Funded by the European Union

6G-SANDBOX

Supporting Architectural and technological Network evolutions through an intelligent, secureD and twinning enaBled Open eXperimentation facility

Deliverable D2.1

Ecosystem analysis and 6G-SANDBOX facility design

Date: 30/06/2023

Version: 1.5

Grant Agreement	101096328
Document number	D2.1
Document title	Ecosystem Analysis and 6G-SANDBOX Facility design
Lead Beneficiary	NCSRD
Editor(s)	George Makropoulos (NCSRD)
Author(s)	George Makropoulos (NCSRD), Harilaos Koumaras (NCSRD), Spyros Georgoulas (NCSRD), Athanasios Papakyriakou (NCSRD), Vasilis Pitsilis (NCSRD), Francisco Luque Schempp (UMA), Pablo Herrera (UMA), Pedro Merino (UMA), Delia Rico (UMA), Bruno García (UMA), Almudena Díaz (UMA), Hua Wang (KEYD), Dimitris Tsolkas (FOG), Giannis Fotis (FOG), Nikolaos Gkatzios (INF), George Theodoropoulos (INF), