecond, enabling real-time processing and decision-making at the edge, which is crucial for applications like autonomous vehicles that figure as part of this use case.

4.3 UC-EDU-1- XR rural school

4.3.1 Description and main objectives

The implementation of the project in two (-2-) rural schools in Romania aims to create captivating and interactive learning experiences that will help students improve their academic performance and reduce the discrepancies between students learning in rural and urban environments, respectively.

The support for this use case will essentially rely on ORO's networks' infrastructure. ORO will provide data connectivity through the commercially deployed network (5GSA) and access to a fully-fledged 5G/6G Experimentation Platform ("testbed") equipped with the latest generation of software and hardware solutions. The VR Caravan, operated from Iasi, Romania, and both rural schools will have the necessary coverage to ensure a good quality experience for students and teachers. Besides the necessary XR equipment, the schools will also receive tablet computers and laptops to support their teaching experiences to ensure appropriate access to the "Digitaliada" platform and content creation processes.

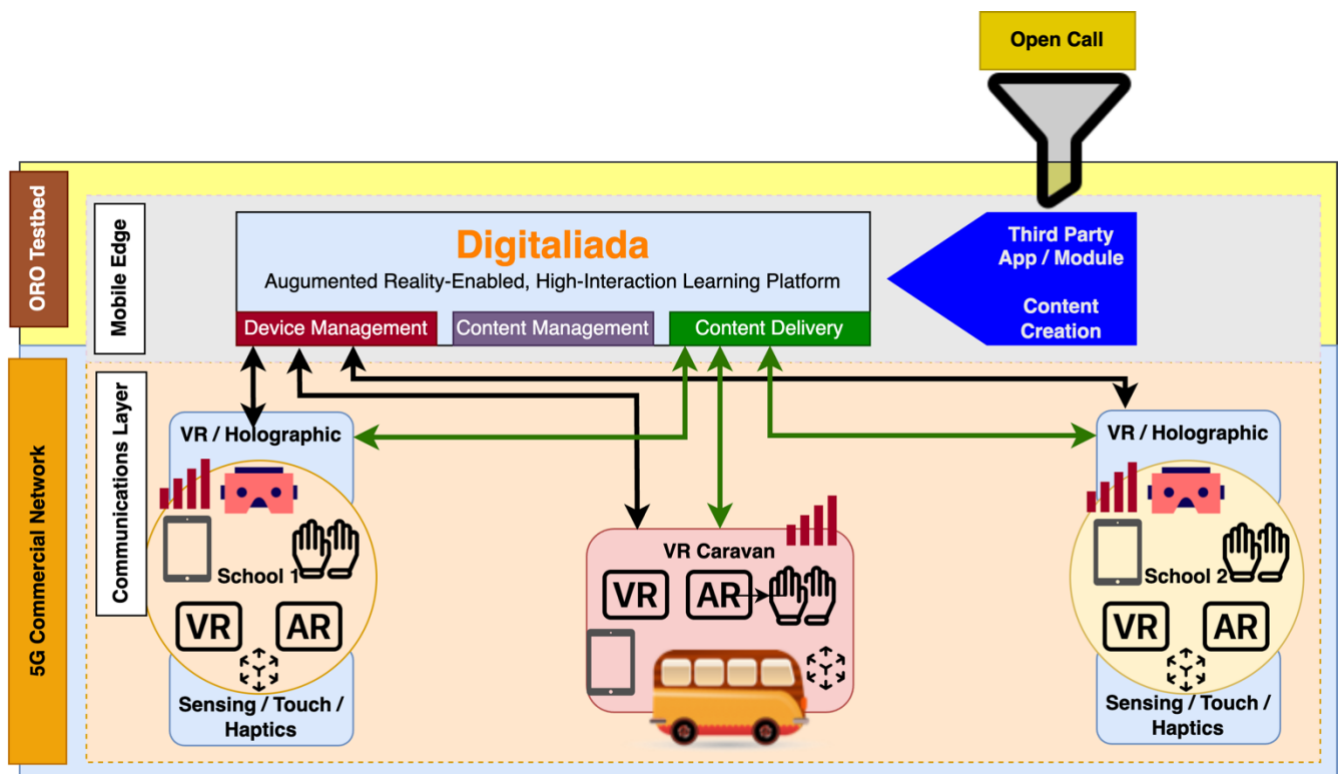


Figure 54. High Level Diagram of UC-EDU-1

This use case also considers the possibility of increasing the teaching experience and materials through the Track C of the Open Calls, where external entities may contribute to the development and integration of new content. The use case will also drive, together with the "Digitaliada" program, the necessary training so that teachers and other faculty staff can contribute. In short, the trials for this user case will include:

- **Interactive multimedia content:** A variety of multimedia resources, such as videos, animations and 3D models, allow students to explore learning subjects in a captivating and interactive way.
- **Personalised learning experiences:** The platform could be designed to adapt the learning experience to the knowledge level and skills of each student. This could help improve students' academic performance and contribute to reducing disparities between rural and urban students.

- **Use of VR/AR devices:** The platform will be compatible with a variety of virtual and augmented reality devices, such as VR glasses or AR-supported mobile phones, to allow students to experience learning subjects in a more practical and interactive way.
- **Collaboration and interaction:** The platform will allow students to collaborate and interact with each other and their teachers in a more innovative and engaging way.
- **Evaluation and monitoring:** The platform will be designed to allow teachers to evaluate students' performance and monitor their progress during the learning process. This could help identify areas for improvement and adapt the teaching material accordingly.

4.3.1.1 Motivation

In Romania, digital education remains a privilege, with nearly 38% of children under 16 and 37.5% of young people aged 16-24 at risk of poverty or social exclusion. This issue is particularly prevalent among those with lower educational attainment; Eurostat data shows that almost 55% of individuals with only a primary school education face poverty or social exclusion, with a notable concentration in rural areas.

Approximately 45% of Romania's children come from rural areas, and nearly 30% of them fail to achieve a passing grade on the National Evaluation. This prevents them from pursuing high school or university education. As a result, many of these children face limited employment opportunities, often relegated to low-paying, menial jobs or sectors that are at risk of disappearing due to robotisation, automation and machine learning advancements.

Studies from Oxford and the World Economic Forum (WEF) indicate that Information Technology (IT) and technology skills will be increasingly in demand. Research within the "Digitaliada" programme shows that a significant number of teachers are receptive to integrating new technologies and digital content into their classrooms, regardless of the school's technological level.

Our motivation for this use case is to harness this openness to enhance academic performance and address the technology adoption gap between urban and rural schools. Additionally, ORO and OROF are dedicated to advancing the use of technology in education and improving existing methods and processes through sustainable innovations such as beyond-5G networks and Extended Reality technology.

4.3.1.2 Key Pain Points

PP1: Low availability of XR-enabled educational content tailored to the Romanian primary and secondary education curriculum.

There is a lack of content being developed and distributed, mapped to the National curriculum for primary and secondary schools. While technological advances are steadfastly making XR available to many new regions in rural areas, the content availability is lagging. This Pain Point should be addressed in 6G-PATH through the Open Calls for developers to construct XR-enabled platforms and services that allow content to be adapted to XR-world.

PP2: Low availability of equipment and IT resources in the rural schools of Romania.

The rural areas of Romania lack the funding and infrastructure required to adopt significant IT resources, including equipment, to enable the utilisation of XR/VR/AR technologies. We aim to address this Pain Point, in 6G-PATH, by acquiring and deploying a functional set-up of portable computers – laptops, tablet computers and XR-enabled interfaces – VR headsets, actuators and control surfaces/control devices – to two (-2-) rural schools and one (-1-) mobile "VR Caravan", to pilot the usage of beyond-5G-enabled technologies in Education.

PP3: Low adaptation of XR-enabled technologies in Education in the rural schools of Romania.

We aim to address this pain point, in 6G-PATH, through “teach the teacher” engagement, co-ordinated by OROF through the “Digitaliada” platform, to enable easy and replicable adaptation of their teaching tools and methods, to the usage of XR-enabled content.

4.3.1.3 Scenarios Description

UC-EDU-1 relies on 2 distinct scenarios of implementing immersive education to 2 target rural schools and the deployment of a similarly equipped “VR Caravan”.

Both scenarios will leverage the utilisation of ORO’s beyond-5G capabilities, in the 5G Lab testbeds, and extending to ORO’s commercial networks and will enable OROF and ORO to deploy “Digitaliada”, the educational platform developed by OROF through the 6G-PATH experimentation framework.

“Digitaliada” will be deployed as a Network-aware application, with components and services in the ORO 5GSA EDGE, and will be improved with additional capabilities including:

- 5G readiness.
- XR-class devices management.
- XR content management.
- 5G-enabled content delivery.

Furthermore, Third-party Network Applications will be able to interact with “Digitaliada” to enable the creation of, and deployment of XR content such as interactive and personalised learning experiences and simulations. The 6G-PATH open calls will support the selection and integration activities for these third-party Network applications.

During the Testbeds Upgrades and Extensions phase, ORO’s testbed will be updated to support the functional and operational requirements of UC-EDU-1, and to enable integration with the 6G-PATH platform’s components.

During the integration phase of the two scenarios, the various 6G-PATH components will be deployed to ORO’s Testbeds (4.3.1.6) and tested for inter-operability with the 5GC and EDGE components of ORO’s testbed.

During the internal trials and pilots for the Education Vertical, the principal activities targeting the two scenarios of UC-EDU-1 will be:

- **Composition of ORO’s testbed and UC-EDU-1 to the 6G-PATH Platform** – this activity will make use of several Experimentation Enabling Components to onboard the required assets of the UC components.
- **Deployment of the UC components to the 6G-PATH platform** – this activity will encompass the creation the Use-Cases Repository assets for UC-EDU-1, such as the Use-Case images for the Network Applications to be deployed – “Digitaliada” and third-party applications through the 6G-PATH Open Calls.
- **Testing and validation of UC-EDU-1** – this activity will fall forward to the two test cases (“scenarios”) to validate the overall use-case ambitions and expected outcomes, supported through the KPIs and KVI to be collected during the piloting.

4.3.1.4 Scenario A – “XR in rural schools”

This scenario targets the deployment of an XR-enabled platform to two primary schools in rural areas of Romania. The two schools will be selected through an internal evaluation process by OROF, building on their demonstrable experience in working with primary education institutions on various projects and opportunities.

The principal actors in this scenario will be:

- **Testbed Operators:** They will interact with the 6G-PATH platform to deploy the UC components, select the KPIs and metrics for monitoring, choose the testbed features required for the piloting, and initiate the piloting of Scenario 1.
- **End-Users 1:** A selected group of teachers from the two schools will use “Digitaliada” to select and deploy XR-enabled content according to End-Users 2’s schedule and create interactive learning experiences and simulations from pre-defined primitives.
- **End-Users 2:** Primary school pupils in the two selected schools will use “Digitaliada” through XR-enabled interactions with user equipment deployed in the schools.

The pre-requisites for running Scenario A are:

- The 6G-PATH platform and its components are available and integrated with ORO’s Testbed Infrastructure.
- The 6G-PATH open calls have resulted in at least one (-1-) successful integration of a third-party application with “Digitaliada”, enabling end-users to create and manage XR-rich content from existing primitives.
- XR-enabled user equipment, such as VR headsets, touch-based interactive surfaces, and controllers, are integrated and managed through “Digitaliada”.
- 5GSA connectivity is available at the two schools involved in Scenario A.
- End-users have received the required training to operate the testbed interfaces and the “Digitaliada” platform.

4.3.1.5 Scenario B – “XR Caravan”

This second scenario targets the deployment of an XR-enabled platform to a purpose-equipped vehicle (a caravan-class automobile) which will travel between rural areas near Iași, Romania, supporting the dissemination of XR-enabled learning to teachers and students in these areas. The primary aim of this scenario is to demonstrate the mobility capabilities and features of the 6G-PATH platform.

The principal actors of this scenario will be:

- **Testbed Operators:** They will interact with the 6G-PATH platform to deploy the UC components, select the KPIs and metrics for monitoring, choose the testbed features required for the piloting, and initiate the piloting of Scenario 2.
- **End-Users 1:** A selected group of teachers will use “Digitaliada” to select and deploy XR-enabled content to a demonstration setup available in the XR-Caravan.
- **End-Users 2:** Primary school students and pupils will interact with the XR-enabled platform, “Digitaliada”, during the caravan’s visits to their localities.

The pre-requisites for running Scenario B are:

- The 6G-PATH platform and its components are available and integrated with ORO’s Testbed Infrastructure.
- The 6G-PATH open calls have resulted in at least one successful integration of a third-party application with “Digitaliada”, enabling end-users to create and manage XR-rich content from existing primitives.
- XR-enabled user equipment, such as VR headsets, touch-based interactive surfaces, and controllers, is integrated and managed through “Digitaliada”. These are available and ready for use in the caravan and supported by the vehicle’s electronics.

- 5GSA connectivity is available in the areas through which the caravan will travel.
- End-users have received the required training to operate the testbed interfaces and the “Digitaliada” platform.

4.3.1.6 Key Components and High-Level Topology

Integration within the scope of EC-EDU-1 will occur in three distinct domains: the 6G-PATH Platform, ORO testbed infrastructure, and the ORO 5GSA MEC deployment (and, if available at runtime, the 5GSA Commercial MEC deployment).

The 6G-PATH platform and its components should be deployed in ORO’s testbed to support experimentation for third-party apps selected in the Open Calls process and should support the feature set chosen by the third-party application developer/experimenter.

The **6G-PATH platform** should consist of all components required for running experiments across the testbeds, including all interfaces, frontend/backend services, and applications. It should be available in instances deployed to the experimentation testbeds. During the project’s lifecycle, the 6G-PATH project consortium will support the deployment of components to target testbeds and/or to a centralised platform interfacing with the federated components in the testbeds.

The **ORO Testbed facility** is located at the University POLITEHNICA of Bucharest within the "5G Lab" and is remotely extended to the 5G Lab in Iași, a major city in the North-Eastern region of Romania. It features a complete 5G SA infrastructure compliant with 3GPP Release 16, as illustrated below:

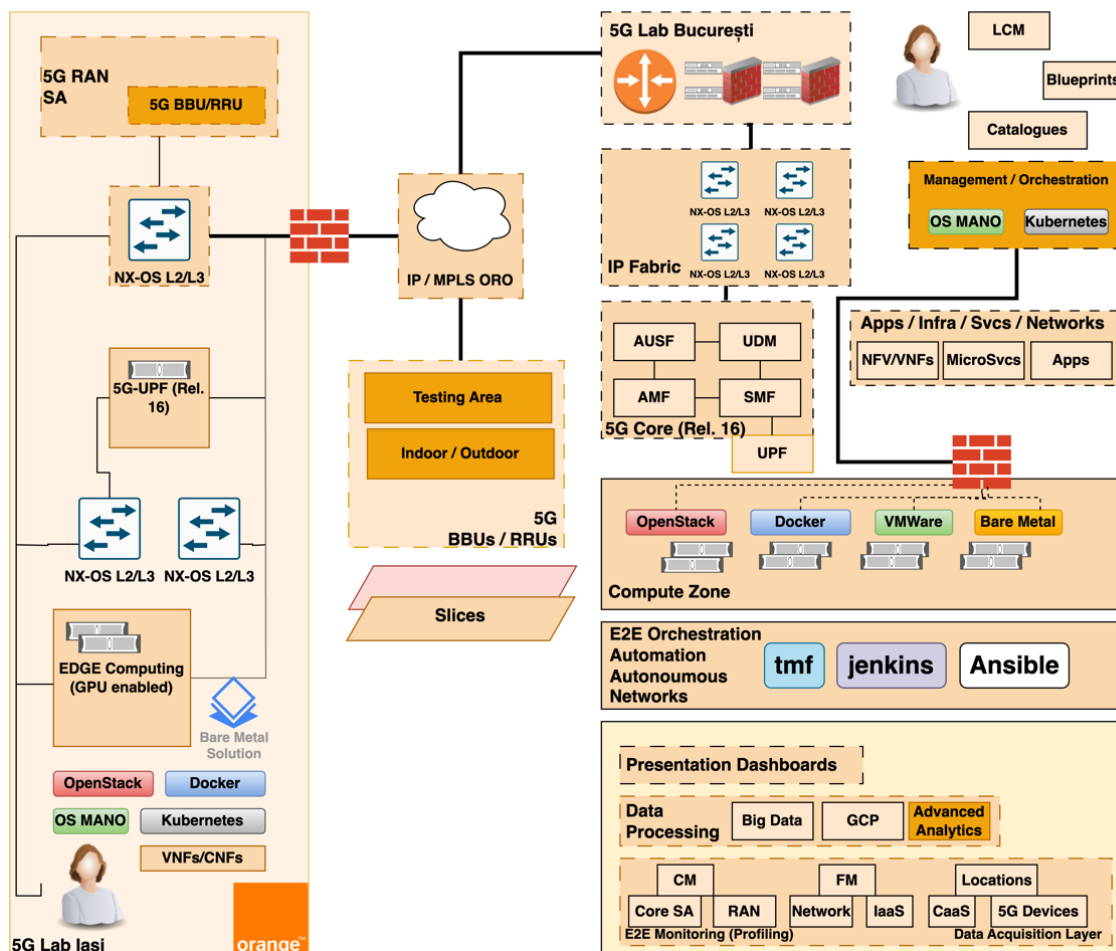


Figure 55. Orange 5G/6G Experimentation Platform

The testbed infrastructure comprises a range of software and hardware components, including open-source tools, integrated into a comprehensive end-to-end functionality scenario. It features state-of-the-art (SotA) software and hardware solutions for 5G SA RAN and 5G Core elements, including but not limited to AMF, SMF, UPF, NSSF and NRF. The testbed also incorporates an advanced programmable network solution based on next-generation Data Centre IPFABRIC concepts.

Additionally, it employs MANO functions (OSMv12/13) for orchestrating OpenStack clusters (controllers, deployment servers, shared storage, and computing servers) or Kubernetes clusters (master nodes and workers) as part of a Cloud Native infrastructure. Security functions are also integrated, including Fortinet 1000D Firewalls and BIG-IP F5 Load Balancers. These components enable the secure implementation and monitoring of various applications, services, and multi-domain or multi-federation testbeds and architectures.

The testbed also offers substantial computing resources, including 12TB of RAM, 1000 vCPUs, 48TB of RAID 1 storage, high-speed network interfaces (10/25Gbps), GPUs, and external storage. Various virtualised functions, such as VNFs or CNFs (VMS or CNs), can be instantiated through orchestration. The testbed ensures the orchestration of network functions, dynamic slice implementation for end-customers, and **5G SA network services that are dynamically connected to EDGE computing**.

The 5G LAB functionality in Bucharest extends to the 5G LAB in Iași, with both infrastructures interconnected through high-speed broadband (100Gbps interfaces). They share a similar technical approach and features regarding 5G SA network capabilities, computing, monitoring, orchestration, and analytics functionality, paving the way for Compute Continuum.

The system also provides network slice capabilities, such as eMBB (1500Mbps/150Mbps DL/UL) or URLLC <3ms one-way delay (average 5ms end-to-end RTT from device to EDGE). The 5G SA spectrum available for the experiments and tests is up to 100MHz in N78 bands, with different radio CA for DL and UL being also available, based on 3GPP carrier aggregation characteristics for improved performance. The ORO testbed has integrated a series of 5G devices and hardware components, as for example Cradlepoint R1900, Siemens MUM856, Quectel RM500Q-GL, Inhand ER805, Nokia FastMile 5G. The setup is suitable use-cases requiring intensive high-capacity transmissions (VR/AR, Digital Twin, V2X, etc.) and experimentation is available in indoor, outdoor and mobile scenarios.

The high-level process for each experimenter, either internal to the project (OROF, as a champion of UC-EDU-1) or external, coming from the Open Calls should permit the experimenter to interact via the 6G-PATH platform's frontend to access the experimentation dashboards which, in turn will allow them to select assets from the composition repositories:

- Testbed features, Topology features will determine the target testbed for the desired experimentation activity.
- Metrics and KPIs features which will determine the baseline and benchmark characteristics for the desired experimentation measurement of outcomes.
- Use-Cases Composition features to determine the overall scope and main flows of the experimentation.
- Control the experimentation lifecycle to start or stop the experiment main flows.

A high-level depiction of the overall Use-Case Topology is presented in the diagram below:

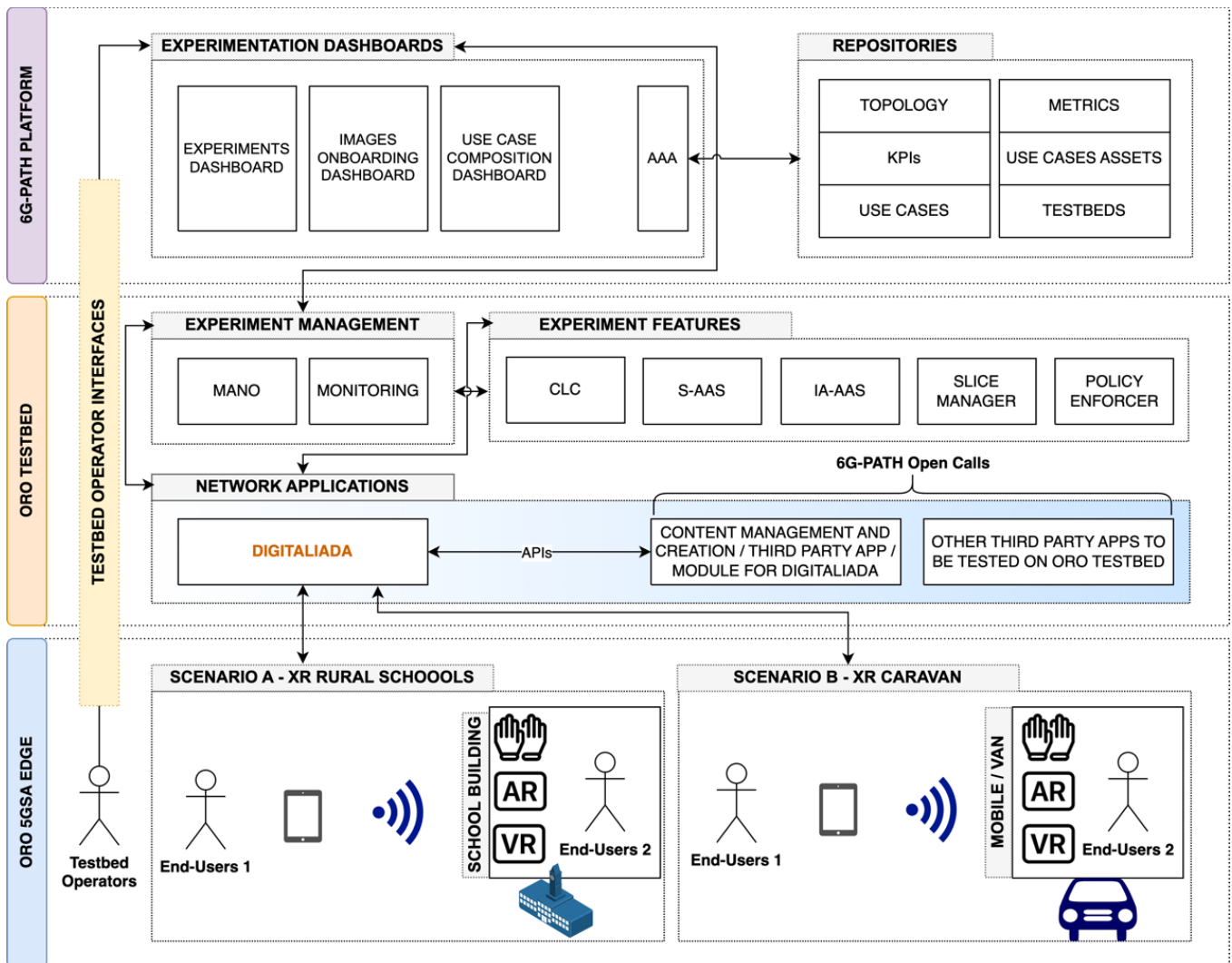


Figure 56. High-Level Architecture and Topology Diagram for UC-EDU-1

4.3.2 6G requirements

4.3.2.1 Functional Requirements

Table 17. Use Case functional requirements

FR	Title	Description
FR1	Beyond-5G Network Connectivity	Availability of 5GSA network infrastructure, offering connectivity in the geographical areas where the rural schools are localised.
FR2	Availability of third-party 'XR' apps	Availability of Third-Party Apps to develop XR-enabled content, from existing curriculum Integration of Device Management functionality for the XR devices, into the "Digitaliada" Platform or as a third-party Application running in the EDGE.
FR3	Availability of XR-enabled equipment	XR-enabled equipment includes VR-headsets, control surfaces and interactive control devices, and the IT infrastructure required to support the operation of the equipment such as laptop computers, tablet computers, Wi-Fi Networks.

4.3.3 Performance Requirements

Table 18. Use Case performance requirements

PR	Title	Description
PR1	Ultra-high bandwidth	>50Gbps bandwidth available to the XR platform and UE
PR2	Ultra-low latency	<3ms available to UE XR devices
PR3	Near-zero Packet Loss	Minimal E2E packet loss

4.4 UC-EDU-2 - Classroom of Future

4.4.1 Description and main objectives

This use case in the UK aims to create a highly immersive and interactive teaching and learning environment, allowing students to experience high-quality educational content comparable to, and in some cases superior to, physical reality.

The implementation will utilise the experimental infrastructure at UWS. UWS will provide access to its customised 5G XR (VR/AR) platform, known as the UWS testbed, which is equipped with the necessary software and hardware solutions for this use case.

As wireless and mobile networking scenarios become increasingly complex in 5G and beyond networks, it is becoming more challenging for university lecturers to effectively explain intricate networking technologies, such as virtualisation, softwarisation, and multitenancy, within the computer networking discipline. Students have struggled to grasp these new concepts alongside traditional telecommunication infrastructure. Additionally, hybrid teaching and learning have become the norm in universities post-pandemic, necessitating innovative approaches to manage these new educational settings while maintaining high standards of higher education.

4.4.1.1 Key Pain Points

- Lack of XR-ready platform for teaching and learning in the 5G and beyond networking discipline.
- Lack of cutting-edge XR-enabled higher education materials for the computer networking curriculum.
- Lack of experience in applying XR-based classroom of the future, especially in hybrid module delivery settings.

UC-EDU-2 centres on a primary scenario involving the teaching and learning of complex 5G/6G virtualised, softwarised, and multitenant infrastructure.

The main actors of this scenario will be:

- **Testbed Operator** – the UWS team in this project will act as the Testbed Operator to manage the 6G-PATH platform to deploy, operate and maintain the UWS testbed and support users including third parties to access the testbed and on board the use cases.
- **Teaching staff as End-User** – the lecturers at UWS will help generate and deliver the required teaching and learning materials for this use case.
- **Students as End-Users** – university students at UWS will help test the use case deployed and provide feedback.

4.4.2 6G requirements

Table 19. Use Case functional requirements

FR	Title	Description
FR1	Reliable and higher performance (beyond) 5G RAN	Upgrade the testbed to have a more reliable and supportive RAN for the testing especially for 3 rd parties.
FR2	Edge computing	Edge computing is required to process the massive data and run the XR service applications closer to the students, reducing latency and improving the user experience.
FR3	XR infrastructure and UE	Achieve the essence of the vision presented in Figure 1 in terms of both network XR components and user XR equipment.
FR4	6G-PATH platform	Northbound and southbound components in the 6G-PATH reference architecture.

Table 20. Use Case performance requirements

PR	Title	Description
PR1	Ultra-high bandwidth	Perceived high bandwidth for the XR application
PR2	Ultra-low latency	Perceived low latency for the XR application
PR3	Ultra-low packet Loss	Minimal E2E packet loss

4.5 UC-EDU-3 - XR health training

4.5.1 Description and main objectives

The XR health training use case focuses on enhancing the training of prehospital nurses. Prehospital nurses must acquire a blend of cognitive and practical skills to effectively manage a wide range of medical emergencies. Practical training is a crucial part of their education and is typically obtained through two (-2-) methods: (i) working with manikins in simulated environments, and; (ii) supervised participation in real clinical prehospital care scenarios. This use case specifically targets the simulated scenario with manikins, which is the focus of the 6G-PATH experimentation.

Manikins replicate human anatomy and physiology, allowing learners to enhance their knowledge through lifelike situations. During manikin-based training, the instructor is usually situated in an adjacent room, providing voice responses and controlling certain reactions based on the students' actions. For example, the manikin's breathing may change when students move its head to clear its airways. The more realistic the scenarios simulated with manikins, the better the learning experience.

Within 6G-PATH, we propose relocating the manikin from its fixed classroom to locations that offer a more authentic medical scenario, such as inside an ambulance. This setup will enable the manikin to be remotely controlled, allowing prehospital nursing students to engage in remote simulated acute/ambulance scenarios in an immersive manner.

Implementing this scenario involves several components. The manikin will be placed at the simulated medical site, equipped with cameras for high-quality video and microphones/speakers for audio input and output. Control of the manikin will occur at a remote site. Additionally, rendering devices at a (possibly distributed) remote training site, such as audio-video peripherals (e.g., monitors or head-mounted displays), will be used by remote students to participate in the scenario immersively.

The main objectives of the use case include:

- Enhance health education by bringing improved realism into XR-based health training, to:
 - Allow more authentic simulated scenarios.
 - Improve the educational experience.
 - Increase the flexibility in the education.
- Demonstrate the benefits of B5G/6G and XR technologies in the context of health education.

4.5.2 6G requirements

The XR health training use case will be implemented in the CARL-W testbed at Karlstad University. To meet the low latency, reliability, and uplink capacity requirements of the use case, the implementation will leverage the B5G features of the testbed as follows:

- The medical site will be connected via the CARL-W 5G network. In the initial implementation, manikin control and audio will be transmitted over the high-priority slice, while video flows will use the default slice.
- To manage end-to-end latency and prevent any queuing delays, L4S (Low Latency, Low Loss Scalable) will be employed.
- Computing nodes, responsible for generating XR content by integrating multimodal inputs collected at the medical site and any additional non-real-time information, will utilise the CARL-W edge infrastructure. Additionally, the application server(s) that provide access to the XR content for students at the training site will also make use of this infrastructure.

A challenge in realising the use case will be integrating all necessary hardware and software components while ensuring optimal performance not just for individual elements, but end-to-end at the system level.

4.6 UC-HEALTH-1 - 3D hydrogel patches

4.6.1 Description and main objectives

The efficacy of wound therapy relies on the ability to identify and treat the underlying condition causing the wound, as well as on the accurate assessment of the wound itself. This is fundamental for providing appropriate and effective treatment tailored to the stage of the disease process. As the disease progresses, a dynamic approach to therapy is essential to address the evolving needs of the wound and to ensure optimal care.

Current technology limits the production of adequate image quality for telemedical "real-time" care. The criteria inherent in telemedical wound therapy require real-time transmission. To enable a valid assessment of the wound, a high-resolution, multimodal sensor approach is necessary. This includes assessing the wound environment, wound margins, and wound bed to determine the appropriate therapy and the timing for subsequent wound treatments.

Scenario:

A nursing professional visits multiple patients with chronic wounds throughout the day. At each patient's location, the nurse parks the vehicle in front of the patient's premises, transports the necessary medical equipment to the site and performs the wound treatment while using the network installed in the vehicle as a local radio network provider and relay to the hospital premises across multiple backhubs. With this system, the nurse can utilise wireless connectivity for various tasks and leverage the on-vehicle edge network, which includes its own storage, to meet specific privacy requirements. As the nurse moves between locations, continuous network coverage is not required. Instead, a small local network is deployed as needed.

This use case aims to validate and evaluate an innovative approach to providing enhanced patient care for individuals with chronic wounds requiring customised patches. It leverages a new 5G/6G-enabled medical service for remote areas, relying on nomadic micro-networks that offer reliable and secure connectivity around the patient when and where needed. The nurse will visit patients at home or in care facilities, bringing specialised devices for conducting accurate diagnostics, creating a stereo 3D model of the wound (high-resolution multidimensional observation data), printing tailored hydrogel patches, and teleconferencing. Expert personnel and doctors will support these operations via remote communication from the hospital to ensure proper handling of the equipment, diagnostics, and instructions for applying the required patches and treatments. The nomadic micro-network, deployed from the nurse's vehicle, will act as an extension of the hospital's campus network. It will be capable of sensing the local environment and selecting appropriate unused frequencies to avoid interfering with existing communications. Additionally, it will discover and select the most suitable backhaul (terrestrial or satellite) for interconnecting with the central hospital campus network.

Main objectives:

- Enhanced patient safety.
- Better decision making.
- Improved response times.
- Accurate wound scans and analysis with its characteristics (matching in diagnostics criteria as well as dimensions).
- Decrease of healing time and complication rate.
- Contribution to public health and societal well-being.
- Long term cost reduction by reducing the complication rate.

4.6.2 6G requirements

Table 21. 6G Requirements

Functional Requirements	The ubiquitous, reliable, and secure backhaul connectivity of edge-core networks to the headquarters across third-party networks.
	The development of a portable, energy-aware micro-edge network suitable to be added as an after-market device to a vehicle.
	Post-market integration of existing medical devices with a 6G mobile network to enable improved patient care.
	Capturing of medical and other sensor data at the medical site.
	Communication of multimodal data, including pictures and description of chronic wounds between the nurse and the other medical devices (3D camera and 3D bioprinter).
Security Requirements	Mutual authentication and authorisation of communication between the edge-core and the core network across third-party backhauls.
	Assigning a temporary user profile for authentication and authorisation to edge-core to maintain the active sessions during the backhaul handover.
	Due to the sensitivity of the data, end-to-end security of communications between the participants must be given.
	The right to privacy of the patients and the users of the system should be protected.
Performance Requirements	The connectivity between the UEs and the care should have a reliability of 5-nines and a 1% packet loss.

	The connectivity between the edge and the core network should not have interruptions larger than 1s (specifically due to the long duration of the establishment of the satellite link).
	It is essential that the connection has a high uplink capacity in order to facilitate the upload of high-definition images from the wounds.

4.7 UC-HEALTH-2 - Elderly monitoring

4.7.1 Description and main objectives

This use case aims to validate and evaluate an innovative approach to providing a higher level of elderly monitoring and care. It relies on 5G/6G-enabled networks to ensure continuous monitoring of elderly individuals through wearable devices and other non-invasive monitoring tools. These tools require real-time data analysis and processing to enhance elderly security and improve their quality of life. The real-time transmission of data collected by these devices, along with assistant features and guided workouts, is supported by advanced AI-powered data analysis. This enables sophisticated automatic pre- and post-diagnostics, as well as threat assessment, which can trigger immediate intervention by emergency responders or care providers. Furthermore, it enhances decision-making for healthcare providers by delivering better-informed data.

This use case aims to deploy an integrated monitoring tool in a set of controlled elderly populations with the following set of wearables, sensors, and devices:

- Smart watch with a multitude of sensors, advanced fall detection, a workout diary and training assistant, and a smart virtual assistant.
- Pain detection algorithm for smart wearable devices.
- Telehealth platform for regular teleconferencing between the elderly and their hospital doctors.

Scenario:

A patient is performing physical rehabilitation exercises at home using secure and reliable connectivity provided by their home network, based on 3GPP technologies. This network is securely connected via third-party backhauled to a central rehabilitation centre, where data is processed centrally.

The patient is monitored using a smartwatch and a 5G smartphone, both of which operate transparently whether the patient is at home or in a nursing home. A secure connection is established with the rehabilitation centre, where the collected data is analysed to detect if the patient has fallen, if their health condition has worsened, or if their risk of falling has increased.

Main objectives:

- Providing reliable and secure connectivity for the eHealth communication of the applications running on the 3D Sensor as well as the wearables.
- Enabling data transmission integrity for video file transmission as well as sensor data from the wearables.
- Multimodal analysis allows differentiating between physiologic and non-physiologic medical algorithms.
- Encouraging and improvement of mobility in older people.
- Improve the well-being and sense of security of elderly people through monitoring and detection of potentially critical conditions.

