6G Vertical trials for Sustainability

Deliverable D3.1
Experimentation Environment - Initial

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0.3	4.12.2025	6G-VERSUS WP3/UMA	Edited version

[1] SEN = Sensitive, only members of the consortium (including the Commission Services). Limited under the conditions of the Grant Agreement

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Abstract

This deliverable presents the initial description of the six 6G-VERSUS testbeds and their associated experimentation tools at the start of the project. It details the technologies integrated across the overall platform and introduces the AI/ML framework, including its mapping to the individual testbed sites. The document also outlines the planned upgrades and developments foreseen during the project, in coordination with Task T2.4, WP4, and WP5. Finally, it reports on the current status of the testbeds by Month 12 (M12) with the final version delivered as part of D3.1.

Keywords

6G-VERSUS Experimentation environment; Testbeds; Integration; AI/ML framework.

Executive Summary

This deliverable provides an overview of the six 6G-VERSUS testbeds and their initial experimentation tools, describing the technological foundations and early developments of the overall 6G-VERSUS platform. It serves as the first comprehensive report on the setup, capabilities, and integration status of the sites at the beginning of the project, setting the baseline for future enhancements and interoperability across the consortium.

The document begins with an introduction that outlines the 6G-VERSUS project, the scope of the deliverable, its intended audience, its relation to project milestones and other deliverables, and the structure of the document. It then details the contributions from each partner site, Bulgaria, Finland, France, Greece, Portugal and Spain. It presents the initial configuration of testbeds, experimentation tools, and infrastructure available for early trials.

Subsequent sections describe the technologies and features to be integrated across the 6G-VERSUS platform, including advancements in the RAN, Core, APIs, cloud/edge infrastructure, devices, transport, energy-related systems and other features. It also states the current status and progress at the completion of this deliverable.

The deliverable also introduces the AI/ML framework, which is a structured collection of tools, components, and workflows designed to streamline and accelerate the adoption of machine learning, enabling the integration of intelligence into the diverse range of cluster scenarios with varying requirements.

In addition, marking one year of progress, D3.1 reports the first concrete steps taken across the project's Ambitions associated with the testbed evolutions and integrations performed in WP3. This deliverable provides the earliest consolidated view of how the experimentation environment is beginning to support the full set of innovations targeted in 6G-VERSUS.

Finally, the deliverable concludes with an overview of the integration activities and next steps planned under Task T3.3, paving the way for the next phase of testbed interconnection and platform consolidation within 6G-VERSUS.

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Acronyms and abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
4K	4K Resolution (Ultra HD)
5G CORE	Centralized 5G Core Network
5GTN	5G Test Network
6G	Sixth Generation (mobile network)
AAQD	Ambient Air Quality Directive
AAU	Active Antenna Unit
AF	Application Function
AGV	Autonomous Guided Vehicle
AI	Artificial Intelligence
AI-App	AI-driven Application
AI/ML	Artificial Intelligence and Machine Learning
AMF	Access and Mobility Management Function
API	Application Programming Interface
AUSF	Authentication Server Function
B5G	Beyond 5G
BBU	Baseband Unit
BESS	Battery Energy Storage Systems
BLER	Block Error Rate
BWP	Bandwidth Part (5G NR feature)
C2	Command and Control
CAM	Connected and Automated Mobility
CAMARA	Common API Framework by GSMA
CAPIF	Common API Framework
COTS	Commercial-of-the-shelf
CQI	Channel Quality Indicator
CU	Central Unit
CUPS	Control and User Plane Separation
DCS	Distributed Control System
DER	Distributed Energy Resources
DL	Downlink
DMS	Demand Side Management
DN	Data Network
DRX	Discontinuous Reception

DT	Digital Twin
BWP	Bandwidth Part
DT	Digital Twin
DTX	Discontinuous Transmission
DU	Distributed Unit
DUT	Device Under Test
EC	Electric Charging
eCPRI	enhanced Common Public Radio Interface
EEaaS	Energy Efficiency as a Service
EIR	Equipment Identity Register
eMBB	Enhanced Mobile Broadband
EMS	Element Management System
EPC	Evolved Packet Core
ESS	Energy Storage Systems
EV	Electric Vehicle
FAIR	Findable, Accessible, Interoperable, Reusable
FDD	Frequency Division Duplex
FHD	Full High Definition (video quality)
FIM	Finnish Meteorological Institute
FOTA	Firmware Over-The-Air
FUWIRI	Future Wireless Research Infrastructure
GbE	Gigabit Ethernet
GEO	Geostationary Orbit
gNB	Next Generation Node B (5G base station)
GPU	Graphics Processing Unit
HazMat	Hazardous Materials
HD	High Definition
KPI	Key Performance Indicator
KVI	Key Value Indicator
LAN	Local Area Network
LEO	Low Earth Orbit
LMF	Location Management Function
LoRa	Long Range Radio
LTE-M	LTE-Machine
MDI	Media Delivery Index
MEC	Multi-access Edge Computing
MIMO	Multiple Input Multiple Output

MOS	Mean Opinion Score
MPC	Mobile Packet Core
MPLS	Multi-Protocol Label Switching
MV	Medium Voltage
N-App	Network Application
N1-N6	3GPP Interfaces N1-N6
NB-IoT	Narrowband IoT
NEC	National Emission Reduction Commitments
NEF	Network Exposure Function
NetAct	Network and Element Management System by Nokia
NFV	Network Function Virtualization
NFVI	Network Functions Virtualization Infrastructure
NITRO GEO	Network performance monitoring platform by VIAVI
NMS	Network Management System
NR	New Radio
NRF	Network Repository Function
NSA	Non-Standalone (refers to 5G Core Deployment Mode)
NSSF	Network Slice Selection Function
NTN	Non-Terrestrial Network
NWDAF	Network Data Analytics Function
OAI	OpenAirInterface
OBU	On-Board Unit
OpenAIRE	Open Access Infrastructure for Research in Europe
OSS	Operations Support System
P4	Programming Protocol-Independent Packet Processors
PCF	Policy Control Function
PHR	Power Headroom Report
PMU	Phasor Measurement Units
PoC	Proof of Concept
PON	Passive Optical Network
pRRU	Passive Remote Radio Unit
PTP	Precision Time Protocol
PUSCH	Physical Uplink Shared Channel
PVs	Photovoltaics
QoE	Quality of Experience
QoS	Quality of Service
QoS-QPP	Quality of Service Priority and Pre-emption capabilities

RAEMIS	5G SA Core by Druid Software
RAN	Radio Access Network
RAT	Radio Access Technology
RCF	Research Council of Finland
RedCap	Reduced Capability
RES	Renewable Energy Sources
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
RLC	Radio Link Control
RoCoF	Rate of Change of Frequency
RRH	Remote Radio Head
RRU	Remote Radio Unit
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RU	Radio Unit
SA	Standalone (refers to 5G Core Deployment Mode)
SaR	Search and Rescue
SDG	Sustainable Development Goal
SDN	Software-Defined Networking
SEE	Service Exposure Enabler
SMF	Session Management Function
SMs	Service Models
SNS	Smart Networks and Services
srsRAN	Software Radio Systems RAN
srsUE	Software Radio Systems UE
TDD	Time Division Duplex
TR	Transmit/Receive
UAV	Unmanned Aerial Vehicle
UC	Use Case
UC1	Use Case 1 (Sewer network monitoring)
UC2	Use Case 2 (Smart watering in green spaces)
UDM	Unified Data Management
UDR	User Data Repository
UE	User Equipment
UERANSIM	Universal Emulator for RAN and UE Simulation
UFFS	Ultra-Fast Frequency Support
UL	Uplink

UMA	University of Málaga
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communication
USRP	Universal Software Radio Peripheral
UWT	Urban Wastewater Treatment
V-App	Vertical Application
VIAVI	VIAVI Solutions (monitoring tool vendor)
VNF	Virtual Network Function
VoLTE	Voice over LTE
VoNR	Voice over New Radio
VR	Virtual Reality
WAN	Wide Area Network
WP	Work Package
WT	Wind Turbines
WWTP	Waste Water Treatment Plant
xApps	Applications for RAN Intelligent Controller
XR	Extended Reality
xSIGHT	Real-time analytics platform by VIAVI
ZeroMQ	Messaging Library for High-performance Asynchronous Messaging

1 Introduction

One of the objectives of 6G-VERSUS is to further develop and enhance the involved sites by refining mature experimentation tools and technologies from previous initiatives, so they can more effectively and reliably support the project's envisioned use cases with a focus on sustainability. Each of these sites (namely Bulgaria, Finland, France, Greece, Portugal and Spain) is upgrading existing experimental 5G networks with state-of-the-art technologies to support a number of use cases with a common approach. Every application in the use cases is split into 3 main components to reflect the logic of the vertical application (v-app), the intelligence (AI app) and the network aspects (n-app).

In light of the above, this document is the first version of the description of the six 6G-VERSUS testbeds and their associated experimentation tools at the start of the project. Future deliverables of WP3 will update the description. This deliverable details the technologies integrated across the overall platform and introduces the AI/ML framework, including its mapping to the individual testbed sites. The document also outlines the planned upgrades and developments foreseen during the project, in coordination with WP2 and more specifically T2.4, WP4, and WP5. Finally, it reports on the current status of the testbeds, summarizing the progress achieved by Month 12 (M12).

1.1 Project Overview

1.1.1 Overview of 6G-VERSUS sites and use cases

6G-VERSUS project is organized into six distinct 6G pilots and in turn these trials are organized into 6 clusters aligned with different vertical sectors and corresponding use cases aiming to validate applications that exploit beyond 5G network features. The use cases covered by the whole project include energy distribution network, energy efficiency, precision agriculture, port operation and collaborative robotics for Search and Rescue activities. Figure 1 summarizes the testbeds used by each cluster in Bulgaria, Finland, France, Greece, Portugal and Spain, with all of them serving as a starting point for the planned development activities The testbeds are expanded following the need of the applications and the common architecture reported in Deliverable 2.2.

Figure 1. 6G-VERSUS testbeds.

1.1.2 Overview of 6G-VERSUS reference architecture

The 6G-VERSUS reference architecture[2] poses a layered and modular framework, designed to transform conventional use cases into 6G applications and native services while embedding programmability, AI-driven intelligence, and energy efficiency aspects. The notion of reference architecture in this context denotes a common baseline that provides architectural coherence across the project, while still allowing each testbed to

[2] The reader may refer to Section 2 in deliverable D2.1 [6GVERD21] for a more detailed description of the reference architecture.

adapt the framework to the specific requirements of its local use cases. This ensures consistency among both the testbeds and the clusters, while maintaining the flexibility needed for diverse deployments, vertical demands, and operational conditions for each use case.

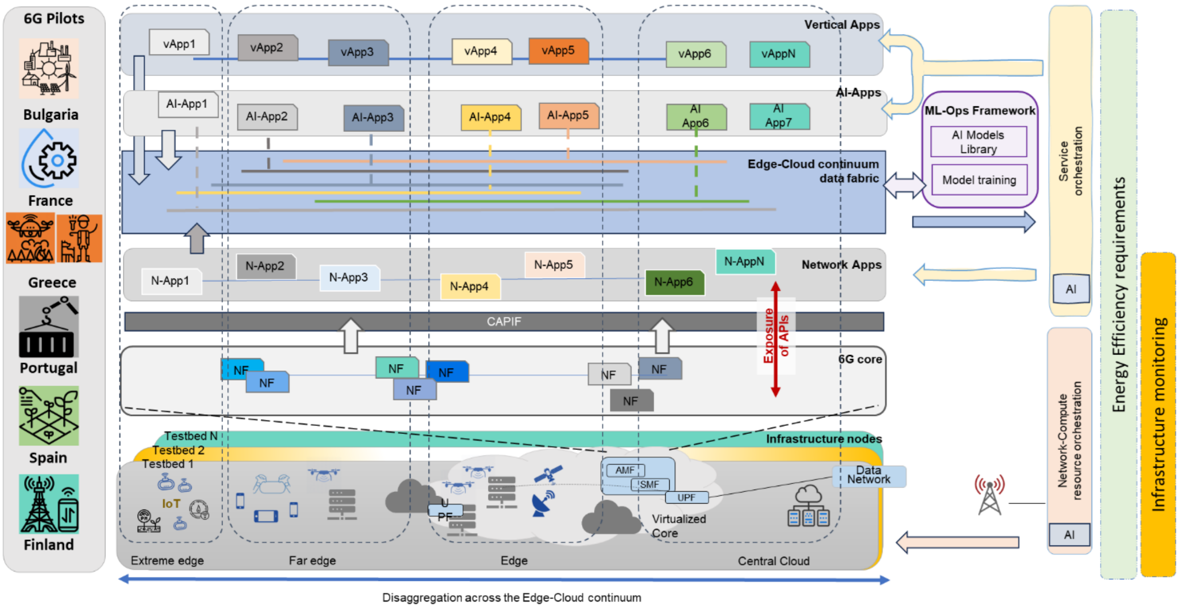

Figure 2. 6G-VERSUS High-level reference architecture.

The architecture – portrayed in Figure 2–promotes modularity and interoperability across layers, supporting intent-based operations where verticals specify objectives such as energy efficiency or latency thresholds and the system dynamically reconfigures resources to meet them. These operations span multiple components of the system, including the AI-apps, and the MLOps framework responsible for continuous model training, validation, and deployment of dedicated models. Together, in certain use cases targeted by the project, they allow the network to interpret intents, translate them into actionable policies, and dynamically reconfigure network and compute resources to meet the specified objectives. At this overview level, the architecture is described in terms of its principal layers and cross-cutting functions, rather than implementation details. At the top, a triad of applications defines the service logic and control flow: the Vertical Application (V-App) encapsulating service functions, the Network Application (N-App) managing connectivity and orchestration, and the AI Application (AI-App) providing context-aware inference and intelligence. These are supported by the Core Network, which enables programmable interaction with network and compute resources, and the Infrastructure Layer, comprising the physical testbeds, devices, and distributed compute and network assets.

Spanning horizontally, the Data Fabric and Intelligence Layer provide data collection, harmonization, and ML-Ops-enabled model lifecycle management. Together with the Service Orchestration and Network/Compute Orchestration domains, this ensures predictive, adaptive, and efficient allocation of resources across the continuum. Edge computing tiers—central edge, far edge, and extreme edge—are explicitly recognized, enabling functions to be placed at the most suitable point for latency, privacy, or resilience.

In summary, the 6G-VERSUS reference architecture offers a unified yet adaptable framework that supports the design and validation of 6G-native services across heterogeneous testbeds, ensuring sustainability, resilience, and interoperability as guiding principles.

1.2 Scope and Intended Audience

This deliverable defines the initial experimentation environment to run all the use cases in the project and outlines the progress in the ambitions, targeting project partners across different use cases and pilots, technical contributors and stakeholders involved in the design, implementation, and validation of 6G-VERSUS technologies.

1.3 Relation to milestones and other deliverables

This Deliverable reports the main activities carried out in WP3 to date and serves as the primary reference for certifying the achievement of Milestone 6 ("Testbeds description and upgrades & extension roadmap") and Milestone 7 ("First version of the experimentation environment integrated with the testbeds"), in full alignment with D2.1, *"Platform architecture and use case requirements – Initial"* [6GVERD21]. Moreover, after one year since the start of 6G-VERSUS, the project has already taken important first steps across its core Ambitions, which are reported in Section 6; although these Ambitions span multiple work packages, their early progress is reported here in D3.1, as the project has now moved beyond the initial planning phase and because WP3 directly addresses the evolution and integration of the testbeds, which in practice are tightly coupled with the implementation of the Ambitions.

1.4 Structure of the Document

The deliverable is organized in 7 sections, including this introduction. Section 2 provides a description of the state of the testbeds at the beginning of the project in order to have the baseline to report upgrades. Section 3 describes the specific customization and configuration of the advanced 5G technologies to be added at project level, organised as subsections per domain. Sections 4 and 5 are organised per site in order to report the status of the upgrades and the next steps, respectively. Section 6 reports the status of the 6G-VERSUS ambitions, which are mainly connected to the work in WP3. Finally, we provide some conclusions.

2 Initial status of the testbeds and experimentation tools

This section provides a detailed, uniformly structured overview of each platform, combining both the infrastructure and the software tools to support experiments and trials. It includes a diagram and a description of the current technology and topology status. By presenting this information, the section offers a comprehensive understanding of the current status of each platform that will be complemented by the anticipated developments required to enhance their functionalities and contribute to the overall objectives of the 6G-VERSUS

2.1 Bulgaria

The Bulgarian platform (Figure 3), operated by A1, applies 3GPP Release 17 functionalities. The technical elements (overall network topology connected with Radio Access Network (RAN) and backhaul and data monitoring process) of the testbed are provided below.

A1's 5G SA network infrastructure integrates Nokia RAN and Ericsson Packet Core, leveraging the Control and User Plane Separation (CUPS) architecture for flexible scaling of the User Plane and dedicated deployment for specific use cases. The network undergoes continuous upgrades to accommodate evolving 5G capabilities and address diverse use cases effectively, including the use-case for the smart grid vertical of 6G-VERSUS.

The core architecture, presented in Figure 3, describes the Ericsson dual-mode 5G Core combines 3GPP network functions from EPC and 5GC architectures into a common cloud-native software platform to support 5G NR SA and NSA, 4G, 3G, and 2G access technologies. The dual mode 5G Core is managed as a single solution and is deployed and operated as a state-of-art cloud-native implementation. The core architecture includes various network functions such as AUSF, AMF, DN, NEF, NRF, PCF, SMF, UDM, UDR, UPF, and AF, facilitating secure exposure of 3GPP network services and capabilities through unified APIs. Additionally, the Service Exposure Enabler (SEE) enables centralized API exposure, empowering operators to monetize telco capabilities to third-party service providers programmatically. As part of the 6G-VERSUS project A1 will implement CAPIF API solution to enable API Providers like the Network Function NEF to expose their Northbound APIs to API Invokers by a unified and standardized approach.

The reference (Lab) networks (located in Sofia and Varna towns) from A1 are available for use in the implementation of the project's use cases.

In the context of 6G-VERSUS, the Bulgarian testbed will explore various approaches to enhance the existing core network capabilities. The goal is to support the creation of private network slices specifically designed for smart grid vertical services. These private slices would provide dedicated, isolated network resources tailored to the unique performance, security, and reliability requirements of smart grid applications—such as monitoring and control of distributed energy resources. By investigating different technical options, A1 aims to determine the most effective way to deliver flexible and secure connectivity solutions for critical smart grid operations through network slicing

In the RAN segment, 5G New Radio (NR) operates across Frequency Division Duplex (FDD)/Time Division Duplex (TDD), with frequency bands below 6 GHz and mmWave bands, supporting various antenna configurations (8TR/32TR/64TR) and multi-RAT connectivity for sub-6GHz bands. Lab Cloud RAN and RAN Intelligent Controller (RIC) solutions have been deployed for energy optimization and interference detection, and are managed within data center platforms, however they are not included within the scope of the current project. An IP/MPLS backhaul network ensures end-to-end transport from RAN/gNBs to the Mobile Packet Core (MPC), facilitating low-latency, secure, and guaranteed network resources through end-to-end network slicing, tailored to serve enterprise customers effectively.

The data collection and monitoring tools used in Bulgarian testbed are VIAVI NITRO GEO platform, Nokia's NetAct platform and VIAVI xSight platform. The first system supports multiple generations of mobile technologies from A1 Nokia RAN vendor, providing continuous monitoring and analysis of network events. Nokia's NetAct platform serves as both a network management and element management system, offering comprehensive operation and maintenance capabilities for core, radio, and transport networks. Additionally, the xSIGHT real-time intelligence platform offers advanced analytics capabilities to capture and analyze relationships between customers, applications, services, and networks in real-time. Amdocs' Helix

Performance Management platform is used for monitoring, optimization and troubleshooting of network and service performance. It collects and processes data for use in performance reporting and resource planning in all network domains (Radio, Core and Transport) helping to increase and enhances the performance. TEMS™ Investigation is a drive testing solution, used by A1BG for initial tuning, 5G site acceptance, software upgrade verification, new feature validation, network troubleshooting and more. TEMS Investigation provides a complete set of predefined test sequences to simplify on-site tests. It supports multiple devices, all network technologies, and the ability to use scanners for detailed RF measurements to meet field test needs. Post-processing and analytics are performed by TEMS™ Discovery, which is a comprehensive network analytics and optimization solution based on mobile network testing data. It provides unparalleled insights into network performance as perceived by subscribers at the device, application, and network level.