4.7.2 6G requirements

Table 22. 6G Requirements

Functional Requirements	A coordinated indoor-outdoor location service, enabling the continuous positioning of the elderly.
	Reliable high-bandwidth, low latency network connection for video transmissions.
	Edge video processing to reduce latency in generating alerts while reducing network traffic.
	Energy-efficient connections to improve battery life.
	Capturing of medical and other sensor data at the medical site.
Security Requirements	Encryption of location data to ensure user privacy.
	Secure video transmission, dealing with privacy constraints and obeying EU GDPR (General Data Protection Regulation).
	Due to the sensitivity of the data, end-to-end security of communications between the participants must be given.
	The right to privacy of the patients and the users of the system should be protected.
Performance Requirements	Low power consumption is required to ensure the device can stay operational for at least one day.
	The connection must have a low packet-loss to avoid interference in real-time streaming.

4.8 UC-CITIES-1 – Connected and sensing city

4.8.1 Description and main objectives

The scenario, depicted in the Figure 57, consists of vehicles (some of them being autonomous), from different types, people and sensors around, such as environment sensors and mobility sensors (video cameras, radars and Lidars as examples), all being connected and sending real-time information between the sensors, roads and the infrastructure. This overall scenario will be used, in a complemented approach, to the following sub-scenarios.

In a use case of high-distribution video on the move, we consider the scenario where people are travelling around while watching high-quality video. The video coding and video distribution services are proactively orchestrated in the new points of access of the people before they arrive, so no video disruption is foreseen. The data of the vehicles, people, of the mobility and network will give information on the prediction of both mobility and network quality, providing a prediction of the needs of the services, in terms of quality and location, to travel with their users.

In a use case of coordinated and controlled mobility, we consider the scenario where an autonomous vehicle is moving around with other vehicles, requiring several services in the infrastructure for dynamic object detection, data fusion and online maps with dynamic objects on the road. These services are distributed through the new locations of the vehicle for seamless autonomous driving services while on the move. In a similar way as in the previous sub-scenario, the data of the vehicles, people, of mobility and network will give information on the prediction of both mobility and network quality, providing a prediction of the needs of the autonomous mobility services, in terms of quality and location, to make sure that all will be ready while on the need when the autonomous vehicles arrive.

In the enhanced city service use case, AI is used to provide better services to citizens, such as detecting stolen cars, badly parked vehicles, car parked in the carriage way and control of shared areas to improve the quality of life in the urban spaces.

In a use case of digital twin, we merge real and simulated traffic in the roads to test traffic management scenarios and understand the impact of the increase and decrease of traffic, and the change of the road conditions, such as road blocking and lane direction change. Autonomous vehicles can also be integrated to test the automatic reaction of the vehicles to the changing conditions.



Figure 57. Scenario to detect potential collisions (top left); ATCLL smartlamp post (top right); Autonomous vehicle development platform (bottom left); and ATCLL digital twin application (bottom right)

4.8.2 6G requirements

To support this use case, most of the beyond-5G/6G capabilities of the ATCLL testbed will be utilised, including:

- Multi-technology communications (5G, ITS-G5, etc.).
- Sensors and edge computing.
- Mobility metadata and network utilisation metrics.
- Resource allocation and service migration with edge computing.
- Autonomous vehicles, and connected vehicles and people.
- UEs and wearable devices on pedestrians (Augmented Reality).
- Mobility and environment sensors on bikes and buses, through IoT.

4.9 UC-CITIES-2 – Automated logistics

4.9.1 Description and main objectives

The 6G-PATH Project aims to foster the development of new technologies supporting 6G, both in close collaboration with other 6G-IA projects and through the process of Open Calls to engage European companies developing innovations for B5G and 6G systems, as well as bringing new UCs and pilot sites to the ecosystem. Such UCs and their corresponding applications will create demanding requirements from the platforms, thus requiring proper validation through KPIs and KVIs.

The Smart Cities UC-Cities-2 – Automated logistics proposes to explore automated logistics processes, focuses on the use of Automated Guided Vehicles (AGVs) and aims to improve both the production process and employee safety. By designing an automated sorting process, the time required to organise the produced products during the last stage of the production process and before they are distributed is reduced. At the same time, the employees are disengaged from this process, avoiding the risk of injury during the transport of the produced items, especially if the products have a large volume and weight.

The key characteristics to be taken into consideration in this use case, and that require advanced 5G and B5G network features are:

- The ability to remotely control the AGV by a human operator. This requires a constant connection to the network, thus increased reliability, and availability of the network as well as high throughput since video streaming should be sent to the remote operator.
- The AGV sensors will detect other objects or people and estimate their distance to avoid accidents. In an industrial environment this means that a high device density must be supported.
- Route optimisation is useful as it will reduce the process time. For this purpose, heterogeneous data sources should be used, which will describe the appropriate location of the products, the current position of the AGV and its destination.

Monitoring of the network KPIs (throughput, latency, packet loss, jitter) will be implemented utilising specialised monitoring equipment.

4.9.2 6G requirements

The network KPI requirements will be achieved by exploring and testing the integration of large-scale extreme IoT-Edge- Cloud scenarios, based on the 5G SA testbed, which will be upgraded to support the UC's requirements.

In this context, beyond 5G and 6G networks play an important role, improving the performance of this solution.

4.10 UC-CITIES-3 – Security coordination

4.10.1 Description and main objectives

Police forces play an indispensable role in maintaining the safety and security of communities. Their responsibilities encompass enforcing laws, preserving public order, and actively contributing to crime reduction and quality of life improvement. Hence, in their daily operations, police officers undertake a diverse array of tasks, ranging from responding to emergency calls to conducting neighbourhood patrols to deter criminal activities.

One critical aspect of daily operations is emergency services communication, which involves dispatching emergency response teams to various locations. Emergency call centres receive calls from individual requiring immediate assistance or rescue, and the call taker must gather all relevant information before

dispatching the appropriate emergency services provider. This information includes the nature of the emergency, the location of the incident, and any other relevant details that can aid in the rescue or assistance efforts.

In our use case, we aim to investigate the utilisation of communication technologies (B5G, 6G) to assess and improve the performance and efficiency of security coordination in response to specific situations. Our objective is to enhance the coordination by implementing the following measures:

- **Secure communications:** Establishing secure and reliable communication channels for exchanging sensitive information and coordinating emergency responses, ensuring the protection of critical data.
- **Refined Geolocation:** Leveraging cutting-edge geolocation technologies to pinpoint the exact location of incidents with high precision, enabling faster and more accurate emergency response deployment.
- **Command and control tools:** Implementing situational awareness dashboards and real-time mapping information to provide a comprehension overview of ongoing incidents and facilitate effective decision-making resource allocation.

By integrating these advanced technologies and tools, we aim to enhance the coordination and efficiency of the first responders, ultimately improving their ability to respond to emergencies swiftly and effectively. Furthermore, these measures will contribute to fostering a stronger sense of trust and cooperation between the different first responders' forces and the communities they serve.

4.10.2 6G requirements

To reach the objectives, we need to describe the communication technology (namely 6G) we rely on in terms of requirements. We propose to describe them in the following:

- **Ubiquitous connectivity and coverage:** One of the primary requirements for 6G networks in supporting plenty of first responders' operations is to provide ubiquitous connectivity and coverage. This means ensuring seamless and reliable communication capabilities across diverse environments, including remote areas, underground locations and specifically disaster zones.
- **URLLC requirements:** with availability close to 100% even in challenging environments.
- **Low latency:** Mission critical applications necessitate end-to-end latency in the order of 1 ms.
- **High mobility support:** which consists of guaranteeing the connectivity to first responders, vehicles, drones, etc., at a high mobility.