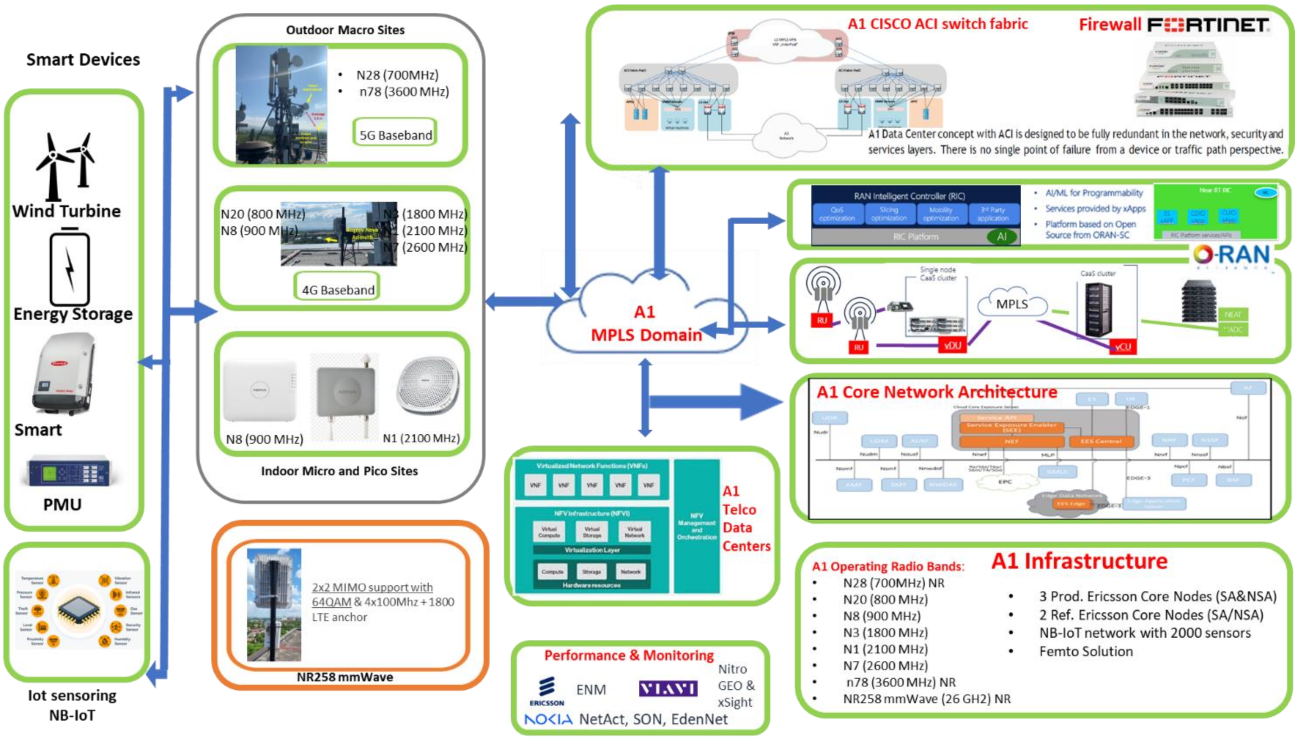

Figure 3. Architecture of the Bulgarian testbed (A1 commercial extended infrastructure)

2.2 Finland

The 5G test network (5GTN) platform, operated by UOULU, and used in 6G-VERSUS is also an enabler for example for the 6G-XR [6GXR] 6G-SANDBOX [6GSBOX], CONVERGE [CONVERGE] and SUNRISE-6G [SUNRISE6G] projects. It is compatible with 3GPP Release 15 and Release 16, and O-RAN functionalities coexist in the testbed too. This platform is at University of Oulu, Finland and its technical elements are enablers for the Finnish Cluster use case (Figure 4).

UOULU 5GTN supports frequency bands up to 6 GHz, cognitive management functionalities and system testing tools for new solutions. This follows 6G research and standardization progress, acting as verification platform for theoretical and applied 6G research. The cellular devices part of the network is composed of 20 5G small cells (3.5, 4.0 GHz) and 6 macro cells (3.5, 4.0 GHz), and mmW cell (26 GHz). The network is complemented with tens of different types of User Equipment (UE) that are easily integrated to any device. 5GTN IP network has been upgraded during the last year. The speed of the core of the network has now increased to 100 Gbps. Most critical functions are now connected using the 100 Gbps connections. Next tier has 40 Gbps connection and the individual devices at the outer rim of the network do have 10 Gbps connections.

There are several different 5G Cores in use: Nokia, Cumucore and Open5GS for the indoor and outdoor 5G networks. There is also CN5G core that is used in OAIBOXes [OAIBOX]. Several 5G networks are operational atthe same time, usually around 10 networks are active using different 5G Cores. Nokia cloud core is used in both indoor and outdoor networks as is the Cumucore and Open5GS. CN5G in OAIBOXes and O-RANs are used only indoors. 5GTN currently uses only SA mode and NSA is not in everyday use, but if there is a need for NSA network it can be established. All networks are 3GPP compliant except that the OAIBOX has also 3 O-RAN systems active with Split8.0 and with Split7.2 with FR1 and FR2 capability for the RU. Supported radio units include several USRP b210s, n310s and X410s + Benetel FR1 And LiteON FR2 RUs.

5GTN offers several high-capacity servers for researchers and experimenters. Both bare metal and virtualized environments are available. These servers, like the rest of the 5GTN, can be remotely used through a VPN connection that can be applied for individual users. GPU acceleration is available.

Network uses bands n78 and n77 for the 5G services. Bandwidth in the n78 is 50 MHz and 10 MHz has been reserved for RedCap. In n77 there is 200 MHz bandwidth available. 100 MHz has been allocated for the Cumucore 5G and another 100 MHz for the OAIBOXes and the O-RAN indoor usage. 850 MHz in band n258 is in use for the mmW radios. Bands B1, B7, B28 and B40 are reserved and available for the 4G use. Currently only B40 with one base station is in use as the research need for the 4G is diminishing at the University of Oulu.

5GTN supports remote connection through the internet and as the external connections towards the testbed are protected by a firewall a VPN connection is required. One 5GTN O-RAN unit is also federated in Slices-RI. 5GTN has an internal connectivity towards the University of Oulu IP-network.

A large amount of User Equipment is available. Around one hundred mobile phones and tablets, including the newest ones, are available for experiments. Offering includes also several pieces of AR and VR glasses, 360-degree cameras, and tens of different 4G and 5G modems from several manufacturers. More than ten 5G hubs, WiFi switches and industrial routers are available. There are several hundreds of SIM cards available for all the active 5G networks. User devices include several drones and even a remote-controlled excavator.

LoRa and IoT sensors are available and couple of thousands of those sensors are even deployed to the University campus and are in active use. RedCap 5G is currently being taken into use.

For testing a Quality-of-Service measurement tool Kaitotek Qosium [KAITO] is available. Keysight Nemo Handy, Outdoor and Analyze are used and available for experiments. Signal generators, channel analyzers, power amplifiers, antennas etc. measurement, monitoring and implementation devices are also part of 5GTN equipment inventory.

Newest additions to 5GTN offering are, for example, Reconfigurable Intelligent Surface (RIS) from more than one manufacturer, 140 and 300 GHz transceivers andTime Sensitive Network (TSN) and Non-Terrestrial Network (NTN) devices.

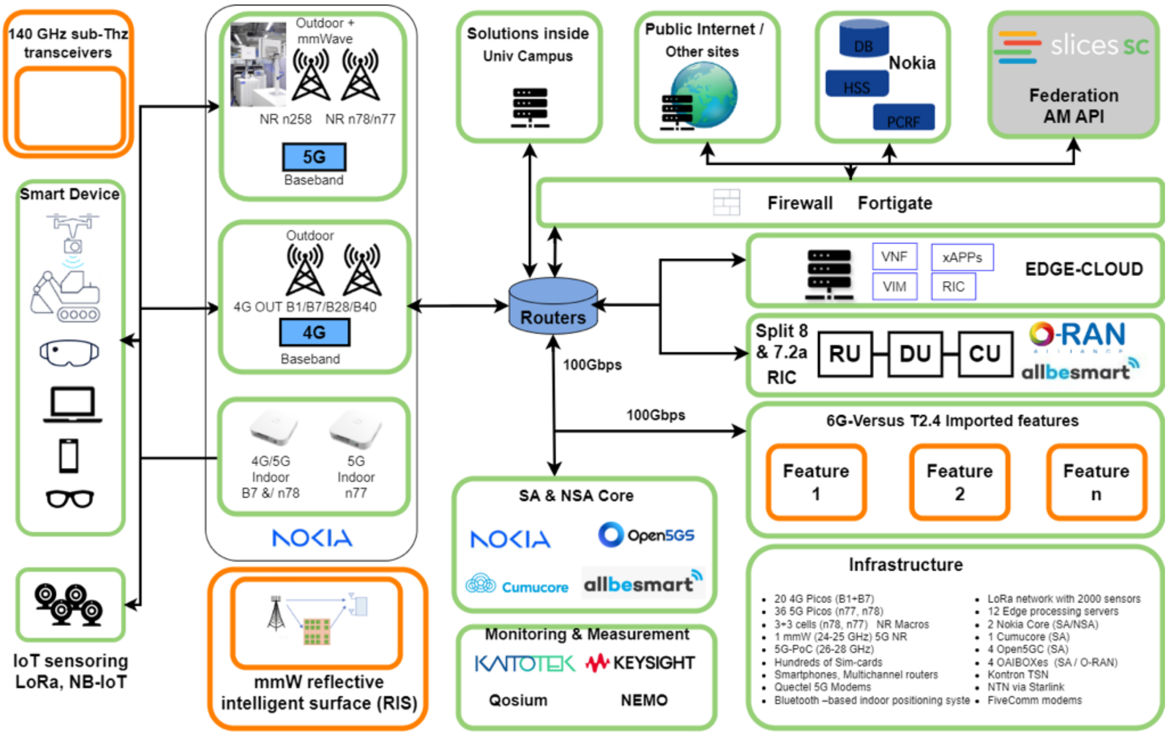

Figure 4. Finnish test platform architecture (5GTN)

2.3 France

The 5G facility of EURECOM (EUR) is located in Sophia Antipolis, southeast of France. It provides experimental 5G services, including enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communication (mMTC). Based on fully open-source tools and open-architecture design, providing the means to on-board new applications in the form of Container Network Functions (CNFs) to the running 5G infrastructure and test them in both a controlled laboratory setting and in a deployed live network. The facility supports the deployment of vertical applications, Extended Application (xApp) that uses Open Radio Access Network (O-RAN) Service Management (SM) or RAN Controller (RC) models, and Network Data Analytics Function (NWDAF) clients that consume NWDAF API. The management and orchestration of the CNFs are done using two entities: Domain Manager and Orchestrator (DMO) and Compute Fabric, where the objective is to separate service and resource management. The Compute Fabric can interconnect with different container systems (CISM), such as OpenShift, Kubernetes, or K3S, using the notion of Broker.

Figure 5 illustrates how the facility is accessible through (1) CAMARA API, supporting edge application deployment as well as 5G CN-related functions such as mobility information, QoS on Demand, and Traffic Influence. The latter is provided via the 5G NEF; (2) TMF 921 for service deployment and provisioning; (3) a well-specified NBI of DMO; (4) a Web portal.

The WebPortal is specifically designed to allow vertical use-case deployment, while the NBI API can be used by an external component of the orchestrator (CAMARA and TMF 921). The facility is connected to an EU federation of testbeds in the context of SLICE-PP, 6GBricks, and Sunrise-6G projects. Through the NBI (or Web portal), the DMO allows the experimental to have access to monitoring and logging information on the deployed CNF, which can be observed using a graphical interface or collected as Raw data via a Broker. The DMO also exposes API to other orchestrators, when belonging to the federation, to enroll in a new CSIM or expose the resources of the managed CSIMs. The DMO acts as a Telco Cloud orchestrator when it belongs to a federation.

The 5G infrastructure is composed of a 5G Radio Access Network (RAN) based on OpenAirInterface (OAI) supporting both FR1 and FR2 deployments, and a service-based 5G Core Network using OAI.

In regard of FR1 deployment, the RAN platform is split into CU, DU and RU following two different functional splits.

- Split 7.2: OAI CU and DU using commercial RUs from commercial providers: VVDN (indoor), LiteON (indoor), and Benetel (indoor and outdoor)
- Split 8: OAI CU and DU using USRPs (B210, N300, X310, indoor) and commercial RUs from AW2S (indoor and outdoor).

The FR1 RAN setup operates at bands 38 (2.6 GHz) and 78 (3.4 GHz) supporting two subcarrier-spacing (15 and 30kHz), six different bandwidth sizes (10, 20, 40, 50, 80 and 100MHz) with multiple Bandwidth Parts (BWPs) support (initial BWP and dedicated BWPs), different TDD configurations enabling asymmetric assignment of uplink and downlink resources with shorter TDD periods (down to 2.5 ms). It also includes the Procedures for 4-layer DL and 2-layer UL MIMO with the support of 256 QAM modulation. For FR2, the current implementation supports FR2 RU from a commercial company LiteON operating at 27 GHz. Completing the O-RAN setup, the facility includes a RAN Intelligent Controller (RIC) (OAI FlexRIC). to run xApp for RAN management and optimization.

Regarding the 5G CN, it is based on OAI CN. It is a partial 3GPP 5GC service-based architecture including the following Network Functions (NFs): NRF, AMF, SMF, UPF, UDM, UDR, AUSF, NSSF, PCF, NWDAF and NEF.

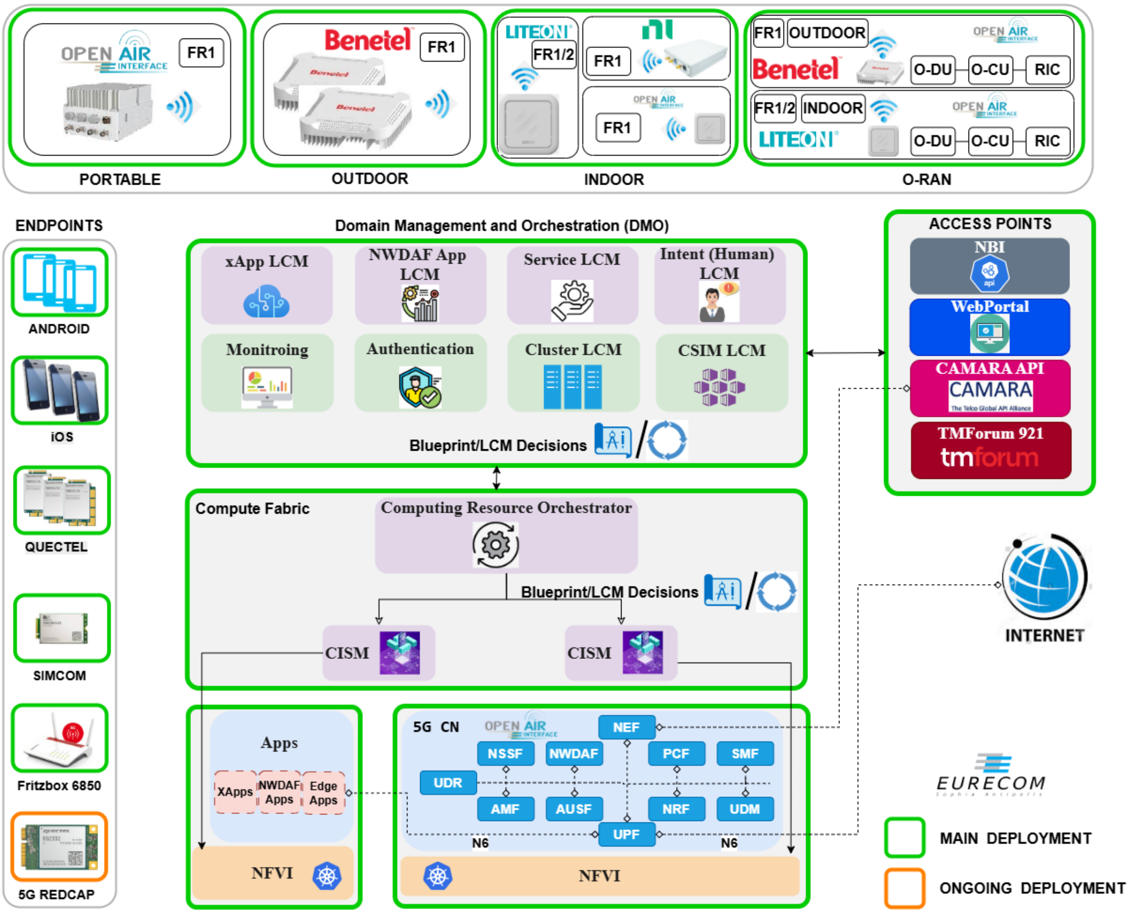

Figure 5. Eurecom test facility architecture.

2.4 Greece

The Athens experimentation platform is an advanced large-scale experimental facility integrating both Beyond 5G (B5G) network infrastructure and an orchestrated computing continuum built and managed using the aerOS Meta-OS (Figure 6). The platform spans two locations within the metropolitan area of Athens—OTE Academy campus and NCSR Demokritos campus—interconnected via dedicated 10G dark fiber links, forming two fully operational experimental networks. While the B5G infrastructure offers a robust foundation for advanced networking experimentation, the aerOS-based continuum enables transparent deployment and dynamic migration of containerized services across the two domains, driven by real-time resource availability, service-level agreements (SLAs), and specific service requirements.

At the core of the platform's continuum lies aerOS's unified execution layer, which abstracts heterogeneous computing and networking resources into a single cohesive resource pool. This layer is supported by a unified network and compute fabric, enabling the aerOS double-layer orchestration model. In this model, an AI-enabled decision layer optimizes service placement based on a global view of the continuum, while the enforcement layer ensures reliable execution on the selected resources. This architecture ensures decisions are based on comprehensive resource awareness, with seamless deployment across domains. The continuum is inherently scalable, allowing for easy integration of new domains and resources as needed, further enhancing its orchestration capabilities.

While service deployment is fully automated and transparent through the aerOS orchestration framework, a comprehensive set of 5G and Non-Terrestrial Network (NTN) technologies forms the backbone of the platform's advanced networking capabilities. The platform hosts two distinct 5G Standalone (SA) networks:

The first network, based on Hewlett Packard (HP) 5G SA Core and Ericsson equipment, spans both campuses. The HP 5G Core, deployed at the OTE Academy, controls two Ericsson BBUs (at OTE and NCSR campuses), each supporting three Ericsson RRU/RAN units, creating a large-scale experimental 5G network with six indoor/outdoor cells in total. OTE also deploys mmWave RAN equipment to enhance experimental capabilities. Moreover, OTE site leverages Open5GS deployment in support of research-oriented activities.

The second network, deployed at NCSR Demokritos, leverages Amarisoft 5G RAN with flexible 5G SA Core options, including Amarisoft and Open5GS. These cores offer varying levels of openness (e.g., NEF, NWDAF, CAPIF) and native AI programmability. The platform also integrates software RAN solutions like UERANSIM (monolithic and containerized) and srsRAN (gNB and UE via ZeroMQ).

In addition to these large-scale infrastructures, the platform also includes:

- An OpenAirInterface (OAI) OAIBOX, which integrates a complete 5G Core with Split 8 architecture, enabling flexible, open-source experimentation. The OAIBOX serves as a versatile testbed for RAN and core network integration in research scenarios.
- A portable 5G system based on Raspberry Pi that features a containerized Open5GS for lightweight, flexible deployments. This compact solution enables rapid setup of portable 5G networks, while allowing integration with a variety of external or separate RAN units, depending on the testing scenario or deployment requirements. It is particularly suited for experiments in constrained, temporary, or remote environments.

For non-terrestrial connectivity, the platform uses the OpenSAND emulator from INF for satellite backhauling emulation. Advanced network slicing techniques, using VLANs and SDN controllers, allow dynamic traffic management between terrestrial and satellite links. Additionally, OTE's infrastructure supports live satellite backhauling via GEO (HellasSat) and LEO (Starlink) networks, fully integrated with the 5G SA architecture.

The convergence of the aerOS continuum with B5G networking is a key innovation of the Athens platform. Containerized 5G network functions (NFs), such as Open5GS UPF, benefit from aerOS's orchestration, allowing dynamic deployment and migration based on application-specific or user-centric policies.

The platform also provides extensive RAN and data monitoring capabilities:

- Amarisoft 5G RAN offers flexible configurations for sub-6 GHz bands, supporting bandwidths up to 50 MHz, multiple subcarrier spacings, and MIMO up to 4x4.

- Ericsson 5G RAN provides high-capacity commercial-grade RAN with BBU 6630 and multiple compatible radio units for indoor and outdoor deployments. Precise GPS-based synchronization ensures reliable operation.
- OAI OAIBOX RAN implements a flexible, open-source 5G RAN architecture based on 3GPP standards, supporting Split 8 functional split for integration with external components. It supports both NSA and SA modes, operates in sub-6 GHz bands with up to 100 MHz bandwidth, 2x2 MIMO, and provides 250 mW (24 dBm) per port output power with up to 32 simultaneous connections. The OAIBOX allows fine-grained protocol stack configuration, making it highly suitable for research-driven, experimental scenarios.
- Data Collection & Monitoring: A monitoring framework based on Prometheus includes a main server with a time-series database, an alert manager for alarms, Node Exporters for resource metrics, and Grafana for real-time visualization.
- Additionally, through its participation in the 6G-SANDBOX Stream C framework, the platform integrates advanced Keysight tools (e.g., Loadcore, CloudPeak) for in-depth KPI measurements and digital twin simulations focused on RAN behavior, leveraging the Exata network modeling tool.

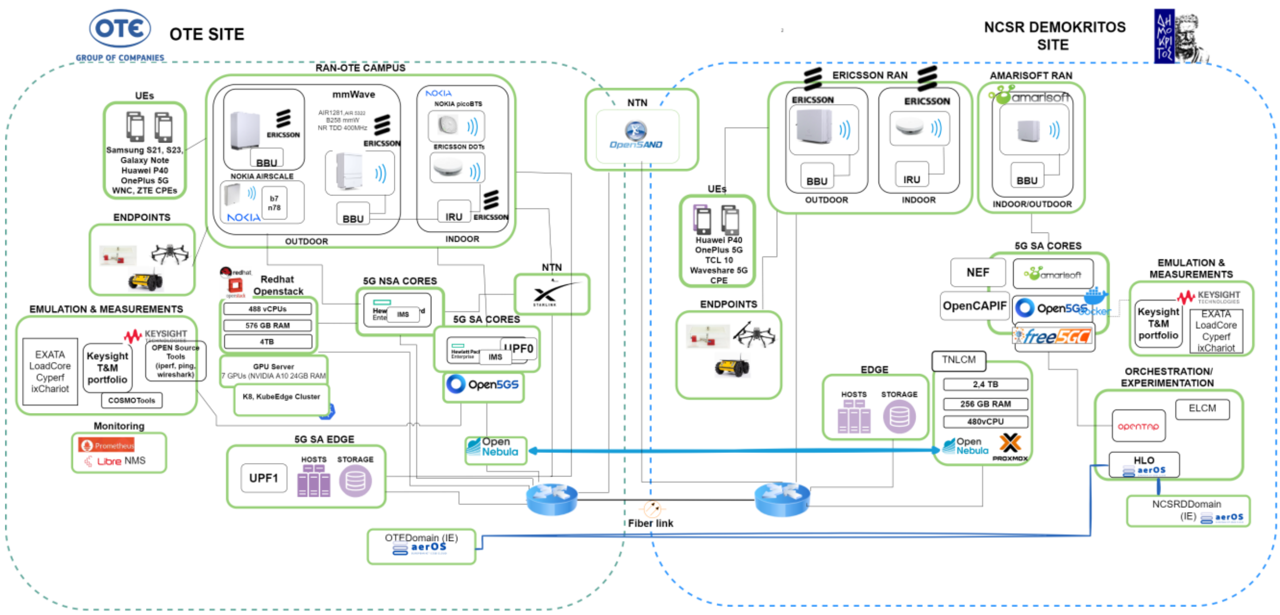

Figure 6. Network topology of Athens platform

Additionally, COSMOTE 5G SA deployment pertains installation and configurations on slicing support with two different schemas have been enhanced and tested, namely:

- DNN (Data Network Name) based slicing, utilizing two UPFs to emulate edge and core 5G network Data planes, slice selected through different DNNs,
- SST (Network Service/Slice Type) template-driven slicing: This approach provides the capability to discriminate data flows by setting different SSTs, utilizing UERANSIM in lack of appropriate UE devices, for the selection of sst/sd (eMBB slices)
- MOCN Configuration of Ericsson RAN@COSMOTE (operates with PLMN 20202 of COSMOTE and 99999 of NCSRD)

Finally, the testbed supports a diverse range of cloud infrastructures, including Red Hat, OpenNebula, and Proxmox, enabling flexibility and adaptability for various deployment needs.

NCSRD hosts a robust data center within the Athens platform, providing 10 high-performance servers each equipped with 256 GB RAM, 2×12-core CPUs, and a combined 2.4 TB storage capacity. The environment leverages OpenNebula and Proxmox for efficient virtualization and cloud orchestration, enabling scalable, secure, and flexible experimental deployments. At the NCSRD site, a complete OpenNebula environment is deployed, with the Front-End running on a KVM-based virtualization infrastructure, providing a robust and scalable foundation for managing virtualized resources. The aim of this setup supports distributed operations, facilitated by the deployment of an additional OpenNebula Node at the OTE site. This node is interconnected with the NCSRD Front-End, enabling resource federation and cross-site deployment capabilities.

2.5 Spain

The Victoria Network platform, operated by the University of Málaga, extends across several strategic locations in the Málaga region (Spain), as illustrated in Figure 7. These include the UMA Campus, Málaga City Center, Dekra (Málaga TechPark), and the IHSM La Mayora Experimental Station (Algarrobo). Additionally, the Roquetas Wastewater Treatment Plant (WWTP) is part of the platform and is connected via Telefónica's national coverage.

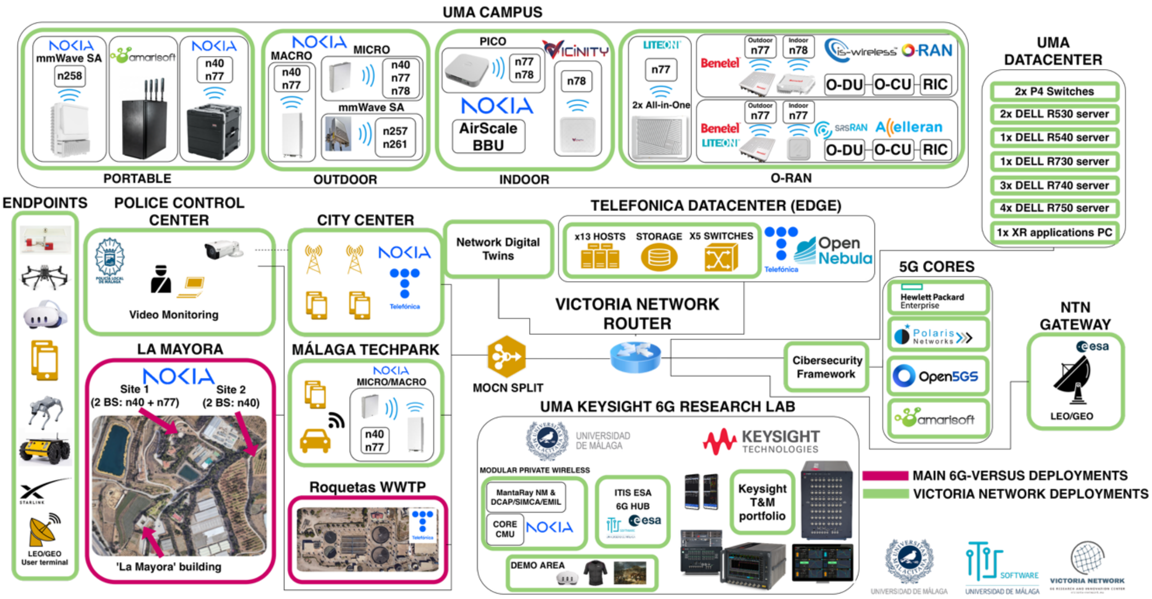

Figure 7. The Victoria Network platform at UMA

This geographically distributed architecture is interconnected through 'Victoria Network router' acting as main router which connects the above locations. Each location includes various components, which are mainly connected using network switches with ports working on 1/10/25 GbE. Additionally, there are 2 Intel Tofino 2 switches with ports up to 400 GbE and allow programmability with P4 language. The main infrastructure assets are presented below.

RAN: 32 Nokia radio units are distributed in different locations (UMA Campus, La Mayora, Malaga Techpark) and used in bands b7/n40/ n77/n78 (FR1) and n258/n261 (FR2), supporting several antenna configurations, including 5G NSA and 5G SA, indoor and outdoor deployments, DL MIMO modes 2x2 and 4x4 and channel and widths 20/100/400 MHz.

Open RAN (O-RAN): The O-RAN solutions are provided by IS-Wireless, srsRAN + Accelleran and LiteON All-in-One, respectively. RU models integrated with these solutions are Benetel RUs (Benetel RAN550 (band n78) for indoor and Benetel RAN650 (band n77) for outdoor) and LiteOn FlexFi RU. In addition, near RT-RIC from IS-Wireless and Accelleran including xApps for KPI monitoring and slicing are available.

Core Network: The Commercial Network from Telefónica is available for use in the implementation of the project's use cases. Additionally, any commercial Open Gateway Services that become available during the course of the project may be utilized to obtain valuable network information or to manage network resources. This will help ensure optimal performance and prevent potential issues that could impact the assurance of service within the use cases. Additionally, there are four 5G core network solutions available: Polaris Unicorn, HPE Aruba Networking Private 5G Core, AMARI Callbox and Open5GS.

Various servers, applications, and endpoints like UGVs, UAVs, XR devices are available in different locations for diverse use cases. Moreover, access to commercial NTN Starlink solution and equipment for SIM card creation and provisioning is provided.

Data Collection and Monitoring Capabilities: The network's basic functionalities for data collection and monitoring are managed by a Network Operations Center (NOC), which includes a Network Management System (NMS) for monitoring and managing devices, ensuring QoS through automated operations via the Operations Support System (OSS). Network traces from gNB and 5GC are monitored, with tools like Nokia Web Element Manager. Additionally, tools by KEYS such as Nemo Handy Handheld Measurement Solution, Nemo Outdoor 5G NR Drive Test Solution, and Nemo Analyze Drive Test Post Processing Solution facilitate air interface parameter measurement and troubleshooting in the mobile network. Finally, the 6G-SANDBOX Experiment Lifecycle Manager enables complete control over experiments, including replicability and resource management.

2.6 Portugal

The 5G standalone trial site is distributed across multiple locations, each serving different operational and geographic needs. At the University of Aveiro campus, two indoor sites are deployed: one at the IT department and another near the campus canteen, providing coverage for academic and community use. The second major deployment is at the Port of Aveiro, where an outdoor setup with three antennas covers a large area and supports the unique demands of a seaport environment. In addition to these fixed locations, the trial site includes a portable, battery-powered 5G system that can be quickly deployed for temporary events, remote testing, or emergency situations, ensuring connectivity in areas without permanent infrastructure. The network operates in both TDD and FDD modes, currently using the 3700 MHz band with 20 MHz of bandwidth. Indoor sites are connected via a dedicated fiber network, while the port site uses a public Layer 2 service to connect to the core network. A robust backhaul infrastructure, including routers and switches, supports efficient data transmission across all locations. It includes key network functions such as mobility management, session control, authentication, user data handling, and network slicing. The infrastructure is designed to evolve over time, incorporating new features and improvements (Figure 8).

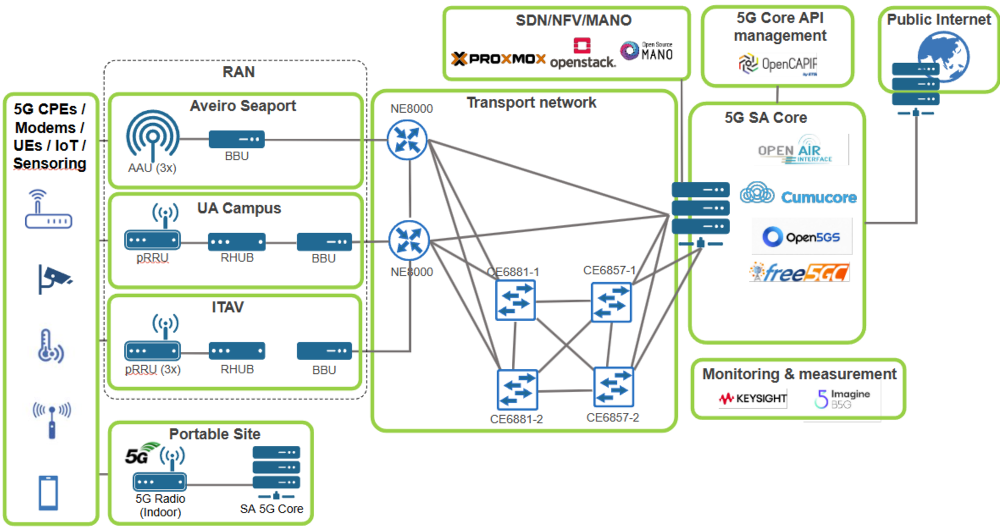

Figure 8. ITAV and Aveiro Port part of the Aveiro Cluster's Infrastructure

In addition, the Altice Labs testbed in Aveiro, features a private 5G network with indoor and outdoor coverage, operating on its own spectrum and integrated with PON technology (Figure 9). Designed as a smart campus, it supports diverse use cases including smart cities, industry, C-V2X, and public safety. Centralized at the campus data center, the testbed hosts two 5G cores (Open5GS and Druid Raemis) connected to a 5G radio network built on an OpenRAN architecture. Thirteen Radio Units connect to Distributed Units using fiber and PON, enabling flexible core connections depending on experiment needs. Servers, including GPU-equipped ones and an Edge Computing platform, support extended 5G slicing. The RAN uses ASOCS CYRUS 2.0, a virtualized software solution operating on standard servers, supporting both O-RAN and 3GPP interfaces for flexible deployment. Outdoor extensions include 5G-based location services and a smart lamppost with renewable energy sources, sensors, and EV charging. The testbed also features IMS-based multimedia services. Given its fully-fledged smart infrastructure capabilities, it will be the target site for performing Scenario 3 trials, while accounting for the characteristics and requirements of the Port of Aveiro as target production environment.

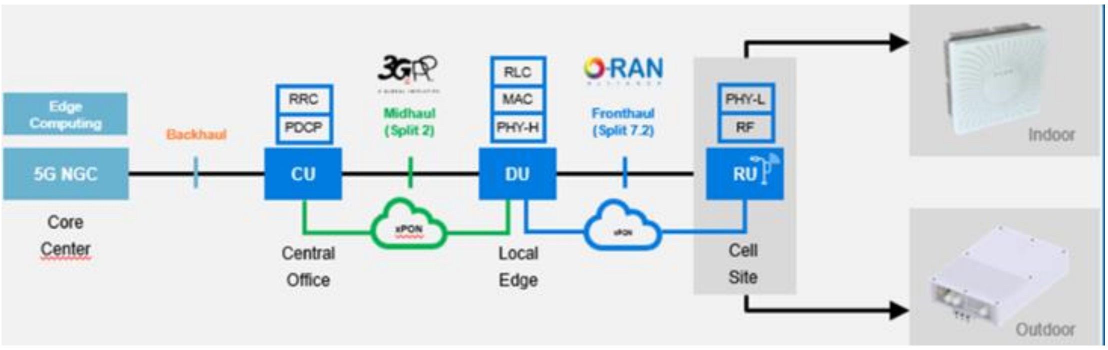

Figure 9. Altice Labs Campus' part of the Aveiro Cluster

3 Description of the technologies and features to be added to the 6G-VERSUS Platforms

The technologies and features presented here are described in detail in deliverable D2.1 [6GVERD21]. In this section, we describe how they are going to be added to the different 6G-VERSUS platforms. Note that the Section is not describing the foundations of the technologies but the specific configuration or customization planned in the project for such technologies and the mapping to the sites.

3.1 RAN features

Multi-Operator Core Network

Given the topology of the Athens testbed including two sites, the MOCN (Multi-Operator Core Network) configuration of the Ericsson RAN at COSMOTE involves the operation of two Public Land Mobile Networks (PLMNs): 20202, which belongs to COSMOTE, and 99999, which is assigned to NCSRD. This setup enables the shared use of the same RAN infrastructure by both sites, while maintaining separate core network functionalities and subscriber identities, thereby enabling realistic multi-operator experimentation and flexible resource sharing within a common radio access domain

D2D sidelink

5G NR sidelink (PC5) technology enables direct device-to-device (D2D) communication without requiring assistance from a gNB. This capability is particularly valuable in PPDR (Public Protection and Disaster Relief) scenarios, where coverage can be limited or entirely absent. For example, during a wildfire response, a squad of first-responder hand-held radios and a robotic dog can form a local PC5 mesh, sharing location, vital signs, and sensor telemetry among them even when the nearest base station is out of coverage. The principles including the description of architectural elements, for sidelink operation, covering both Mode 1 (base station-assisted) and Mode 2 (autonomous) have already been introduced and analysed in D2.1 [6GVERD21].

In the context of the project's experimental testbed, ICCS will incorporate commercial off-the-self equipment that supports the experimentation and validation of 5G NR sidelink features. In particular, the ETTIFOS SIRIUS platform [ETTIFOS] will be integrated as a primary UE device for sidelink evaluations. SIRIUS is a programmable OBU (On-Board Unit) capable of operating as a sidelink device, compliant with 3GPP Release 16 and supporting both LTE-V2X (Rel. 14/15) and 5G-V2X sidelink operation. It provides a modular software stack, including NR PHY/MAC implementations, PC5 support, and flexible configuration of radio parameters such as channel bandwidth, numerology, and transmission power etc. Its hardware architecture supports SDR-based operation, enabling over-the-air sidelink testing with high-performance RF front-ends, multi-antenna configurations, and programmable baseband processing. Finally, SIRIUS device supports all PC5 communication modes including broadcast, groupcast and unicast with several QoS configurations. These capabilities make it suitable for the coverage-extension scenarios that are central to the Greek Testbed use case.

Figure 10. The SIRIUS device product.

Figure 10 depicts the SIRIUS device product and supports the following key technical specifications:

- Dimensions: 165 mm (W) × 212 mm (H) × 64.5 mm (D)
- Channel bandwidth support (5G-V2X): 10, 20, 40 MHz; (LTE-V2X): 10, 20 MHz
- Transmit power: typical +20 dBm; maximum +23 dBm
- Memory/storage: 8 GB LPDDR4 RAM + 32 GB eMMC storage
- Operating temperature range: –40 °C to +85 °C
- RF/front-end configuration: two C-V2X antenna ports + one GNSS antenna (SMA type)
- Subcarrier spacing support: 15, 30, 60 kHz (for sidelink)

In parallel with the commercial ETTIFOS platform, ICCS will also investigate the ongoing 3GPP-compliant implementation available in OpenAirInterface (OAI). Recent work (e.g., the OTA 5G NR sidelink testbed demonstrated in [MEL2023]) shows that OAI already supports key sidelink PHY components, including PSBCH, PSSCH, DMRS generation, synchronization procedures, and LDPC/polar channel coding, validated through both RF simulation (RFSIM) and USRP-based over-the-air setups.

O-RAN

Remote Basestation that is built for 5G Test Network in the University of Oulu is based on O-RAN architecture. In O-RAN the Basse station is split into three different devices, Centrla Unit (CU), Distributed Unit (DU) and Radio Unit (RU). University of Oulu is utilizing the Allbesmart OAIBOX implementation of the O-RAN. In OAIBOX CU has the 5G Core functionalities, Near-RT RIC (FlexRIC) and OAIBOX dashboard running in it. DU contains the time critical physical functions of the system. RU in the implemented system is planned to be Benetel FR1 radio. In the 6G-VERSUS implementation the RU is located in the outdoor Remote BTS site and the CU & DU are located on the 5GTN network side in server rooms. Connection between the DU and RU is handled by Nokia Microwave link where there is one antenna in the network side connected to the DU and one on the remote site connected to the RU. Near-RT RIC in the CU is hosting the xApp that is gathering the radio and UE related info from the E2 interface. That info is then passed through CAPIF and N-App to the data repository of the system to be utilized by one of the AI apps in 5G network related decision making. The O-RAN system is depicted in Figure 11.

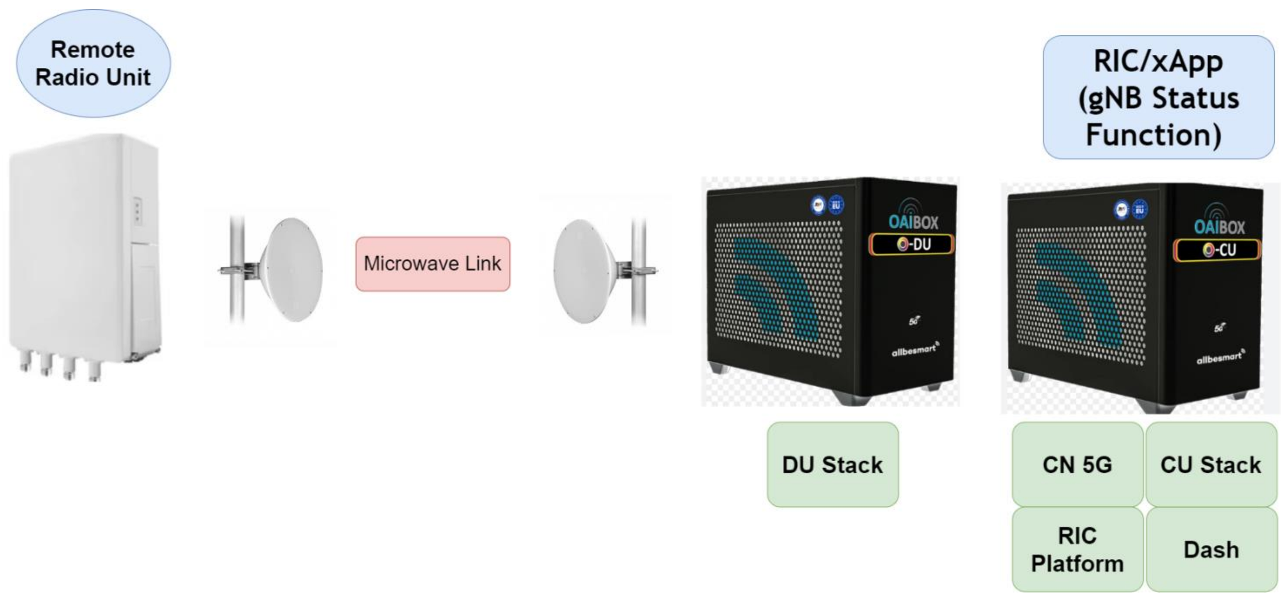

Figure 11. 5G O-RAN setup of the University of Oulu

In Figure 11 O-DU unit with 5G core, Dashboard, CU stack and the RIC platform is seen on the right side. It is connected to CU with fiber optic cable connection. CU has Microwave link connectivity with the Remote Radio Unit.