5 Extensions and new features

5.1 ORO Testbed

ORO considers the following upgrade activities for the 6G-PATH project's duration. Multiple upgrade and extensions activities will be performed simultaneously and the status for implementation will be available in the reporting and deliverables of 6G-PATH.

Table 23. Timeline for the implementation of Upgrades and Extensions to ORO's testbed

ID	Upgrade / Extension	Due by (Project month)
EXT1	Extend 5G SA coverage to new locations to include the geographical areas of the Use-Case beneficiaries (the two rural schools)	M20
UPG1	E2E Network Slice definition for UC-EDU-1	M20
UPG2	gNBs and UPF implementation	M21
EXT2	Extend EDGE cluster to end-user's service deployment location for UC-EDU-1	M22
UPG3	New 5G XR device acquisition and validation for usage in the 6G Testbed	M16
UPG4	5G/6G network configuration and slice adaptation for UCs traffic requirements	M20
UPG5	APIs and Adaptors implementation for dynamic network configuration and services deployment	M22
EXT3	Interfaces definition, development and integration for the integration with the 6G-PATH Service Framework	M18
UPG6	Local EDGE/UPF and slice implementation, slice configuration	M22
UPG7	5G SBA with CP/UP separation and 5G slice deployment with EDGE support	M22
EXT4	6G-PATH network and services KPIs and data collection, and exposure to app layers (for 3 rd party experimenters)	M18
EXT5	E2E 6G-PATH assets / KERs (Key Exploitable Results) integration, testing and validation of functionality	M24

The timeline for implementation has been running since Month 4 of 6G-PATH (April 2024) and we expect confirmation of implementation by Month 24 of 6G-PATH (December 2025), enabling the onboarding and testing and experimentation activities in WP6.

5.2 UWS Testbed

UWS would like to consider the following potential upgrades and extensions for the 6G-PATH project's duration with estimated timelines, as listed below:

Table 24. Timeline for the implementation of Upgrades and Extensions to UWS's testbed

ID	Upgrade / Extension	Due by (Project month)
EXT1	Deploy ELCM	M10
EXT2	Deploy Portal	M10
EXT3	Deploy other architectural components defined in 6G-PATH architecture, upon their availability from the project	M11
UPG1	E2E Network Slice Manager upgrading	M11
UPG2	E2E Network Slice definition for the new UCs' traffic	M11

ID	Upgrade / Extension	Due by (Project month)
UPG3	Network infrastructure and service configuration for new UCs traffic requirements	M12
UPG4	E2E Network Slice control implementation for the new UCs' traffic	M12
UPG5	New XR device acquisition and validation	M16
EXT4	Interfaces definition, development and integration for the integration with the 6G-PATH Service Framework	M18
EXT5	6G-PATH network and services KPIs and data collection, and exposure to app layers (for 3 rd party experimenters)	M18
EXT6	E2E 6G-PATH assets / KERs integration, testing and validation of functionality	M24

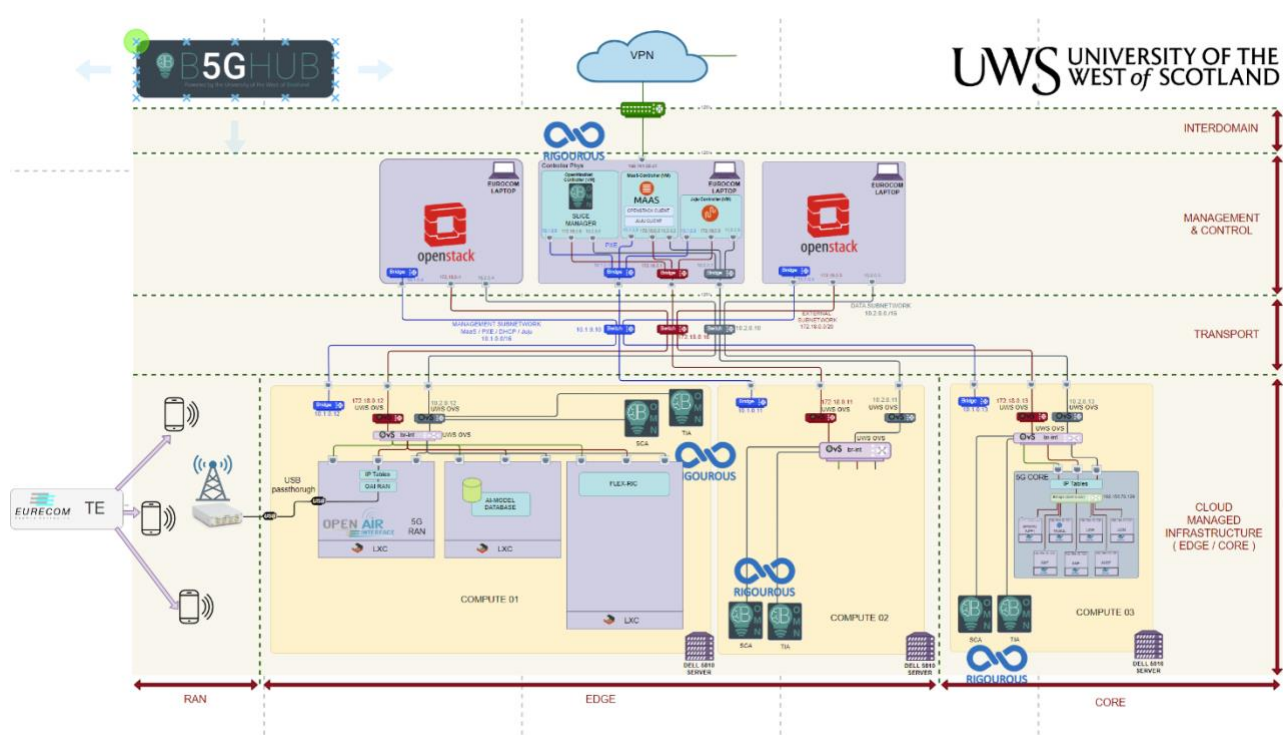


Figure 58. UWS B5GHub Testbed Envisioned with Advance 6G-Ready Features Deployed

5.3 FOKUS Testbed

We plan to perform the upgrade of the current infrastructure with an advance 6G-ready feature. To be concrete, the 6G-Ready End-to-End Network Slicing Feature is currently being developed under the Horizon Europe RIGOUROUS project. These capabilities will allow the exposure of an End-to-End network slicing API to allow users to create and delete slices dynamically and to dynamically attach network flows and devices into such network slices. The idea is to be able to warranty minimum bandwidth, limit the maximum bandwidth and provide strict priority control of the traffic.

Our intention is to be able to deploy such rigorous components so that the intended testbed we want to release for the final open call is depicted in **Error! Reference source not found.**, while the same testbed but without any advanced capabilities will be available for other open calls.

The infrastructure we have today exposed in the Open Call #1 is similar to the one indicated in Figure 27 but with an early functional prototype of the End-to-End Network slicing capabilities.

5.4 IT/ALB Testbed

IT considers the following upgrade activities for the 6G-PATH project's duration. Multiple upgrade and extension activities will be performed simultaneously and the status for implementation will be available in the reporting and deliverables of 6G-PATH.