DRX and BWP features

RAN configuration allows to optimise dynamically RAN features such as DRX and BWP. DRX is a mechanism that will be used for the French cluster to improve the battery life of the sensors. It manages different states of sensors depending on the configuration of DRX. If not active, the sensor can be in a state which will save its battery life, while still being connected to the base station. This period of time has to be optimally configured.

Extended DRX (eDRX) is an enhancement of DRX that further extends the duration of the sleep mode. This is particularly beneficial for IoT devices, as it significantly reduces power consumption by allowing the device to remain in a low-power state for longer periods (up to 3hours). eDRX is designed to synchronize with the network to ensure that the device wakes up at the correct intervals to check for paging messages, thereby optimizing battery life. eDRX is designed for IoT or RedCap devices that do not require ultra-low latency but need to optimize energy usage.

As a complementary feature with DRX which operates in the time domain, BWPs help in power saving in the frequency domain. BWPs are a key 5G feature designed to optimize spectrum utilization and enhance energy efficiency. A BWP is a set of continuous PRBs (Physical Resource Blocks) within a carrier bandwidth, allowing for flexible and dynamic switch between wider and narrower bandwidth upon the actual needs.

Typically, during off-peak hours, not much spectrum is needed. So, we can decide to put the sensors on the reduced BWP, such as BWP#0 on the figure above. Whereas during peak hours, a lot of traffic can be streamed and needs to have a wider BWP, such as BWP#1.

In 6G-VERSUS, configuring optimally DRX and BWP will efficiently save power consumption of the 5G sensors and then extend their battery life. To do that, a 5G radio station is serving RedCap compliant sensors. Traffic is sent in Downlink/Uplink. The optimal configuration of the RAN (DRX/BWP parameters) is inferred from the native RAN data collected on RAN.

Two step RACH

The Random Access Channel (RACH) is a fundamental mechanism used for initial access and connection establishment between a User Equipment (UE) and the 5G network, to be implemented by the French cluster. According to 3GPP Release 15, the standard contention-based RACH procedure follows a four-step process. The messages involved in this sequence are:

- **Msg1:** Random Access Preamble
- **Msg2:** Random Access Response
- **Msg3:** Scheduled Transmission
- **Msg4:** Contention Resolution

This four-step procedure requires two round-trip communications between the UE and the gNB, resulting in increased latency and additional control signaling overhead.

To address this, 3GPP introduced the Two-Step RACH procedure, which reduces latency and control overhead by compressing the process into a single round trip (see Figure 12). This is achieved by:

- Combining Msg1 and Msg3 into a single message from the UE, called MsgA
- Combining Msg2 and Msg4 into a single response from the gNB, called MsgB

The Two-Step RACH procedure is already implemented in the OpenAirInterface (OAI) codebase for both the gNB and the UE.

The implementation includes:

- Integration of new Release 16 Information Elements (IEs) related to Two-Step RACH in the SIB1 broadcast message
- Handling of MsgA at the gNB, which includes processing both the PRACH preamble and PUSCH
- Generation and transmission of MsgB from the gNB to the UE

This implementation has been merged into the official OAI repository.

The Two-Step RACH procedure is especially valuable in scenarios involving:

- Massive IoT: where devices transmit sporadically with small data packets, reducing collisions and improving efficiency such as for the use case of smart watering in green space.
- Sewer network monitoring: where low-latency communications are essential for real-time responsiveness and coordination which ensures timely transmission of critical water network data (e.g., overflow alerts or blockages)

Due to the current unavailability of commercial UEs supporting the Two-Step RACH procedure, testing will be conducted using the OAI software-based UE.

For the final TRL (Technology Readiness Level) assessment, expected to reach TRL 6, the French cluster plans to use a hardware-based commercial UE that supports Two-Step RACH, if such devices become available in the coming months from any vendor.

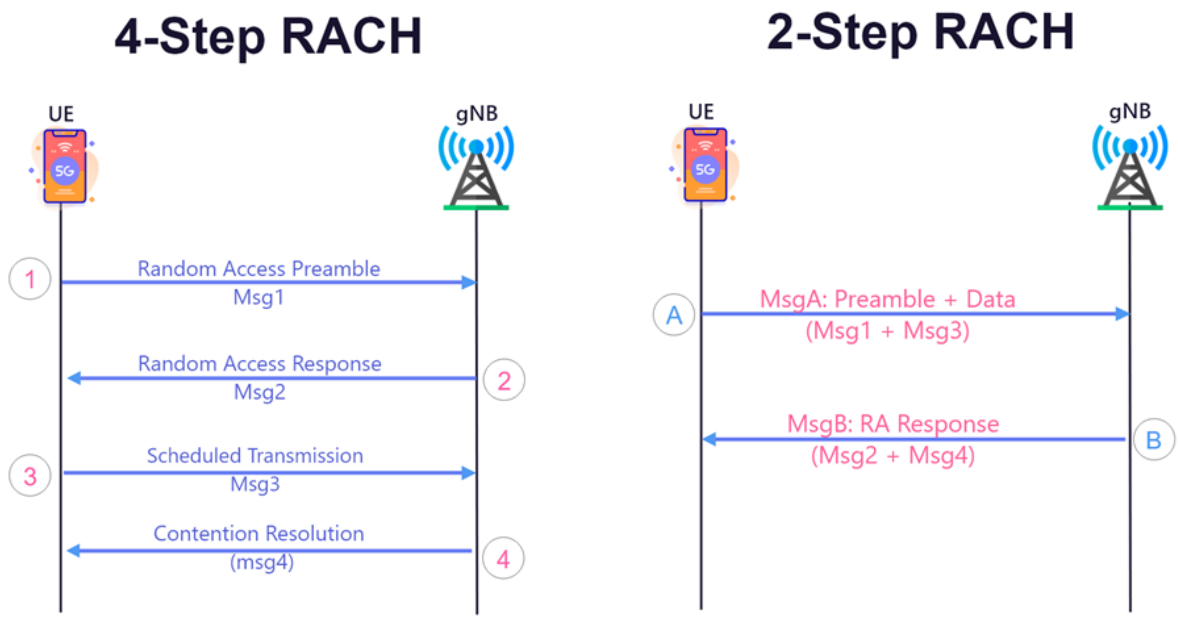

Figure 12. 2-Step RACH vs 4-Step RACH

Portable Nodes for Flexible Radio Access

The Nokia portable FR2 node at University of Málaga (UMA), operating in the n258 band, provides a flexible solution for on-site, on-demand deployments, enabling rapid setup in temporary or hard-to-reach locations. Its portability allows for extending coverage and boosting capacity in areas where permanent infrastructure is limited.

In addition, a portable Nokia FR1 node supporting n40 and n77 bands complements the FR2 node, offering multi-band coverage to adapt to different environments and deployment needs. Together, these portable nodes provide versatile and scalable private radio access, allowing flexible coverage in experimental setups, temporary events, or emergency scenarios. Their quick configurability and mobility make them ideal for dynamically adapting coverage and ensuring reliable access in a variety of on-site situations to be exploited in the Spanish platform.

Non-Terrestrial Networks (NTN)

Non-Terrestrial Networks (NTN) in the context of 6G aim to extend mobile network coverage beyond terrestrial infrastructure by integrating satellite segments in some parts of the network. The University of Málaga (UMA) is actively engaged in supporting 6G-NTN developments. UMA will deploy two antennas: one in La Mayora and the other one in the Ada Byron building (Victoria Network main lab). The first one, in La Mayora, will serve as a UE that needs to connect to the 6G network from a remote, no service area. This antenna will send the information collected (from drone, sensors...) to a satellite which will act as a relay and send the signal in *backhaul*, *transparent* or *regenerative mode* to the antenna that is in the Ada Byron building. This antenna will be an NTN Gateway, not a UE antenna, that will collect the information from the UE and forward it to the correspondent core network. A diagram summarizing this scenario can be shown in Figure 13, illustrating how the satellite provides service in the RAN segment in remote areas.

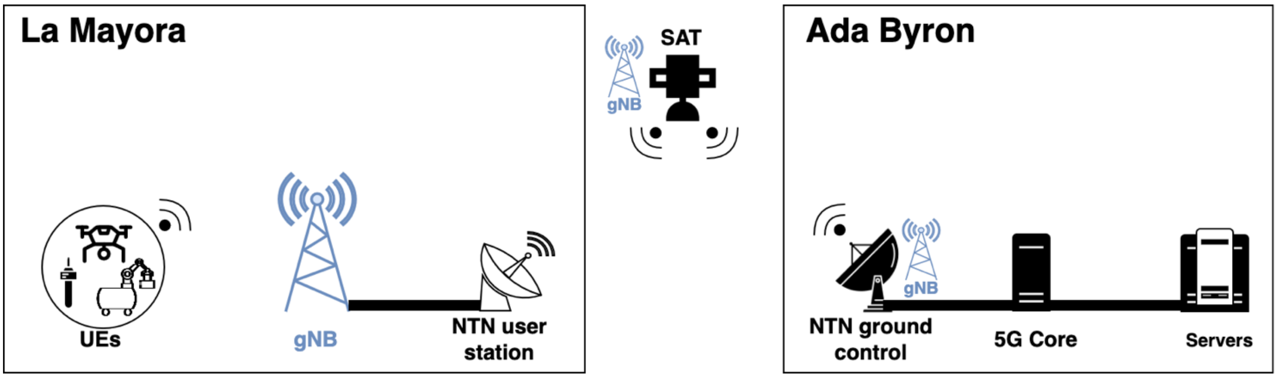

Figure 13. NTN connection in La Mayora

3.2 Core and APIs

Open5GS API

The APIs implemented within several 6G-VERSUS testbeds will utilize the features and interfaces provided by Open5GS, ensuring compliance with the microservices-based 5GC architecture. In this sense, each network function (NF)—such as AMF, UPF, or NRF—is deployed as a separate container, each including all essential protocols, signaling, and dependencies, aligning with cloud-native principles. This modular approach provides advantages like better automation, more efficient orchestration, and simplified monitoring. Using orchestration frameworks such as Kubernetes, the lifecycle management of 5G NFs is streamlined, allowing the platform to take full advantage of cloud-native scaling, resilience, and self-healing capabilities. A multi-stage Docker build is used to generate intermediate images before assembling the final runtime image for each NF, as a good practice optimizing container size and reducing unnecessary dependencies.

Athens testbed will also use the Open5GS monitoring event API. The system comprises two main components: a backend AMF Log Agent and a frontend NEF Monitoring Event API. The AMF Log Agent is tasked with detecting UE registration events by periodically polling AMF container logs. When a UE registers with the network, its unique identifier (such as the IMSI) appears as a Registration Event in these logs. Upon detecting such an event, the agent parses the log data, extracts the necessary registration details, and constructs two JSON objects—one containing raw metadata and another formatted to represent UE location information in accordance with 3GPP standards. Both JSON objects are stored in an external MongoDB database, within collections named *ue_events* and *location_info,* respectively. This approach effectively decouples the UE event handling from the core network and provides a lightweight method for accessing location data.

On the frontend, the NEF exposes an asynchronous RESTful Monitoring Event API that allows external Application Functions (AFs) to subscribe to location-related events. The API supports creating, retrieving, and deleting subscriptions via standard HTTP methods (POST, GET, and DELETE). When a POST request is received, the NEF records the subscription and its parameters in the same MongoDB database used by the backend. It then asynchronously checks for matching UE identifiers based on entries received from the AMF logs. If a match is found, the NEF retrieves the corresponding location information and sends it to the AF through a callback interface, ensuring the data is structured according to 3GPP specifications. This architecture enables the NEF to deliver location data without requiring direct, real-time interaction with the 5G Core, simplifying system integration, and promoting interoperability with different core network vendors. The system is deployed in a cloud-native environment, with all components containerized using Docker and managed via Docker Compose. Both MongoDB endpoints and log polling intervals are fully configurable, ensuring flexibility and ease of deployment in a variety of infrastructure setups.

Open CAPIF

Open CAPIF is integrated in the Bulgarian, French, Greek, Portuguese and Spanish cluster.

In the Bulgarian testbed, Open CAPIF will be installed and integrated within Data center of A1, located in Sofia. The integration between Open CAPIF and the Ericsson Network Exposure Function (NEF) will be established for exposing 5G Core network capabilities where CAPIF acts as a unified API exposure and management platform, offering functions such as API discovery, onboarding, authentication, and auditing, while the NEF continues to provide the 3GPP-compliant interfaces for network service exposure. Through this interworking, NEF API such as traffic influence, event exposure, or representation an application-level session that requests or is associated with specific QoS parameters will be explored and will be used as part of the Bulgarian use-case dealing with a 6G-triplet serving a smart grid service, and it will particularly support the exposure of real-time network metrics to be consumed by the N-App and for inference of one of the AI-App module dealing with an advisory function that optimize exposure parameters based on requests and feedback coming from the V-App Central.

In the French cluster, OpenCAPIF is deployed within the OAI-based testbed and is being integrated with the OAI Network Exposure Function (NEF) and the OAI NWDAF to support unified exposure of 5G Core capabilities. The NEF provides the 3GPP-compliant interfaces for service and event exposure, while OpenCAPIF enables centralized API discovery, onboarding, authorization, and monitoring. The integration will allow the French triplet-app to access network-level metrics, event notifications, and analytics insights exposed by the NWDAF, enabling experimentation with network KPI monitoring, energy analytics, and adaptive control functions. Initial validation of the CAPIF–NEF–NWDAF workflow has started, and the first end-to-end demonstrations will be aligned with the French cluster use cases during the upcoming integration cycle.

Regarding the Greek cluster, the OpenCAPIF component has been deployed in the Athens testbed of the Greek cluster since the early stages of the project. It has been actively utilized to support the initial templates provided to the clusters for the N-App implementation. A complete end-to-end demonstration of CAPIF's functionality is planned for the first round of trials in February 2026, during which the N-App will interact with the AI-App through the monitoring event API via the CAPIF framework.

In the Portuguese cluster, OpenCAPIF has been deployed and configured in the IT-Av testbed. Software developments being pursued in the Network Operations N-App are currently under way, as well as the integration with the 5G core networks available at the testbed (i.e., currently Open5GS). An initial version is already integrated comprising the application triplet and the testbed features (i.e., X-Apps, OpenCAPIF, ONEmNEF, Open5GS). The first public demonstration involving OpenCAPIF is planned to take place as part of first trial phase.

Finally, in the Spanish cluster, a main OnenCAPIF instance will be deployed within the IHSM La Mayora site. The Mayora deployment will leverage the concept of Trial Networks from 6G-Sandbox [6GSBOX], enabling a fully automatized deployment of as Virtual Private Cloud [VPC] with an OpenCAPIF instance inside. Traffic within the Trial Network will be proxied through the TN bastion, a node ensuring proper network isolation, increased security policies, and a declarative whitelist of addresses that can bypass its firewall. The architecture of the target Trial Network is shown in Figure 14.

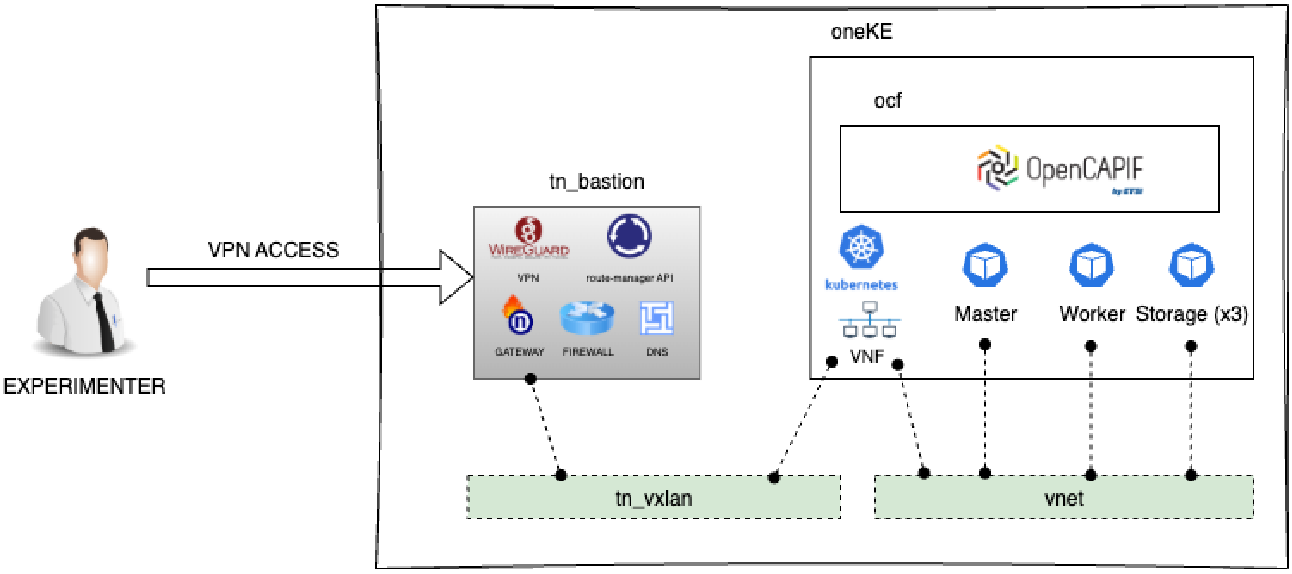

Figure 14. Architecture of the target Trial Network

The OpenCAPIF cluster is expected to be integrated with the HPE's 5GC API, and the N-app.

The Spanish cluster will additionally count with a separate OCF instance for development and testing purposes, deployed within UMA campus in a k8s cluster with increased computing resources. This development OCF will first run without isolation and afterwards imitating the setup at La Mayora.

Open CAPIF is not part of the Finnish cluster implementation for the 6G-VERSUSdue to the nature of the architecture and the fact that there is only one platform in the Finnish Cluster (5GTN). Platform architecture for 6G-VERSUS in the Finnish cluster is not open and access to NEF or NWDAF is not shared with anyone. Open CAPIF on the other hand is part of the 6G-Sandbox Toolkit that is offered for experimentation as part of the 5GTN as described in D2.1 [6GVERD21].

OpenGateway

Open Gateway is a global framework of common network APIs that simplifies access to mobile operator networks. By providing developers and cloud providers a single point of access to the world's largest connectivity platform, Open Gateway accelerates service deployment and fosters innovation. It supports application portability and seamless user experiences, helping the telecom and tech industries fully realize the potential of 5G. With standardized open APIs, Open Gateway transforms how developers build and deliver services.

Telefonica commercial 5G network supports the consumption of several Open Gateway Service APIs defined in CAMARA. Specifically, for the Roquetas, Spain scenario, the Quality on Demand API will be available. This API empowers you to control the networking performance for your applications, enhancing the user experience, and not having to worry about the telco operator that your client is subscribed to.

ONEmNEF

OneSource will expand the capabilities of the ITAV and ALB testbeds in Portugal by deploying ONEmNEF, a microservice-based 5G Core network function designed to securely expose 5G and 6G network features to authorized partner applications (Figure 15). Built on a cloud-native architecture and compliant with 3GPP Releases 16 and 17, ONEmNEF enables standardized, dynamic interaction between the core network and external Application Functions. Its architecture comprises four main components (northbound and southbound gateways, NEF API services, and database services) coordinated by a central message broker that manages communication, validation, and data handling. Integrated load balancers and proxies ensure secure, efficient data flow. ONEmNEF will leverage advanced API exposure for intelligent traffic control, adaptive network behaviour, and smart data management to improve the testbed functionality. Ultimately, Quality of Service and Experience will be improved, especially for demanding applications such as streaming and low-latency services, while promoting seamless, programmable integration with next-generation network services.

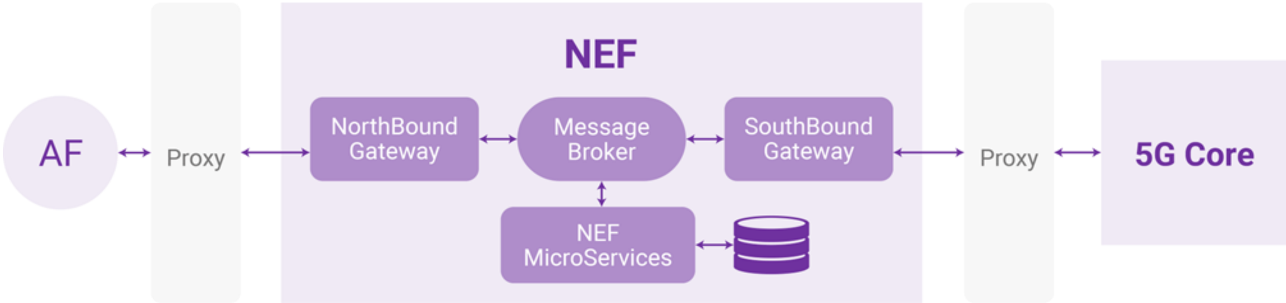

Figure 15. ONEmNEF high level architecture

Dynamic Slicing

Industrial organizations proposed many use cases with completely distinct requirements, demanding extreme network flexibility to accommodate them. However, existing network slice managers supported by projects and research have limitations in configuration. They cannot adjust the 5G network to ensure the required performance for each use case. The proposed use cases necessitate a more flexible network slice manager capable of configuring the 5G network to support the required network slice, ensuring the necessary performance for each use case. The Slice Manager, available in the Portuguese cluster in the ITAV infrastructure, generates slices tailored to one of the three primary 5G services [eMBB (enhanced Mobile Broad band), prioritizing throughput and spectral efficiency, URLLC (Ultra Reliable Low Latency Communication), focusing on low latency and high reliability, and mMTC/mIoT (massive Internet of Things), aiming for low device energy consumption and high connection density] based on provided network Key Performance Indicators (KPIs). It provides dynamic slicing enabling the adaptation of the slice performance in real time without communication disruption. The simplest implementation of slice mapping involves selecting a pre-configured slice. However, the network slice mapping can be enhanced with the capability to provide slice customization. This customization is enabled by location-based slicing and adjustment to Policy and QoS management enforcing the required SLAs. The developed solution includes all standard network functions. The external endpoints of CSMF and NSMF, as identified in the TMFs, are currently limited to create, update, delete, and get. These endpoints are open as a REST request, enabling the end user to interact with the PoC to implement and configure the necessary network slices.

The current version of the Slice Manager accepts REST requests to configure the 5G network, allowing it to work with Postman and any software capable of sending REST commands. It can also be converted into a container for easy deployment, management, and replication. It is able to manage multiple slices, support E2E slices, map network slices to network configurations, and enable dynamic slicing. It also includes the essential capabilities of network resource monitoring and slice feasibility evaluation, which are crucial for the operation of other components. However, it supports only part of the slice lifecycle management, lacking supervision and reporting. As a result, dynamic slicing can only be triggered by external requests. Additionally, the Slice Manager, originally custom tailored to operate with the commercial-graded network existing at ITAV, is being extended to interoperate with other 5G cores, in spite of the fact that some functionalities might differ or not be present in other 5G network implementations.

Last but not least, in order to make the Slice Manager fully aligned with the 6G-VERSUS architecture, ITAV is developing CAPIF support, allowing the Slice Manager to be a CAPIF-enabled NF interfaceable by N-Apps.

Open5GS Provision of IP address

One of the functionalities to be implemented in the Immersive remote driving Use Case of the Spanish Cluster is the translation of the IMSI to the IP address of the data plane to which this IMSI is connected.

The intention of implementing this is to support the Ambition 2 (Transformation of the verticals into 6G applications), that is to Transform the verticals into 6G applications. Currently in many testbeds, the configuration file of the vertical must include the IP address of the data plane to which the Device is connected to perform the connection, that requires to find out this IP address and to set it up in this configuration file. Of course, if the 5G connection is reset or the device is re-attached, the IP changes and this process must be repeated.

That is a work-around that should be eliminated in an application, so the proposal here is to use in the configuration file the IMSI and include in the triplet a mechanism to get the IP address automatically from the CORE. A simple modification has been made to the SMF of the Open5GS core (v2.7.6-67-g51b967f+). The modification consists of exposing a REST API through a configurable port and the "/pdu-sessions" endpoint, which offers a GET method that returns a JSON object with the list of sessions currently active in the SMF and their associated information.

```
$ curl http://127.0.0.4:7771/pdu-sessions

[{"imsi":"999990000000402","pdu_session_id":1,"ipv4":"10.45.21.2","sst":1,"sd":"ABCDEF"},{"imsi":"999990000000404","pdu_session_id":1,"ipv4"
:"10.45.23.4","sst":1,"sd":"ABCDED"}]
```

The value this modification adds to Open5GS's core functionality is providing information about the status of UE sessions: Open5GS allows you to obtain session configurations by accessing the MongoDB database, including the IP address that will be assigned to a UE when it registers on the network. However, without this modification, it was impossible to know whether a UE was registered at any given moment, at least without inspecting the SMF logs, a procedure that is not very reliable.

The NEF function is performed by the NaC (Network as Code) component, which publishes a REST API through CAPIF. This API is consumed using a client Python library. An example of using this Python library is shown below:

```
from nac_client import NacApi

imsi='999990000000025'

api = NacApi()

session = api.UE_sessions_get('Nodo_2', imsi=imsi, status='active')

if session:

  print(session[0].pdu_address.ipv4)

else:

  print(f'Session for IMSI {imsi} not established')
```

This new version of Open5GS will be installed in La Mayora in a specific server hosting also the triplet for the Immersive driving application of the use Case.

3.3 Cloud/Edge technologies

GPU at the edge

A GPU server residing at the OTE edge site furnishes the Athens platform with powerful computational equipment, necessary to execute video analysis for the wild-fire detection as well as to support beyond 6G use cases such as XR/VR demos. The specifications of the server are as follows: Apollo 6500 ProLiant XL675d Gen10 Plus, with the following specs: (2) AMD EPYC 7453 28-Core Processor, 112 VCPUs, 128 GB RAM, 8 TB storage and 4x NVIDIA A10 24GB PCIe NonCEC Accelerator.

Securing edge

The reference (Lab) networks (located in Sofia and Varna towns) of A1 are available for use in the implementation of the project's use cases. By utilizing two UPFs — one representing the central core (in Sofia) and the other the edge (in Varna), positioned closer to the wind farm and near the base station — we are going to emulate a fully distributed 5G data plane. This setup enables: Testing of traffic routing and steering mechanisms between the edge and the central core, based on QoS policies and application-specific requirements; Verification of network slicing operations and local breakout functionality; Performance evaluation for low-latency services and Exploration of AI-driven network optimization techniques for enhanced traffic management and service delivery.

Dedicated UPF at edge

The dedicated UPF at the edge for the Spanish cluster is a P4programmable, 3GPPcompliant User Plane Function designed to accelerate 5G core user plane processing through a flexible, high performance data plane that decouples packet processing logic from the underlying hardware to support advanced 6G use cases.

This UPFP4 technology, developed by UMA within 6GSBOX [6GSBOXD33], is available in two deployment options to balance agility and performance: a software implementation on BMv2 P4 [BMv2] switch for maximum portability and rapid iteration, and a hardware implementation targeting Intel Tofino 2 to achieve line rate throughput and deterministic low latency for demanding scenarios. Both variants implement the core UPF feature set— GPRS Tunneling Protocol – User Plane (GTPU) tunnel management alongside processing of Packet Detection Rules (PDRs), Forwarding Action Rules (FARs), QoS Enforcement Rules (QERs) and Usage Reporting Rules (URRs) —under the control of a standard 5G control plane.

The UPFP4 is targeted for deployment within the Spanish cluster at the La Mayora site as a dedicated edge UPF to support the platform's Cloud/Edge technologies scope. Its programmable data plane will enable dynamic creation and enforcement of forwarding and QoS rules to prioritize critical connections and satisfy stringent latency and reliability requirements for advanced 6G scenarios. The software option enables agile experimentation on general purpose servers, while the hardware option delivers extreme performance for production grade trials when required. This combination provides a unified, 3GPP-compliant user plane that can adapt policy and traffic treatment per use case while maintaining high efficiency at the Edge.

Cloud servers

Azure cloud servers will be used to store and manage datasets generated by selected applications, including the data that will later be used to train and validate AI models. This includes scalable storage for data ingestion and preparation, automated data pipelines, and data/catalog versioning to ensure traceability and consistent reuse across model development and operational workflows. Once trained, the AI models—as well as other application components—will be deployed on Azure to support production use. Azure will also provide secure access controls, encryption, monitoring, and reliable integration with downstream applications.

The amount of computational and storage resources provisioned by the servers will vary depending on application demands and workload intensity. Thus, capacity will be scaled up or down as needed to accommodate peak processing and reduced during lower-usage periods, optimizing performance and cost while maintaining service reliability.

Local storage

University of Oulu has implemented local data storage. It is based on NetApp device model AFF-30 with 32TB storage capacity. Main use for the data storage in 6G-VERSUS is to store the runtime measurement data produced by the Remote Base Station system, log AI decisions, store the data from the xApp and store the FMI weather data fetched every 3 hours from the Finnish Meteorological Institute. It will also be used to store the datasets that are to be published.

New Edge server

A new server will be deployed in La Mayora to support the Immersive remote driving use case. It is an AR S5001A 2A Xeon v5 Skylake model with two Intel Xeon E5 6130 v5 (or 6138) processors, 16 cores, 120W power, and an Intel C621 chipset. It includes titanium power supply, 192 GB DDR4 2666 MHz memory, and two 2.5 inch 960 GB SATA SSDs.

The server will host:

- Open5GS Core
- A VM to host the CAPIF and Network as Code (NaC) instances, as well as the N-App and V-App.
- A VM to host the AI-App.
- A VM to host an InfluxDB time series database, along with the Grafana application for analyzing and visualizing the data series generated by the use case executions.

The aim is to have the separate configurations for the different applications used in La Mayora in order to use one or another depending on the application to be used.

3.4 Devices

USB 5G dongles

The USB 5G Dongle, powered by the integrated RM530N-GL Module [USB5G], delivers high-speed 5G connectivity for faster data transfer and improved network performance (Figure 16). Supporting both Sub-6 GHz and mmWave frequencies, the module enables high-bandwidth, low-latency communication, making it an ideal solution for connectivity across a variety of environments and applications, and will be utilized in the Greek use case.

Figure 16. USB 5G dongles

5G outdoor modem such as TP-LINK NE200 can be used to connect different devices to the radio unit in the remote unit system (Finnish Use Case). For example, the modem can be connected by cable in the control system (e.g., Victron Cerbo GX) then can communicate via the radio unit and microwave link towards the 5GTN. Thus, the data of renewable energy sources, batteries, and sensors connected in the control system can be communicated between the remote unit and 5GTN. Also, the option to connect the control system to radio unit or to microwave link though Ethernet cable may be possible (in this case the 5G outdoor modem may not be needed in the remote unit).

CPEs Bulgaria

Zyxel NR7501 5G NR Outdoor Router will be used in the Bulgarian cluster as a GW to connect field devices (PMU, remote sensors, etc.) over 5G SA network to a core network and backend. This device is featuring the latest 3GPP Release 16 standard with both Sub-6 and mmWave and was selected over the other available options in its class because it is specifically designed for 5G FWA deployments, enabling 5G SA service and capability of delivering high throughput and good coverage even in challenging or remote locations, without needing additional wired infrastructure. The NR7501 supports a wide operating range of temperatures and humidity, making it particularly suitable for rural area, where most of the Bulgarian pilot will take place.

RedCap

For the purpose of the use-case deployment, the French facility will support 5G Reduced Capability (RedCap) operations, leveraging the RG255C series to optimize network performance for low-power, cost-efficient devices (Figure 17). The RG255C series is a 3GPP Release 17-compliant module designed for IoT, industrial automation, and smart city applications requiring reduced complexity, lower power consumption, and enhanced spectral efficiency compared to traditional 5G NR devices. Key technical features of the 5G RedCap RG255C Series are as follows:

- **3GPP Release 17 Compliance:**
  - Supports Reduced Capability (RedCap) NR-Light operation for low-power, bandwidth-efficient connectivity.
  - Operates in FR1 (Sub-6 GHz) spectrum, ensuring optimal coverage and penetration.
- **Network Adaptability & Performance Optimization:**
  - Offers maximum downlink/uplink throughput of up to 200 Mbps / 100 Mbps, suitable for mid-range IoT and industrial applications.

    - Utilizes single-antenna MIMO support to reduce complexity while maintaining robust connectivity.
    - Supports network slicing, allowing optimized resource allocation for latency-sensitive applications.
- **Power Efficiency & Low Latency:**
    - Implements power-saving mechanisms like eDRX (Extended Discontinuous Reception) and PSM (Power Saving Mode) for extended battery life in IoT scenarios.
    - Supports URLLC-grade latency optimizations, making it suitable for real-time industrial control and smart metering solutions.
- **Security & Reliability:**
    - Features secure boot and encryption protocols, ensuring end-to-end data integrity and protection.
    - Supports OTA (Over-the-Air) firmware updates to enhance longevity and adaptability in dynamic network environments.
- **Integration with the Facility Infrastructure:**
    - The RG255C series will be deployed within the facility's OAI based 5G SA (Standalone) core network and RAN, and integrated with the Greencityzen (i.e., the French cluster partner) sensors (i.e., water level and soil humidity sensors) enabling end-to-end RedCap validation.
    - Performance benchmarking for latency, packet loss, reliability, and energy consomption metrics will be carried out under controlled testbed conditions.

By supporting the 5G RedCap RG255C series, the French facility enables scalable, cost-effective 5G connectivity for massive IoT, industrial applications, and smart infrastructure, ensuring seamless integration with next-generation networks while maintaining low complexity, reduced energy consumption, and optimized spectrum utilization.

Figure 17. The Quectel 5G RedCap RG255C series [QUECTEL]

The RedCap UEs used by the UOULU are based on the very same Quectel RG255C chipset, and specifically the RG255C-GL [QUECTEL2] mPCIe module containing this chipset. The module is further mounted on the Quectel 5G-M2 EVB [QUECTEL3] development board, which is further connected through a USB to a computer (either a full-featured personal computer or a single-board computer). Subject to minor hardware modifications, measurement of the current consumption of the module can be enabled by connecting an external power supply and measurement equipment. Two different testbed setups, both being part of the 5GTN, are implemented in UOULU. The former one is based on using the commercial-grade gNBs and the main 5G SA core networks. The latter and alternative one is based on the use of gNB and core network implemented by OAIBOX 40 Max from Allbesmart. While the former one enables industrial-grade reliability, the latter allows more flexible control over configurations and easy access to network key performance indicators.

Equally, the Portuguese cluster will employ RedCap UEs using the Quectel RG255C chipset, which connect to OAI 5G RAN and Open5GS 5G core. In the cluster context, RedCap module provides connectivity for enabling real-time environmental data transmission from deployed buoys platforms. It interfaces via UART with integrated power monitoring hardware that tracks its energy consumption patterns during operation.

Preliminary use-case agnostic energy consumption measurements assessing 5G NR RedCap against regular 5G NR are provided in section 3.6.

Unmanned Vehicles (UGVs, UAVs and USVs)

The Robotic Dog that will be used in the Greek cluster is the Unitree Go2 [UNITREE] model and will be employed in the 6G-VERSUS trials as a next-generation autonomous ground unit for demanding emergency and rescue environments. Equipped with a high-performance AI computing unit, it will support real-time Simultaneous Localization and Mapping (SLAM), obstacle avoidance, and adaptive path planning in unstructured terrains. The platform will rely on a battery pack enabling up to 2 hours of continuous operation and will reach speeds of over 5 m/s, allowing agile movement in disaster-stricken areas.

The Go2 will integrate a 360° LiDAR sensor, depth cameras, and IMU modules, providing situational awareness and precise navigation in GPS-denied environments. When connected over 5G/6G sidelink, the robotic dog will transmit telemetry and high-resolution video feeds to nearby UAVs or directly to the command center, ensuring seamless coordination in search and rescue missions. Combined with UAV relays and edge computing, the robotic dog will become part of a resilient multi-agent system, where ground and aerial units cooperate to extend coverage and reliability of mission-critical communications.

In the same cluster, the DJI Mavic [DJI] will be employed in the 6G-VERSUS trials as a lightweight aerial platform supporting live video streaming, environmental monitoring, in mission-critical scenarios. The drone will feature a telephoto camera, a wide-angle sensor, and a high-resolution imaging unit, enabling responders to obtain detailed situational awareness. With a flight time of up to 45 minutes and a maximum speed of 21 m/s, the Mavic will provide rapid deployment and coverage of large operational areas.

When integrated with 5G/6G connectivity, the drone will transmit real-time video feeds and data. In this way, the Mavic 3T will enhance situational awareness, enable early detection of hazards such as wildfires, and ensure reliable links between aerial and ground agents, forming an integral part of the multi-agent 6G-enabled rescue ecosystem.

In the Spanish cluster, particularly in La Mayora, a remote-controlled drone will be deployed to allow an operator to manage its movements and collect samples. The use of the drone will enable precise and flexible sample collection while reducing the need for manual fieldwork. Additionally, a Unitree Go2 robot will be also deployed to perform automatic surveillance and intruder detection in farming operations. The robot operates in coordination with a 5G Integrated Sensing and Communication (ISAC) system, using 3GPP-compliant radio parameters to enhance detection accuracy. This integration enables real-time monitoring of the environment, improving security and operational awareness while minimizing the need for manual supervision. Both could be complemented with a robotic arm to fulfill their missions.

Additionally, a Robotnik AGV will be deployed, which has been modified to integrate a remote teleoperation system with bidirectional communication capabilities. This platform is also being designed to support fully autonomous mission execution, enabling navigation through predefined waypoints and routes. The objectives of this implementation include enabling continuous and scalable crop monitoring, improving data acquisition, reducing operational costs and human exposure in the field. Furthermore, the system aims to support advanced agricultural analysis through the collection of sensor data, facilitating informed decision-making and enhancing the efficiency and sustainability of agricultural operations.

In the Portuguese cluster, remote-controlled drones (DJI Mavic 3M (enterprise) and DJI Mavic 3 Pro) will be deployed and connected to the Mobitrust platform (V-App). These devices will stream live video feeds to Mobitrust, enabling AI-assisted video analysis for detecting potential water pollution and floating objects that might pose a safety risk for ships.

Remotely operated RC boats with autonomous navigation capabilities will be used within the port of Aveiro to support environmental and navigational safety monitoring. Each RC boat is equipped with a range of sensors for comprehensive data collection, including water and air temperature, pH, turbidity, sonar, camera, and GPS.

Sensors

Concerning Roquetas de Mar in the Spanish cluster, cameras with 5GSA connectivity will be used to monitor various processes at the plant and ensure that the treatment processes are working correctly. In addition, water quality sensors (E. coli) will be used to monitor the quality of the water at the plant's outlet and ensure that the treated water is suitable for use in irrigation, as E. coli is highly harmful to health. In addition, within the same cluster water quality sensors will also be installed at La Mayora to monitor water quality and ensure that the water used for irrigation is of high quality and safe for irrigation purposes.

The Fuel Gauge and Power Profiler with RG255C Modem Module is a custom hardware that combines battery monitoring and power profiling with the RG255C modem through a UART interface, enabling precise power consumption analysis and 5G connectivity in the Portuguese cluster. This solution is deployed on a custom-designed buoy, equipped with an energy harvesting system and modular sensor interfaces - supporting submerged sensors for water quality and pole-mounted sensors for air quality monitoring. The platform provides real-time power profiling and energy metrics, ensuring robust connectivity and data integrity for 5G-enabled environmental monitoring applications during field deployments.

Cameras

The ASECAM 4K 8 MP IP camera, to be used in the scope of scenario 2 of the Portuguese cluster, is a high-resolution network surveillance device designed for reliable indoor and outdoor monitoring (Figure 18). It delivers 3840×2160 (4K) video using H.265 compression, reducing bandwidth and storage requirements. The camera supports Power over Ethernet (PoE) for simplified installation and features a weather-proof metal housing (IP66/IP67), infrared night vision, and ONVIF/RTSP compatibility for integration with standard video management systems. Some variants also include AI-based motion or face detection, making it suitable for cost-effective, high-definition surveillance in industrial or smart-infrastructure deployments. In the scope of the Portuguese trials, this AI capability will be replaced with a server-based version at the network edge for enabling the camera’s video feed to be used to detect the scenario’s specific aspects, namely license plates and hazardous cargo symbols.

Figure 18. The ASECAM 4k mp IP surveillance camera

The DarkFighter IR AcuSense Network Speed Dome will be deployed as part of the wildfire detection vApp in the use case of the Greek cluster and will act as an intelligent sensing node that continuously delivers high-resolution RTSP video streams to the AI application for real-time smoke and flame detection. The cameras support remote pan-tilt-zoom control, IR-assisted low-light operation, and stable network transport over IP (typically with PoE power), ensuring wide-area coverage and continuous operation in the outdoor conditions target by the Greek use case.

Figure 19. The DarkFighter IR Accusense camera

Customer-premises equipment (CPE)

To be involved as well in the scope of scenario 2 of the Portuguese cluster, the 5G CPE Pro 2 is a customer-premises equipment (CPE) device that enables fixed wireless broadband access through 5G mobile networks. Supporting both non-standalone (NSA) and standalone (SA) 5G modes, it integrates dual-band Wi-Fi 6 connectivity to deliver high-speed local area networking. With theoretical downlink rates of up to 3.6 Gbps and Gigabit Ethernet interfaces, the device facilitates the deployment of ultra-broadband services in contexts where fixed-line infrastructure is limited or unavailable. Its design exemplifies the use of advanced radio and networking technologies to extend broadband coverage and support emerging digital services in residential and small-office environments

Phasor Measurement Unit (PMU)

In the Bulgarian testbed and use-case, several UEs will send to or receive data from the 6G-VERSUS triplet such as Phasor Measurement Units (PMUs), power electronic inverters connecting the emulated or physical energy storage system of EE' wind farm to the MV power substation, and other IoT sensors which monitor the power flow of the wind farm. However, for the V-Apps the key sensors are the PMUs and the inverter. Below, there is a brief description of the functionality, and the communication protocol used by these sensors to exchange information with the 6G-VERSUS V-App.