Availability of new equipment and functionalities

- New servers in the datacentre, some of them with GPU (NVIDIA RTX 4000 ADA).
- Upgraded edge computing in the smart lampposts, using NVIDIA Jetson Orin Nano and Minisforum MS-01 edge servers (mini-ITX with NIC 4x 10G SFP+).
- 4 more USRP B210 and new 5 units of USRP E313 to extend the SDR RAN part to more testbed sites.
- Automotive Evaluation Kits for Software-defined Vehicles (NXP).
- CAN (Controller Area Network) Network simulator.
- More switches to the TSN testbed (Relyum).
- IoT sensors and satellite communication for bikes.

New areas for the city testbed and controlled environment for autonomous vehicles

The ATCLL testbed currently covers the following part of the city of Aveiro:



Figure 59. ATCLL map of the current infrastructure

In the following months, the testbed will be expanded to cover more areas, represented in the following map:

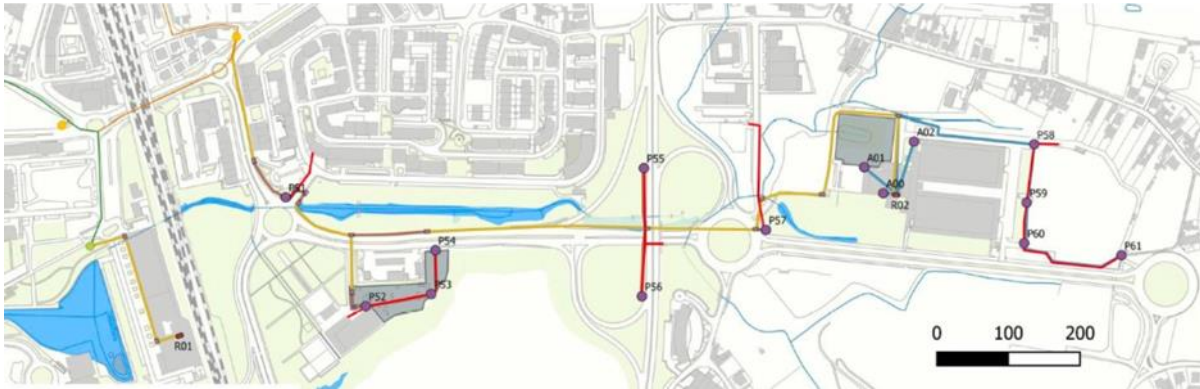


Figure 60. Map of the planned expansion

The area marked by smart lampposts P58 to P61 is a controlled zone, a closed park, designated exclusively for testing autonomous vehicles. This park is better visualised in the figure below.



Figure 61. Map providing a close look at the expansion of the ATCLL, featuring new smart lamp post locations and the optical fiber network

Similar to the rest of the infrastructure, the presence of smart lampposts in this area (equipped with sensors, edge computing, and various communication technologies) will support the development and demonstration of collective perception and planning for autonomous vehicles.

5.5 UMA Testbed

Extensions of relevance for the UMA testbed include:

- Sensors (with 5G integration).
- Agricultural machinery (with 5G integration).
- Robotic solutions ready to be integrated with 5G connectivity.
- Advanced solutions (software and hardware) for multispectral/hyperspectral images collection and analysis.
- Satellite solutions to be integrated into the 5G network available in La Mayora.
- Software and tools for AI as-a-Service (AlaaS).
- QoS/QoE measurement tools for automated measurement collections.

5.6 KAU Testbed

Extensions of relevance for the KAU testbed include:

- QoS/QoE measurement tools for automated measurement collections.
- Haptic devices (with 5G integration).
- Other software, tools and devices for immersive communication.
- Software and tools for AI as-a-Service (AlaaS).
- Software, tools and devices that target the 6G-PATH focus areas of Education, Health, Smart Cities and Smart Farming.
- Additional solutions for enhancing terrestrial and/or satellite connectivity (beyond the fixed 4G/5G dots and Starlink antenna already available as part of the testbed).
- Remote nodes/services that can be connected to the testbed to help build use cases within the 6G-PATH focus areas of Education, Health, Smart Cities and Smart Farming.
- HW/SW solutions for enabling joint sensing and communication (JCAS) experimentations.
- HW/SW solutions for enabling accurate user/device positioning in indoor environments.

5.7 OTE Testbed

The current infrastructure installed in the OTE testbed is planned to be upgraded to fulfil the requirements of 6G-PATH. More specifically, the upgrades planned are:

- Integration of an external monitoring tool to measure network KPIs, e.g., throughput, latency and packet loss. This involves installing probes at various points in the end-to-end infrastructure to monitor network performance both overall and segmentally.
- Extending the coverage outdoors with the installation of an additional gNB. As the use case includes the autonomous navigation of AGVs, it is considered necessary to increase the coverage so that there is sufficient space to implement applications such as the identification and avoidance of obstacles and the selection of the optimal route.
- Network upgrade to support Rel. 17 features. The current implementation uses Rel. 16, while the features of Rel. 17 are gradually implemented and become available for use. There is a plan to gradually integrate and test these new features to support more demanding services.
- The Slicing mechanism will be upgraded offering more features. Currently there is a process in progress to determine which new features will be implemented.

6 Data Management

The 6G-PATH consortium is firmly and fully dedicated to the principle of utilising open data possible, whenever such utilisation aligns with the practicalities and feasibility of the given context. However, this commitment to open data is linked with a firm respect for the privacy and protection of personal information, which is considered of paramount importance. In line with this core value, it is a fundamental expectation that any piece of information, regardless of its nature or origin, will be carefully withheld from public access and not be made available for general dissemination if it is determined that the release of such information could potentially compromise an individual's right to privacy, violate any existing confidentiality agreements, or introduce any kind of security risk or vulnerability, whether it be minor or major.

A diverse range of data will be collected to successfully fulfil the specific aims of the 6G-PATH project. Several project tasks and objectives necessitate data gathering, including:

- **Understanding End-User and Stakeholder Needs:** By comprehending the expectations, challenges, and requirements of end-users and stakeholders, the project can design and construct architectural components that are effectively tailored to real-world demands, rather than relying on assumptions.
- **Refining Components and Tools Based on Feedback:** Tracking and assessing how the core 6G-PATH components perform in various use cases, considering the perspectives of both stakeholders and technical partners, is crucial for developing the final versions of these components and tools.
- **Measuring Project Impact and Adjusting Strategy:** Tracking and assessing the outcomes of dissemination and communication efforts allows the project to gauge its impact, adapt its agenda as needed, and meet the reporting obligations set by the Commission.

Each piece of the collected data will be carefully catalogued with information on its characteristics, format, source, estimated size, storage location, intended use and potential for reuse. The following are only a few examples of the anticipated data types:

- **Pre-existing datasets:** Information that existed prior to the project and is being incorporated for analysis or reference.
- **Direct contributions:** Data provided by project partners or external stakeholders, such as survey responses, research findings, or technical specifications.
- **Data from usage scenarios:** Information gathered during real-world testing and implementation of the project's technologies, including performance metrics, user feedback, and operational data.
- **Workshop and collaboration data:** Notes, summaries, and recordings from workshops, meetings, and collaborative sessions with stakeholders.
- **Social media analytics:** Data gleaned from social platforms like LinkedIn profiles and website traffic to assess reach and engagement.
- **Public database information:** Data extracted from publicly available repositories for comparison or contextualisation.

This comprehensive categorisation ensures that data is organised and utilised effectively throughout the project, maximising its value for research, development and decision-making.