Synchronized measurement technology is an advanced enabling technology for smart grid applications such as Wide Area Monitoring and Control, having as key element the Phasor Measurement Unit (PMU). The PMU (Figure 20) uses GPS synchronized equipment and provides accurate and synchronized voltage and current phasor measurements, as well as frequency, rate of change of frequency (RoCof) of the busbar of the grid with high reporting rate (e.g., typically with 50 frames (phasors) per second for 50Hz AC grids, while more recent models can even send up to 200 phasors per second [SYNC]). In the pre-piloting phase of the Bulgarian pilot, a commercial PMU (e.g., Sentinel-Arbiter Model 1133A [ARB]), available at the UCY testbed will be used, while for the final tests at the EE premises another model (to be decided) of PMU will be installed at the MV point of common coupling (PCC) of their wind farm. Both PMUs report with 50 frames/second for 50Hz grids.

Figure 20. Phasor Measurement Unit (PMU) used for monitoring and control of smart grids

The PMU's communication protocol, defined by IEEE C37.118, uses TCP/IP or UDP/IP to transmit synchrophasor data between PMUs and a physical or virtual (application-based) Phasor Data Concentrators (PDCs). The standard specifies different frame types (Configuration, Data, Header, Command) for efficient data transfer. TCP provides reliable, connection-oriented communication, while UDP offers lower latency but without guaranteed delivery.

One STER PMU, installed at the MV bus of the PCC of EE with the Bulgarian distribution power grid, will communicate via the 5G network of A1 with the V-App (WAM&C deployed at the central cloud of A1). Because PMUs are not 5G ready, a 5G-gateway, equipped and configured with a SIM card of A1, will connect, via an Ethernet cable, with the PMU such that the whole system to behave as an A1's UE.

Power electronic inverters

Prototype or commercial inverters of a wind turbine, and/or of a Battery Storage System (BSS) or digital-twin replicas will be used in the Bulgarian use-case. A smart inverter is a power electronics device used to convert the DC power of a DER (Distributed Energy Resource) (e.g, PV), or a Battery Storage System (BSS) into AC power in order to properly inject the power into the grid in a synchronized and controllable manner. The inverter is an intelligent actuator that is able to maximize the DERs production and control the charging and discharging procedure of the BSS. In actual systems, the DC side of the inverter is connected to an actual battery stack, or a DC source with BSS emulation capabilities can be used instead of an actual BSS stack. The AC side of the inverter is connected to the power grid in actual setup. The embedded controller of the inverter is equipped with IoT functionalities and can be used to report measurements regarding the operating conditions of the inverter, and it can receive coordination signals (set-points) to regulate the operation of the inverter (e.g., reference active or reactive power) according to third party applications (e.g., V-App/Regional Controller). The exchange of measurements and coordination signals is performed through the Modbus TCP/IP protocol (every 200ms), where the inverter is the server and the V-App is the client (thus, V-App can exchange signals with the inverter).

The power electronic inverters are not 5G ready. Thus, similar to the PMU, the 5G-gateway will be used to connect this device to A1 5G network via an ethernet cable.

3.5 Transport

NTN as transport

The University of Málaga provides 5G NTN service as a transport solution, in backhaul mode, which places the satellite link between the gNB and the core network. This approach allows connectivity to be established between various sites with gNB coverage and different emplacements with core network deployments, enabling flexible deployment to support the specific use cases. UMA will connect their laboratory with the Mayora fields, one of the emplacements of the Spanish use case, to support this connectivity mode. Monitoring and Measurements Tools

Keysight tools

Keysight provides the project with a comprehensive suite of tools for network performance measurement and monitoring in the transport part, including Cloud Peak, Hawkeye, IxChariot, LoadCore, Nemo Solutions, RICtest, and WaveJudge. Depending on the specific test cases, these tools are employed across multiple trial clusters to perform measurements. The functionality and intended usage of each instrument are described below in more detail:

- **Cloud Peak**: It is a web application for functionality validation and performance benchmarking of virtualized network infrastructure through realistic workloads and traffic emulation. Within 6G-VERSUS, Cloud Peak will be employed in both the Greek and Portuguese clusters for Network Functions Virtualization Infrastructure (NFVI) validation scenarios.
- **Hawkeye**: It is an active network monitoring platform capable of simulating application traffic and collecting key performance metrics. When necessary, it can complement IxChariot by providing detailed insights into live network behavior. Potentially, Hawkeye may be deployed in the Finnish and Greek clusters when specific measurement requirements cannot be fulfilled with other monitoring tools, such as IxChariot or Kaitotek Qosium.

- **IxChariot**: It simulates real-world applications to predict device, system, and network performance under realistic load conditions. This tool can generate diverse realistic traffic patterns, such as voice and video, and conduct measurements on various Key Performance Indicators (KPIs), including throughput, packet loss, jitter, delay, voice Mean Opinion Score (MOS), and video Media Delivery Index (MDI). Real-time visualization of these metrics is also supported. Within the project, IxChariot will be used in the Finnish, French, Greek, and Portuguese clusters to characterize network performance for different types of application-level traffic patterns.
- **LoadCore**: This software-based solution enables 5G core network validation, which is able to emulate up to millions of realistic subscribers and conduct performance testing with complex call models. LoadCore will be applied across several clusters, including the French, Greek, Portuguese, and Spanish pilots. For example, the Spanish cluster will utilize this tool to conduct wrap-around testing for the 5G core network, enabling characterization of its performance and energy efficiency under different configurations and load conditions.
- **Nemo Solutions**: Nemo is a comprehensive suite designed to evaluate performance and quality of mobile networks (Quality of Service (QoS) and Quality of Experience (QoE) testing) from an easy-to-carry mobile phone. Depending on the use case, Nemo toolkits include several options and combinations of hardware and software components. On the software side, Nemo Handy (mobile application), Nemo Outdoor (laptop-based drive test tool), and Nemo Analyze (desktop-based post processing solution) are available, while hardware instruments, such as Nemo Diagnostic Module and Nemo Active Probe, enable flexible testing on different devices and environments. Nemo Solutions will be widely used in 6G-VERSUS, across Finnish, Greek, and Spanish clusters. For instance, in the Spanish cluster, Nemo Handy will be installed on a commercial-off-the-shelf (COTS) phone, placed inside a Nemo Active Probe for continuous and unattended deployment in La Mayora. The collected data will then be analyzed and processed by Nemo Outdoor and Analyze, generating insights about the network such as the coverage map.
- **RICtest**: This software-based platform is capable of simulating hundreds of O-RAN nodes, such as Central Unit (CU), Distributed Unit (DU), and gNB, along with their associated User Equipments (UEs), which can be connected via the standard-compliant O1 and E2 interfaces to the Device Under Test (DUT). RICtest creates a digital twin for performance, conformance and interoperability testing of near-RT RIC / xApps and non-RT RIC / rApps. As a key enabler for testing AI/ML processing, it will be used in both the Finnish and Portuguese clusters within 6G-VERSUS.
- **WaveJudge**: By combining over-the-air capture of IQ data with real-time protocol decoding and PHY analysis, this instrument provides real-time visibility into interactions between protocol and physical layers. Thus, it facilitates the signaling and performance characterization and optimization of various wireless technologies such as 5G NR, O-RAN, NTN, and Reduced Capability (RedCap). The Portuguese cluster will leverage this tool during its trials.

Energy measurement system

In the Finnish cluster the plan is to implement the measurement system that combines energy production (solar panels, wind energy, and hydrogen energy), energy storing, energy consumption, energy-weather forecasting and weather measurements. This measured data will be used by the AI-App to perform decisions about the actions performed in the remote unit system. For example, the energy consumption of the remote unit can be decreased, for example by decreasing communications capacity or bandwidth, if the production of the energy is currently low. Victron Energy and Carlo Gavazzi provide a large variety of professional energy meters that could be used to measure the energy consumption of different devices in the remote unit. Furthermore, energy consumption in 5GTN (e.g., CU and DU of O-RAN) could be measured to have additional information by using Netio Power Box AC power meters (already in use at UOULU) or Carlo Gavazzi energy meters (used by UOULU project partner in the previous project).

3.6 Energy Efficiency related equipment

Energy Efficiency as a Service (EEaaS)

Energy Efficiency relies heavily on two aspects: a) real-time fine-grain monitoring of power consumption, and b) intelligent algorithms to apply optimization/policies based on QoS and real-time metrics. The Greek platform will feature real-time fine-grain monitoring. It will be primarily achieved via custom SW and vendor APIs, which themselves give access to the current/voltage draw of various HW components and various HW counters of the computing system. During development/testing stage, the analysis will be also supported by 3rd-party HW monitors, e.g., from Keysight.

The tools to be used for the Intel-based sub-systems of the platform will be the RAPL interfaces, which can provide a couple of power values per socket (incl. DRAM) and few more values per core, which we will combine with real-time counters regarding resource utilization (e.g., CPU%, accesses#), in order to perform a more fine-grain analysis. For embedded GPUs, we will rely on integrated tools, such as Tegra-stats and Jetson-stats. The tools themselves rely on integrated HW (INA3221) and report real-time metrics to the user. In the case of server-class GPU, we will rely on the NVIDIA Management Library (NVML). For ARM-based subsystems, we will exploit the INA3221 TI integrated chip. This auxiliary controller will provide to us a Triple-Channel, High-Side Measurement, Shunt and Bus Voltage Monitor with I2C- and SMBUS-Compatible Interface.

Redcap

Preliminary energy consumption tests have been executed in the Portuguese cluster testbed, using OAI 5G RAN and Open5GS 5G core, to compare 5G RedCap module Quectel RG255C (see description in section 3.4) against a standard 5G Release 15 unit. For testing purposes, continuous 30 Mbit/s IP downlink and uplink traffic was generated with iperf. Energy consumption was recorded for 3 minutes in each scenario. In addition, the test was also executed in idle mode, without any traffic. The test results (Figure 21) show that the RedCap module has a significantly lower energy consumption under all traffic load conditions. For downlink and idle mode, the consumption pattern is quite stable, but for uplink traffic an oscillatory behaviour can be observed in the RedCap module.

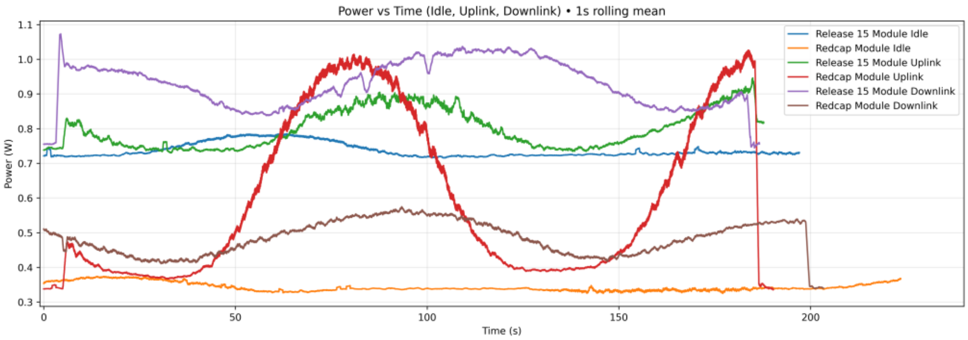

Figure 21. Preliminary RedCap energy test results in the Portuguese cluster

Initial energy consumption measurements for RedCap were carried out by UOULU using the setup described in Section 3.2. During these measurements the antenna ports of the RedCap kit and the OAIBOX were connected through cables with attenuators and splitter; maintaining RSSI of -89dBm and RSRP of -63dBm with ±1 dB variation, allowing RedCap to operate using the maximum modulation coding scheme (MCS) supported - 28. The 5G RedCap network was set up in band n77 as TDD network with 3DL/1UL TDD pattern and 51 RB bandwidth and 5 ms periodicity. 1 MIMO layer and single UL and DL antenna ports were used. The dev. kit was modified following the manual [QUECTEL3] to enable external power supply and measurement of the current consumed by the RedCap module. This was done using the N6705B Agilent/Keysight DC-DC power analyzer, configured to provide 3.8 V DC current. The current consumption was logged with a sampling period of 40 microseconds. During the tests the UE was connected to a test laptop, which controlled it – activated, and, once connection to the network is established could generate the uplink or downlink traffic using iperf tool.

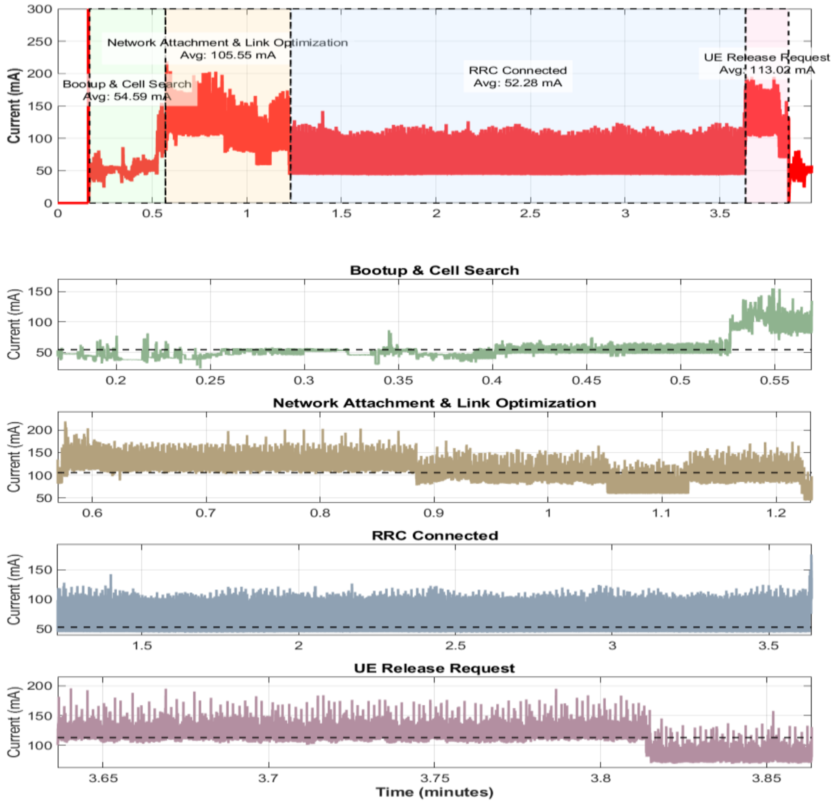

Figure 22. Illustrative current consumption profiles of 5G RedCap (note that in the shown case no extra UL/DL traffic was generated by iperf)

An illustrative current consumption profile is depicted in Figure 22. Using this scenario as a reference, also the cases when maximum possible traffic over TCP and UDP in UL and DL was transmitted were measured (i.e., around 70 Mb/s for DL, and 27 Mb/s for UL). The average current consumption for these modes with reference to the no-traffic case shown in Figure 23. Additionally, the energy consumption of the GNSS receiver and the sleep mode are depicted. Comparing these results against the table characteristics of full-functional 5G modules (e.g., RM500Q-GL [RM500]) one can see that the measured RRC connected current consumption of RedCap is lower than the idle consumption of the 5G module by about 18% (note that the supply voltage for both cases is the same – 3.8V).

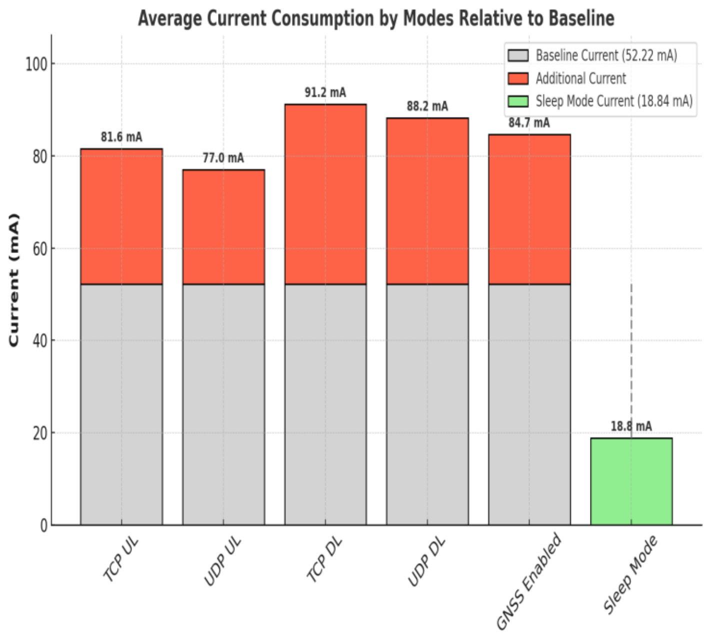

Figure 23. Current consumption

Currently, the work proceeds on measuring the other test cases (including FDD mode and other radio channel conditions) and experimentally comparing the RedCap and conventional 5G under the same channel conditions. Also, the studies related to the development of an AI-based solution for predicting the energy consumption of a 5G RedCap UE were initiated.

Energy-harvesting system for IoT devices

In the scope of the Portuguese cluster, a remote monitoring buoy is equipped with a comprehensive energy harvesting system designed to ensure autonomous operation in field deployments. Solar panels mounted on the buoy structure capture ambient solar energy to power the onboard systems, including the RG255C 5G modem module, sensor array, and monitoring hardware. The energy harvesting architecture integrates seamlessly with the custom-developed power management hardware, which features a Fuel Gauge for real-time battery state monitoring and a Power Profiler for detailed energy consumption analysis. This configuration enables continuous tracking of energy production versus consumption, allowing the system to optimize power usage based on available solar energy and battery capacity. The modular design supports scalable solar panel configurations, with the final number of panels to be determined through AI-driven simulations that model energy consumption patterns of the 5G connectivity, sensor operations, and data transmission cycles against expected solar energy production under various environmental conditions.

Energy-harvesting-aware EV Charging

In the scope of the Portuguese cluster, in order to optimize the energy usage of electric vehicle (EV) chargers, solar panels will generate energy, and the production data will be sent to the V-App, which will in turn forward it to the AI/ML-Ops Framework. Using this data, together with weather forecast information, the model will be able to predict the amount of energy that will be produced in the following hour. Based on these predictions, the V-App will act on the EV chargers to limit their charging power, thereby increasing the share of energy coming from solar production relative to the total energy consumed by the chargers.

Meanwhile, the N-App will collect the real-time geolocation of devices and send this information to the V-App, which can then control the streetlights by increasing their brightness when a device is detected nearby. When no devices are detected in the vicinity of a streetlight, its brightness can be reduced, thus saving unnecessary energy consumption.

Solar Panels

UOULU has already an installation of Trina solar panels (54 pc) on the roof. The decision that how many of these panels will be connected in the remote unit system (or do we replace the old panels with the new more powerful panels) will be made later (most probably eight new panels will be used). Matlab simulations to estimate the energy consumption and production of the remote unit system are performed to select the sufficient energy production capacity such as the number of solar panels.

Wind Turbines

One vertical wind turbine will be mounted on the roof of UOULU to provide energy for the remote unit system. The selection will be made between three different SkyPower wind turbines with the maximum rated power of 3 kW, 5 kW, or 10 kW. Wind turbine provider will visited UOULU to guide us to select the most suitable option of these turbines to be mounted on the roof (most probably the 5 kW model). In addition, Matlab simulations are also performed to estimate the sufficient wind energy production capacity for the remote unit system.

Batteries

Enough batteries with 51.2 V rated voltage will be selected for a battery bank to provide the sufficient energy storage system capacity for the remote unit system. One potential option for a battery is Victron LFP-51,2V/100Ah/5120Wh, and, for example, 18 these batteries could provide about 92 kWh capacity for battery bank. The operation temperature for charging the batteries is typically between 5 C and 40 C. Thus, there is need for outside storage box and heating during the winter months in Finland. Battery provider will visit UOULU to guide us to select suitable batteries and the related equipment to enable a dynamic energy storage system. In addition, Matlab simulations are also performed to estimate the sufficient capacity of the energy storage system for the remote unit.

Hydrogen Fuel Cell Generator

In UOULU, Hydrogen fuel cell generator is applied to provide energy for the remote unit system as the last method, i.e., hydrogen is the energy source in case no sufficient energy can be obtained from solar panels, wind turbines, or batteries. There are currently two options for the generator: UP400 or UP400 IND, both from PowerUP Energy Technologies. Both can provide electrical power up to 400 W with 12/24 V output voltage, consuming one liter of hydrogen per hour with maximum power. The operation temperature for the generators is between -5 C and 40 C. Thus, there is need for outside storage box and heating during the winter months in Finland. UP400 IND is the updated version of UP400 designed particularly for video surveillance and provides some advanced features such as enhanced communications capabilities that need to be considered when doing the selection between the two models. Both models support CAN protocol for communication that enables controlling and monitoring (e.g., on/off and AC power information) of the device, for example by using Victron Cerbo GX device via Victron's CAN VE.Bus or VE.CAN communicating protocols. In addition, only UP400 IND supports communication via ethernet cable (RJ45) and USB-C to enable the use of a router. UP400 IND also supports an IoT remote monitoring system enabling users to access parameters via cloud and control the generator remotely. Furthermore, Matlab simulations are performed to estimate the annual hydrogen consumption for selecting the sufficient number and size of hydrogen tanks, for example, tanks with 9- and 50-liters capacity are available. Note that hydrogen generator filters (2 pc) must be changed after every 3 months or 1000 hours of operation in wet environments (6 months or 2000 hours in dry environments). Also, the generator has an internal battery that can run flat if the generator is stored for a long period of time. Thus, it is recommended to run the generator every 12 months for at least one hour to charge the battery (also an external AC charger can be used manually).

Storage Boxes and Heating System

There is need for outside storage boxes and heating during the winter months in Finland. Hydrogen fuel cell generator requires a ventilation hole in the storage box for getting oxygen from air for its operation, but ventilation is not necessary for batteries at least during the winter months. Thus, separate storage boxes need to be built for the battery bank (probably also other devices are stored in the same box) and for the hydrogen fuel cell generator. Polyurethane foam and mineral wool are potential insulation materials for the storage boxes having good characteristics: water resistance, reduced flammability, and low thermal conductivity. There are several ways to heat storage boxes, such as low-wattage DC heating pads or heating films. For the storage box of hydrogen generator, the most suitable option may be to locate a low-wattage heating pad or film under the device to prevent a risk that in case of hydrogen leakage the heating causes a fire (hydrogen is lighter than air). For the storage box of battery bank, a good option might be to mount a low-wattage heating pad under and on the sides of batteries. In addition, separate thermostat controllers are needed for both storing boxes to keep the temperatures at the required levels, e.g., at minimum 5 C for hydrogen generator and 15 C for batteries.

Control system

Victron Cerbo GX MK2 device is a potential device for controlling and monitoring the renewable energy devices described earlier in the Hydrogen Fuel Cell Generator in UOULU. For example, there are cases where PowerUP hydrogen fuel cell generators have been controlled using a top layer IoT solution that communicates with Cerbo and the generator(s) to give an on/off command, when needed, or to monitor power information of the generator. Victron's CAN VE.Bus or VE.CAN communicating protocols can be applied to enable information exchange between the renewable energy source devices and Cerbo. Typically, VE.CAN protocol is used with third party devices (not Victron’s devices). In addition, Raspberry Pi (mini-PC on Linux) could be connected in Cerbo GX (via USB port) to provide a device where controlling algorithms could be also implemented.

RAN configuration for energy efficiency

In the French cluster, the battery lifetime of the sensors depends on how the RAN is configured. RAN parameters features related to discontinuous reception (DRX) and/or bandwidth part (BWP) are configured by an AI-App to expand battery life of sensors. For example, DRX can allow sleep periods for communications interfaces of sensors and BWP can optimize the size of bandwidth used by the the radio unit in the remote unit system. Thus, the sensors do not have to be awaken when not needed, which increases its energy efficiency.

Energy optimization software

Energy optimization framework developed at UOULU enables AI based energy aware budgeting to optimize energy usage of a remote radio site by forecasting energy availability and traffic demand. Using the Cerbo GX or an intelligent controller, all monitoring and control functionalities will be performed over the microwave link with the ORAN CU-DU setup. The AI-App will suggest energy balancing strategies to the intelligent controller for activating/deactivating power saving modes. It also performs dynamic energy storage system (DESS) using battery management system (BMS) for optimal energy storage and utilization, enhanced energy efficiency and reliable operation under harsh arctic conditions with polar nights.

Core Network/AI energy profiling

In the Spanish cluster, multiple test cases will be carried out to characterize the energy consumption of different components. Specifically, the energy footprint of the core network, AI training, and AI inference processes will be evaluated. Such experiments require high-precision power measurements, thus, Keysight PA2203A AC Power Analyzer will be used. This instrument is able to collect up to 33 KPIs in voltage, current, power, and energy, offering a comprehensive characterization of the overall energy profile. By connecting the power analyzer to the power supply of the server running core network or AI workloads, precise and reliable energy assessments can be obtained for those targeted entities.

3.7 The 6G-VERSUS AI/ML framework

In principle, an AI/ML Framework is a structured collection of tools, components, and workflows designed to streamline and accelerate the adoption of machine learning, enabling the integration of intelligence into broader systems. Its role is to provide a well-defined architecture and to establish data pipelines that manage the entire lifecycle of ML applications — from data ingestion, processing, management, and storage, to model training and reporting.

The framework not only orchestrates the various stages of the ML pipeline but may also be capable of executing machine learning models directly. However, the ability to perform inference or real-time execution depends on the specific type of framework instantiated and the computational resources allocated.

In 6G-VERSUS project, the AI/ML framework must be highly adaptable and generic, capable of supporting a diverse range of cluster scenarios with varying requirements. This flexibility is essential to ensure the framework can address the unique constraints and objectives identified in each use case.

To address the variability across the use cases defined within the project, two architectural approaches are proposed. In both approaches, the core AI/ML framework is deployed on a centralized server, ensuring consistency and scalability across deployments. Meanwhile, the AI-App, which interacts more directly with real-time data and local resources, operates on an edge server, closer to the data source and end-user environment.

The following sections present the two proposed architectures, along with a detailed breakdown of the components within each, highlighting their roles, interactions, and deployment contexts.

3.7.1 Centralized processes to train and execute ML models (A1 scenario)

In the first approach, both the training and execution model run on the framework. Each component of the architecture is detailed in Figure 24.

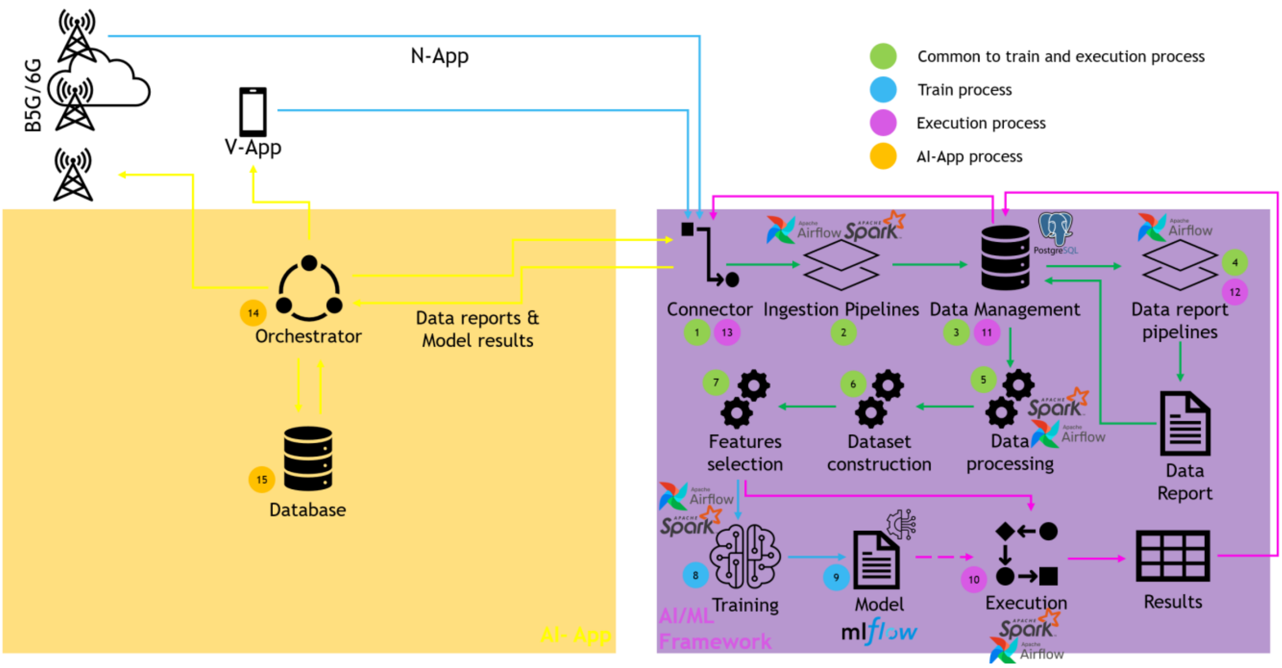

Figure 24. Architectural approach of A1 scenario

<u>Processes running on AI/ML Framework</u>

Common processes to train and execute ML model

1) Connector will be responsible for receiving data from external sources.

2) Ingestion pipelines will be responsible for ETL processes, so ingestion pipelines will extract, transform and load the data into the database.

3) Data management will be responsible for managing the data ingested.

4) Data report pipelines will be responsible for generating statistical reports from ingested data.

5) Data processing will get from the database the data needed for the training or execution flow. It will also do initial data processing (e.g., select data required to dataset construction) and prepare the data for the next process.

6) Dataset construction will be responsible for building the features for training/execution.

7) Features selection will be responsible for selecting the features for training/execution.

Training processes

8) Training will be responsible for training the model and generating the artifact of the trained model.

9) Model is the artifact of the model trained. MLFlow will be responsible for managing the trained models.

Execution processes

10) Execution will receive the dataset and the trained model and produce the predictions.

11) Data management will be responsible for managing the model results and data reports and preparing them to export to external sources through connectors. It will be also responsible for the management of model results.

12) Data report pipelines will be responsible for generating reports from model results data.

13) Connector will be responsible for exporting model results and data reports to external sources.

Processes running on AI-App

14) The orchestrator will be responsible for receiving the model results and the data reports from AI/ML Framework and export them to N-App and/or V-App.

15) Database will manage the data received on AI-App.

Advantages

One of the main advantages of this architecture is the elimination of data duplication, which reduces the required storage space and minimizes inconsistencies between components. All data, from raw inputs to model outputs, is centrally managed within the AI/ML Framework, ensuring data integrity and coherence throughout the entire lifecycle.

Additionally, this approach leads to a lower computational demand on the AI-App, since the most resource-intensive tasks, such as model training, dataset construction, and statistical report generation, are performed exclusively on the central server. The AI-App acts merely as an orchestrator and distributor of results, handling the delivery of outputs to consuming systems (N-App and V-App).

Another strong point is the elimination of process duplication. With the entire machine learning pipeline centralized, there is no need to replicate transformation logic, data processing, or reporting across multiple components. This promotes greater operational efficiency, easier maintenance, and consistency in results.

Disadvantages

The main drawback of this approach is the higher computational load on the AI/ML Framework. All intensive processing — from data ingestion and preparation to model training and execution — takes place on the central server. This may require a more robust infrastructure with higher scalability, parallel processing capabilities, and fault tolerance.

Additionally, a potential consequence of this centralization is the increased dependency on connectivity between the AI/ML Framework and the AI-App. In scenarios where latency or connection reliability is critical, like real-time response applications, the architecture might require further optimization

3.7.2 Centralized processes to train ML Models and parallelized processes to execute ML models (A2 scenario)

In the second approach, the training model runs on the framework and the execution model runs on the AI-App. Each component of the architecture is detailed in Figure 25.

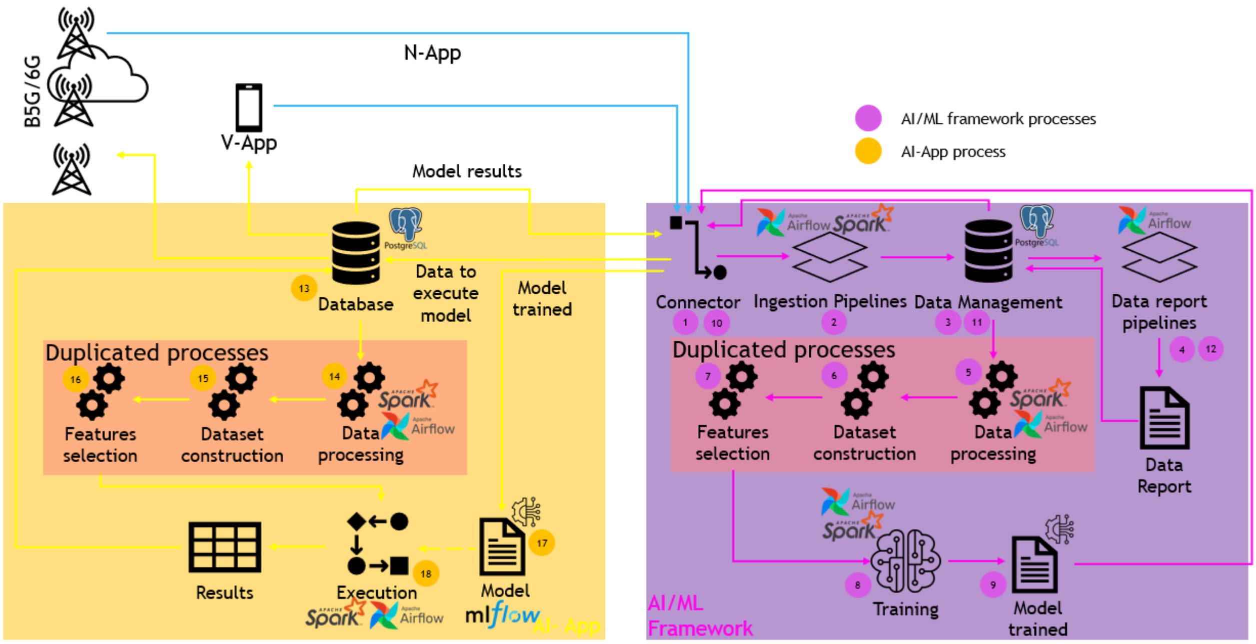

Figure 25. Architectural approach for A2 scenario

Processes running on AI/ML Framework

Common processes to train and execute ML model

1) Connector will be responsible for receiving data from external sources.

2) Ingestion pipelines will be responsible for ETL processes, so ingestion pipelines will extract, transform and load the data into the database.

3) Data management will be responsible for managing the data ingested.

4) Data report pipelines will be responsible for generating statistical reports from ingested data.

Training processes

5) Data processing will get from the database the data needed for the training or execution flow. It will also do initial data processing (e.g., select data required to dataset construction) and prepare the data for the next process.

6) Dataset construction will be responsible for building the features to training/execution.

7) Features selection will be responsible for selecting the features for training/execution.

8) Training will be responsible for training the model and generating the artifact of the model trained.

9) Model training is the artifact of model training. This artifact will be exported to AI-App through Connectors.

10) Connector will be responsible for exporting model trained artifacts.

Execution process

11) Data management will be responsible for managing the model results and data reports and preparing them to export to external sources through connectors. It will be also responsible for the management of model results.

12) Data report pipelines will be responsible for generating reports from model results data.

Processes running on AI-App

Execution processes

13) Database will manage the data received on AI-App and the model results. will be responsible for exporting the model results and the data reports to AI/ML Framework, N-App and/or V-App.

14) Data processing will get from the database the data needed for the training or execution flow. It will also do initial data processing (e.g., select data required to dataset construction) and prepare the data for the next process.

15) Dataset construction will be responsible for building the features to training/execution.

16) Features selection will be responsible for selecting the features for training/execution.

17) Model is the artifact of the model trained. MLFlow will be responsible for managing the trained models.

18) Execution will receive the dataset and the trained model and produce the predictions.

Advantages

This architecture offers significant advantages, particularly in scenarios where real-time model execution is required. By deploying the AI-App at the edge, close to the data source, it is possible to execute models locally with minimal latency, which is critical for use cases that demand immediate decisions.

Another major benefit is the distribution of computational workload. The AI/ML Framework is relieved from execution-related processing, focusing instead on centralized tasks such as data ingestion, storage, report generation, and model training. This allows the framework to function primarily as a data repository, training hub, and statistical reporting engine.

Meanwhile, the AI-App takes on the role of orchestrator, model manager and model executor, handling the runtime inference tasks, managing trained model artifacts through MLFlow, and distributing both predictions and reports to other systems (N-App and V-App). This design leads to reduced central resource requirements, and improved scalability through edge computing.

Disadvantages

Despite its strengths, this architecture introduces some notable trade-offs. The computational demand on the AI-App is significantly higher, as it must support data preprocessing, dataset construction, feature selection, and real-time inference independently from the central framework. This can require more powerful edge infrastructure, which may not always be feasible depending on the deployment environment.

Additionally, there is duplication of processes across both layers: data processing, dataset creation, and feature selection are performed both in the AI/ML Framework (for training) and in the AI-App (for inference). This increases operational complexity, requires careful version control, and can complicate debugging and maintenance.

Another important downside is the duplication of data and the heavy data transfer required between the AI/ML Framework and the AI-App. Trained model artifacts and relevant datasets must be exported to the edge for execution, potentially causing bandwidth bottlenecks or latency issues in environments with limited connectivity.

3.8 Other features

3.8.1 6G-SANDBOX toolkit

As it was described in D2.1 [6GVERD21], and as part of T2.4 task it was decided to leverage 6G-SANDBOX Toolkit into this project. An instance of the 6G-SANDBOX toolkit has been deployed in La Mayora by TID, in 5GTN at the University of Oulu and at NCRS Demokritos for the Greek Cluster. More specifically for the

Greek cluster, a full OpenNebula deployment is deployed the NCSRD site, comprising both front-end (FE) and KVM hypervisor. OTE on the other hand, operates a dedicated OpenNebula node with KVM, enabling integrated resource utilization across the two distributed locations of Athens platform. Both sites are fully unified under the Athens Platform framework, allowing for centralized administration, management, and maintenance operations from a single front interface

UMA will follow up defining an initial trial network descriptor and validating its operation incrementally. Some of the potential components that could be deployed, may comprise P4 based UPF and a network core. University of Oulu will offer 6G-Sandbox Toolkit as an extension to 5GTN platform offering. 6G-Toolkit is not directly used as part of the Finnish cluster trial as it will have its own dashboard and orchestrator that will be used in the off-grid BTS trials. It is a possibility that 6G-Toolkit could be used to verify the performance of the off-grid BTS but at this phase it is not planned.

The 6G-SANDBOX toolkit will play a key role in supporting the trials, for example by providing functionalities such as the ELCM, which will streamline experiment orchestration and improve the overall trial and testing workflow of the trials. The final scope and selection of the trial network components will be refined and confirmed in subsequent phases, once the detailed requirements and integration aspects of the trials will be decided.

3.8.2 Multi-connectivity

Multi-connectivity mitigates the risk of single-point of failures by providing redundant communication paths. When one link experiences degradation due to interference, congestion, or physical obstructions, traffic can be seamlessly rerouted through alternative links without service interruption. This redundancy is particularly critical for applications that require low-latency such as remote control explored in the Spanish cluster use cases. UMA will work on protocols with multi-connectivity support with the aim of remoting controlling devices. This includes tailored resource allocation mechanisms for how to allocate application traffic over the available connections in the various targeted use cases. The protocols under study include the Multi-connection Tactile Internet Protocol (MTIP), which manages multiple paths and selects them according to the network state and application preferences, among other protocols and functions.

3.8.3 ISAC

Integrated Sensing and Communication (ISAC) is a key 6G technology that enables wireless networks to perform communication and environmental sensing simultaneously using the same radio signals. This integration allows the network not only to transmit data but also to perceive and interpret its surroundings in real time, paving the way for more intelligent and context-aware networked systems.

In the context of 6G-VERSUS, ISAC plays a central role in enabling situational awareness and safety in automation scenarios. Within the Spanish cluster, the integration of ISAC is being developed at La Mayora test site, focusing on safety and surveillance in agricultural environments. Here, ISAC-based radio sensing will be combined with other onboard sensors from robotic platforms — such as LiDAR, and cameras— to enhance detection accuracy and robustness. This will enable the reliable detection of human presence or movement within the monitored area, even under occlusions, poor visibility, or dust, contributing to safer human–robot interaction in farming operations.

The approach builds upon developments achieved in the 6G-SANDBOX project, where ISAC was successfully used to detect people within a defined coverage area. The system visualized real-time detection results through a dedicated dashboard, demonstrating the capability of radio signals to provide sensing functionalities. Within 6G-VERSUS, these results are being extended to larger outdoor areas and enhanced through fusion with robotic and environmental sensors. Furthermore, ISAC data will be used to trigger automated alarms or responses when critical events are detected, reinforcing both safety and operational efficiency.

4 Current status of extensions in testbeds

The purpose of this section is to provide a summarized overview of the features already available at M12 by the platforms and to present other work in progress in every testbed to complement previous sections above. In this summary, the features are categorized into six groups: RAN/Coverage, Core and APIs, Cloud/Edge, Transport network, UEs-Devices, Test and Measurement tools, Energy related tools, selection of the AI/ML approach to be installed in each cluster, and finally other features that will support that will support the use cases.

TESTBED	RAN/Coverage	Core and APIs	Cloud/Edge	Transport	UEs/ Devices connected	T&M	Energy related	AI/ML framework	Other features
Greece	MOCN (ready) Ericcson (ready) Amarisoft outdoor (ready) Outdoor at NCSRD (ready) ORAN (ready)	Open5GS (ready) Open5GS portable (ready)	Edge devices (ready) GPU Server for WF AI (ready) WF Application Servers (in progress)		Cameras for RTSP video feed (in progress) End points (UAV, Robotic dog)	Keysight (ready) 6G-Sandbox Experimentatio n tools (ready)	EEaaS measureme nt tools (in progress)	A2 scenario	
Bulgaria	mmWave 26GH Radio Coverage, rural area for Smart grid (in progress) 7GHz Radio channel N104 as a study/PoC (ready)	OpenCAPIF (in progress) Ericsson NEF API (in progress)	Telco DataCenter- VMs deployment (ready) Securing Edge at Varna (ready)	5G GW - Zyxel CPE instalation (in progress) Starlink satellite backhaul as a backup option (not started)	WT (ready) PMU (in progress) BSS (in progress)	Measurement tools (in progress) 6G-Sandbox Experimentatio n tools (not started)	NR	A2 scenario	
Finland	O-RAN with microwave link (in progress)	CAPIF (in progress)	Edge servers (ready)	Microwave link (in progress)	Hydrogen Fuel cell (not started) Wind turbine (not started) Solar panels (not started) Batteries (not started)	Measurement framework (in progress)	Network side EM SW (in progress)	A2 scenario	Using intelligent control (in progress) Arctic remote BTS site power system design with BMS, DER MQTT, MPPT, Lynx, Dump loads (in progress) Energy aware power budgeting/balancing (in progress) Sensors, heating, energy meters integration (in progress)
France	2 STEP RACH (ready)	CAPIF (ready)			5G RedCap RG255C Series (ready)	Measurement tools (ready)		A2 scenario	
Spain	FR2 portable node (ready) RIS (not started) NTN in RAN (in progress) Commercial TID deployment in EDAR Roquetas (ready) O-GW APIs availability (in progress)	OpenGateway (not started) Open5GS core IP AutoProvision (in progress) CAPIF (ready)	Dedicated UPF far edge (in progress) Dedicated server for core and edge processing (in progress)	NTN in Backhaul (in progress)	Robotic arm for drone (in progress) Sensors for water quality monitoring in La Mayora (not started) Sensor for water quality monitoring (e.coli) in Roquetas de Mar (ready) 5GSA cameras for model training in Roquetas de Mar (in progress)	Keysight measurement tools (ready)	Keysight AC Power Analyzer (ready)	Not in use for privacy reasons	ISAC (in progress) Multi-connectivity (in progress) DT (not started)
Portugal	Commercial-graded 5G SA R16, 20MHz (ready) OAI RedCap-enabled Portable (ready)	Commercial-graded 5G SA R16 (ready) CoreOpen5GS Portable (ready) CAPIF (ready)	Datacenter for VMs (ready) DC extension: fiber link to OAI RedCap Portable when @AveiroPort (in progress)		5G RedCap IoT devices (ready) UAVs (ready) RC boats (ready) 5G cameras (in progress) 5G-enabled Smartlights (not started)		EV Chargers (not started) Solar panels (not started)	A1 Scenario	

5 Integration activities/next steps

The work to upgrade the testbeds and to integrate the applications developed in WP4 is still ongoing after M12. This section reports the plans per country for the remainder of the project.

Bulgarian Cluster

A1 is preparing the testbed by applying network adjustments and targeted deployments, to ensure seamless integration, connectivity, validation of the devices, and applications required for the Bulgarian pilot environment. The installation and configuration of VMs in A1's Telco Data Center for hosting the triplet applications has been completed, and the allocated virtual machine resources are now available for partners to deploy and run their software. A1 is now focusing on integrating and implementing CAPIF and its core entities. Activation of the Ericsson Core Network NEF API, aligned with the vendor's roadmap and required software upgrades, is scheduled to begin once the CAPIF environment is fully deployed. This will support interactions with various network components to retrieve relevant data and events. The N-App for QoS-related APIs exposed via the NEF will be developed and validated in the testbed, including configuration and testing of mechanisms for dynamic QoS control to support the Bulgarian cluster use cases.

A new mmWave 26 GHz base station (BTS) has been deployed to provide radio coverage across the rural segment of the pilot area. The deployment includes full radio integration, backhaul provisioning, and initial on-site validation to confirm operational stability. The next phase involves installing and configuring the dedicated 5G gateway (Zyxel CPE) that will interface with this BTS. The gateway will ensure proper anchoring of user traffic routing toward the testbed's core network functions. This step also includes establishing secure transport links, performing interoperability testing with the mmWave radio, and validating end-to-end performance to ensure the site is fully ready for partner device onboarding and service experimentation.

Finnish Cluster

Finnish cluster has started the integration activities by developing an xApp to measure the data received from the E2 interface in the O-CU of the O-RAN. CAPIF has been installed to act as an interface between the light N-App mock-up that was developed to help the integration of the xApp. xApp was integrated with CAPIF and N-App so that the data could be received from the E2 interface and transferred through CAPIF to N-App to be delivered to the data storage.

Simulations for the Remote Base station setup have been completed and the draft HW setup with components has been defined. Currently Finnish Cluster is progressing with the definition of the system architecture for the Remote Base station System. After the system design work has been completed, the next phase is to initiate the SW architecture work, followed by SW implementation. Integration for the system can be started after the HW setup has been implemented and the module tested SW has been released.

System design phase has been ended mid-December 2025 followed by SW architecture work that will be completed latest mid-January. HW and SW implementation is to be ready before the end of March 2026 so that during April 2026 the Remote BTS System can be tested and to be deployed beginning of May 2026. Completed platform will then be run for the duration of 12 months to run the Finnish Use Case.

French Cluster

The next integration phase will focus on connecting the GreenCitizens sensors (i.e., water level and soil humidity sensors) with a UE (i.e., a Raspberry Pi and a RedCap device) using the UART protocol between the Raspberry Pi and two V-Apps deployed on the EURECOM extreme edge, one for each type of sensor, to retrieve the payloads from the sensors and send them to the Raspberry Pi. Then, the RedCap devices will be connected to the EURECOM 5G network to enable data exchange and validation under realistic edge conditions, where another V-App will be running to receive the sensors data and feed a data server on the cloud. The identified V-Apps and AI-Apps will be deployed on the EURECOM edge using the web portal as CNFs, allowing containerized execution, dynamic scaling, and real-time monitoring. Moreover, the exposure of N-Apps through CAPIF will enable the B5G-Connector V-App on the edge to support simple use cases such as event monitoring via the NEF and analytics via the NWDAF, with datasets collected in CSV format. These datasets will feed the ML-Ops framework, where the training API will be exposed for AI-App model development. Work on the two-step RACH procedure is already completed for the OAI UE, and if future commercial UEs support this feature, it will be further integrated. Finally, the EURECOM Core Network will be securely exposed to Thales via VPN, enabling the integration of their AI-Apps for RAN reconfiguration leveraging DRX and BWP mechanisms to optimize the sensors' energy consumption and extend their battery life.

Greek Cluster

For the Greek cluster, the next integration phase will focus on conducting initial testing of the testbed end points, specifically the UAV and robotic dog, to progressively incorporate them into the use case workflow. Additionally, the camera will be properly configured to enable RTSP video streaming. Given that development of the first API (Monitoring Event) is already complete, integration efforts will now target the AI-App for location services and the relative V-App (robotic dog or/and drone), ensuring these interfaces work as intended. This plan is centered on components that are selected for use during the first round of trials in February, with the aim of validating interoperability and system readiness for the subsequent trials.

After this round of integration, the Greek cluster will prioritize the deployment and integration of AI microservices for the following AI-driven applications: Microservices for AI-Powered Detection, Intelligent identification of casualty location, and Tracking, and the Early Wildfire Detection App. These microservices will be deployed in the testbed with the appropriate interfaces to ensure seamless interaction and validation of the workflow. Configuration adjustments will be necessary both in the central cloud and at the edge, to support the required processing capabilities for real-time analytics.

The N-App for QoS will be prepared for testing in the testbed. This will involve configuring and validating the mechanisms that allow dynamic QoS control and measurement for the relevant service flows that will feed the camera.

Portuguese Cluster

As testbed owner, ITAV has started to provide VPN access, along with VM deployment capabilities for partners to deploy the necessary software / xApps for implementing the target scenarios. ITAV will soon make available the different network instantiations for partners to connect their devices and necessary Apps. ITAV has also been focusing on integrating CAPIF capabilities to N-Apps required for scenario 2, after having finished the implementation of CAPIF's main entities. Equally as part of the testbed extensions, the ONEmNEF (OneSource's NEF implementation) is currently being integrated into ITAV's Open5GS production environment, allowing it to tap into different components and obtain associated data and events. ONEmNEF has already been integrated and validated with the Mobitrust V-App, N-App and OpenCAPIF in an experimental setting, preceding the upcoming testing activities of xApps (i.e. their communication and functionality) in the trial network. The integration resulted in extended N-App features, including a modular cloud-native deployment in Kubernetes of the N-App, the automated onboarding of the N-App as an Invoker in OpenCAPIF and a first version of CAMARA API integration, with the goal of abstracting requests to NEF and the core network. The N-App template is being further extended to support the functionalities required from the Portuguese cluster V-Apps. These extensions will be further described in D4.1 [6GVERD41].

JSIO and IPN have performed integration and testing activities involving the IoT devices and the environmental monitoring V-App components (data logger, server and client) in lab environments. In the next stage, JSIO and IPN will deploy and provision both the IoT devices and associated 5G RedCap communication modules in the testbed's field, as well as the xApps on the testbed VMs. Afterwards, the associated functionalities will be tested ultimately aiming to validate the complete scenario workflow (i.e. communication capabilities, device and network configuration, NEF and CAPIF APIs invocation, etc). Multiple QoS configurations will be tested for each device in order to observe the resulting impact (in the network, devices, and service / V-App).

ALB will provision access to the MLOps framework within ITAV's testbed, in order to perform initial testing, including transmission and processing of the currently collected data or dummy datasets, and invoking the library for AI training and inference. Finally, IPN aims to test the QoS recommendation logic, guaranteeing the ability to select the associated QoS profile - at this stage, without involvement of AI-App (for QoS configuration recommendation).

Spanish Cluster

During the next integration period, the Spanish cluster will continue with the preparation of the Victoria Network experimentation environment, enabling laboratory and field trials across Roquetas, Málaga and Mayora locations. In this phase, Telefónica and Cetaqua will work on the integration of Open Gateway APIs into the Distributed Smart System (DSS). At this stage, the Quality-on-Demand API is expected to be available for experimentation, although potentially other APIs could be used depending on the suitability and availability.

Nokia will contribute to the Spanish cluster by supporting the deployment of new infrastructure required for the next phase of experimentation. A new edge server will be installed to host local applications closer to the radio access, enabling low-latency execution for the Spanish trials. In parallel, a new 5G core instance is planned for deployment, incorporating enhanced provisioning capabilities that allow allocation of IP addresses based on IMSI, improving control and flexibility for connected devices.

UMA will advance on multiple integration efforts. First, the robotic arm will be incorporated into the experimentation workflow, enabling automation functionalities relevant to the agricultural use cases. Integration is expected during the first half of 2026, with initial laboratory trials planned for January and February and subsequent field testing during the second execution phase. In parallel, Integrated Sensing and Communication (ISAC) will be integrated with a new RAN stack over the same period, starting with controlled lab operation before transitioning to field operation for the second round of trials.

Regarding NTN connectivity, the deployment of the satellite antenna infrastructure is scheduled for 2026. License provisioning with the satellite operator is in progress, with an estimated activation window of six to twelve months for transparent-mode transmissions. Remote drone operation will also be incorporated by integrating the dedicated control API, allowing the drone to operate through both 5G connectivity.

An instance of the 6G Sandbox Toolkit has been deployed in La Mayora. The next related step is completing the integration of the Experiment Lifecycle Manager and the network core so that the site can be automatically instantiated as a trial network.

CSIC/CET will integrate the water sensor once UMA finalises the provisioning of the required virtual machine, and the sensor procurement is completed. It is currently not confirmed if the multiparametric sensor will be available by the first trial period.

In addition, HPE, Keysight, and UMA will progress with LoadCore wrap-around testing for the validation of the core network. The next stage includes laboratory energy profiling of the HPE Aruba Networking Private 5G Core running at UMA. A precision power analyser will be attached to the server powering the core, enabling accurate measurement of consumption under different load conditions and throughput levels. This setup will emulate a high number of connected users and sessions, ensuring a comprehensive evaluation of the core's behaviour under realistic conditions.

Finally, Keysight will continue with the development of a Digital Twin of the La Mayora deployment. The model will incorporate detailed 3D terrain and foliage information and will be calibrated using real measurement data collected on-site. The resulting virtual representation will provide accurate field-equivalent predictions of metrics such as RSRP and will be used to support experimentation in energy efficiency, critical communications and other use cases relevant to 6G-VERSUS. This development will not be available in the beginning of 2026 so the integration with the use case is expected to happen later in the year.

6 Progress related to 6G-VERSUS ambitions

After the first year of activity, 6G-VERSUS has already taken the first concrete steps across its core Ambitions reported below. Ambitions are not limited to only WP3 scope, but range from core network integration and vertical application enablement (Ambitions 1 and 2), energy-efficiency mechanisms and EEaaS (Ambition 3), the ML-enabled edge-to-cloud continuum (Ambition 4), UAV-based relaying (Ambition 5), RedCap-driven efficiency (Ambition 6), deterministic and low-latency connectivity (Ambition 7), two-step RACH (Ambition 8), remote-control protocols (Ambition 9), and O-RAN/RIC intelligence (Ambition 10). Progress with ambitions is reported in D3.1 for they are closely tied with the overall evolution of the testbeds. The table below summarizes the progress.

Ambition Number	Ambition	Ambtion Leader	Use Case (UC Leader) Involved	Progress & Current Status
1	Interaction with the Core Network	NCSRD	Greek (ICCS) Finnish (UOULU) Spanish (UMA/CSIC) French UC2 (GREEN) Bulgarian (EE) Portuguese (IPN)	The N-App template was completed in M09 by the responsible partner NCSRD and subsequently released to developers across all testbeds for further extension and adaptation as required per use case. API tracking is being conducted by NCSRD across all clusters and use cases to monitor their evolution and ensure alignment with the overall architecture. The progress of this ambition is reflected through the ongoing development of the template N-App, which interfaces with the core network through defined APIs. Three main API categories have been identified: (i) Analytics Exposure (NWDAF), (ii) Monitoring Event (Location Reporting), and (iii) QoS Management. Development activities are progressing according to the planned schedule.
2	Transformation of the verticals into 6G applications	NOKIASP	Greek (ICCS) Finnish (UOULU) Spanish (UMA/CSIC) French UC1 (THALES) French UC2 (GREEN) Bulgarian (EE/UCY) Portuguese (IPN)	Software design roles and development assignments completed per UC. Software requirements and constraints documented and tracked. Development has started and is currently in progress across all UCs. First executables at M10.
3	Energy Efficiency as a Service	ICCS	Greek (ICCS) Finnish (UOULU)	Activities are progressing as planned, following a work-in-progress blueprint for defining Energy Efficiency (EE) and Energy Efficiency as a Service (EEaaS)

				within the 6G-VERSUS framework. Although 3GPP has not established a single formal definition of EE, both 3GPP and ETSI commonly recognise it as the ratio between useful service output and the corresponding energy consumed, subject to operational sustainability and performance constraints [3GPP1] [3GPP2] [ETSI1]. Within 6G-VERSUS, this notion is extended to the compute–connect continuum, encompassing network, compute, and edge resources jointly optimised through AI-assisted orchestration and adaptive resource management. Building on this, EEaaS is defined as a managed framework delivering adaptive, policy-driven energy-efficiency capabilities across domains, continuously analysing telemetry and historical data to identify energy-saving opportunities, coordinating control actions, and exposing energy-related KPIs to authorised stakeholders. In 6G-VERSUS, EEaaS is realised through the 6G Application Triplet—comprising the N-App, AI-App, and V-App—where the N-App enforces energy-aware decisions, the AI-App provides intelligent adaptation recommendations, and the V-App supplies live service-level data to support coordinated, energy-efficient operation across the continuum.
4	ML-enabled continuum from central cloud to far edge	ALB	Finnish (UOULU)	Framework definition completed. First workshop held with Bulgarian cluster.
5	UAVs as B5G/6G network relays	ICCS	Greek UC	Activities are progressing as planned, with no major issues reported. A clear plan is in place and the initial steps have been taken for integrating the PC5 equipment with the relaying UAV, alongside the design of a controller scheme that assigns and enforces policies for choosing between UAV-based relaying and standard Uu connectivity to a gNB. The initial view on these policies explores both signal and service quality, covering inputs from the network up to the service layer, and may also incorporate power-related

				information, such as device battery levels or the consumption of connectivity and compute resources.
6	Optimizing Energy Usage with RedCap Technology	UOULU	Portuguese UC (IPN) French UC1 (GREEN) French UC2 (GREEN) Finnish UC	Finnish cluster purchased equipment and conducted a full set of initial throughput and low-power measurements. Prototype measurement results refer to favorable channel conditions. French cluster has tested RedCap with device energy consumption measurements. Portuguese cluster has conducted initial validation tests; full evaluation pending.
7	Low latency/deterministic communications	UMA	Spanish UC (UMA/CSIC) Bulgarian UC (EE/UCY)	Spanish Cluster: UPF at the edge planned, based on AI model to ensure latency and availability. UPF exists but still requires on-site deployment. Bulgarian cluster: A1 will rely on existing core with full UPF capabilities.
8	Two-step Random Access Channel (RACH)	EUR	French UC1 French UC2	Code has been merged with OAI. Validation will be performed using the OAI UE. Future adoption of commercial UEs is possible, if available.
9	End-to-end protocols for precision agriculture	UMA	Spanish UC (UMA/CSIC)	The Multipath MTIP protocol has been selected for initial testing activities. Both the protocol and an accompanying remote drone-control application have been implemented within an emulated environment and currently operate independently, pending integration. Further enhancements and alternative multipath protocol implementations are planned for evaluation and inclusion in subsequent project trials.
10	ORAN intelligent controller towards reduced energy consumption	UOULU	Finnish UC	Requirement and architecture work for the Intelligent Controller HW and SW has been started in the Finnish cluster.

7 Conclusions

This deliverable has outlined the initial configuration of the six 6G-VERSUS testbeds together with their experimentation tools and the enabling technologies supporting the first version of the integrated platform. It has provided a comprehensive view of the testbed capabilities and their roles within the project, demonstrating the complementary nature of the sites and their collective contribution to the 6G-VERSUS ecosystem.

The document has also presented the main technological components planned for integration throughout the project, including enhancements in RAN, Core, APIs, cloud and edge infrastructures, user and connected devices, transport, energy efficiency and other features, and its current status. In addition, it has introduced the AI/ML framework, which establishes the foundation for coordinated and intelligent experimentation across the platform. The deliverable has outlined the next steps in the integration activities and has reported the status of the project's ambitions (mainly connected to WP3).

Future work will focus on further integration of the testbeds, evolution of the AI/ML framework, and enhancement of experimentation capabilities to advance the development of a unified, AI-enabled 6G-VERSUS platform.

References

[3GPP1] 3GPP TR 32.972, Study on Energy Efficiency of 5G Networks, v17.0.0, Dec. 2021.

[3GPP2] 3GPP TS 28.310, Telecommunication Management; Energy Efficiency Management; Concepts and Requirements, v17.0.0, Jun. 2021.

[6GSBOX] https://6g-sandbox.eu/

[6GSBOXD33] 6G-SANDBOX Project. D3.3 - Final 6G-SANDBOX Library - https://6g-sandbox.eu/wp-content/uploads/2025/10/6G-SANDBOX_D3.3_Final.pdf

[6GVERD21] 6G-VERSUS Project (2025). D2.1 – Platform Architecture and Use Case Requirements – Initial. Month 10, October 2025.

[6GVERD41] 6G-VERSUS Project (2026). D4.1

[6GXR] https://6g-xr.eu/

[ARB] https://www.arbiter.com/catalog/product/model-1133a-power-sentinel.php

[BMV2] https://github.com/p4lang/behavioral-model

[CONVERGE] https://converge-project.eu/

[DJI] https://store.dji.com/shop/mavic-series

[ETSI1] ETSI ES 203 228, Environmental Engineering (EE); Assessment of Energy Efficiency of Wireless Access Network Equipment, v1.2.1, Feb. 2017.

[ETTIFOS] https://www.ettifos.com/product-sirius

[KAITO] https://www.kaitotek.com/fi

[MEL2023] Melissa Elkadi, et. al., "Open Source-based Over-The-Air 5G New Radio Sidelink Testbed", arXiv, Oct. 2023, doi: https://doi.org/10.48550/arXiv.2306.09286

[OAIBOX] https://www.oaibox.com/

[QUECTEL] https://www.quectel.com/product/5g-redcap-rg255c-series/

[QUECTEL2] https://mc-technologies.com/wp-content/uploads/2023/12/Quectel_RG255C-GL_5G_RedCap_Specification_V1.0.0_Preliminary_20230928.pdf

[QUECTEL3] https://www.quectel.com/product/5g-m2-evb-kit/

[RM500] https://docs.rs-online.com/31d0/A700000008434713.pdf

[SOSELEC] https://cdn.soselectronic.com/productdata/86/35/1f7da276/5gm2evbkit.pdf

[SUNRISE6G] https://sunrise6g.eu/

[SYNC] "IEEE standard for synchrophasors for power systems," 2011, [online]: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6111222

[UNITREE] https://www.unitree.com/go2

[USB5G] https://www.waveshare.com/wiki/RM530N-GL

[VPC] https://en.wikipedia.org/wiki/Virtual_private_cloud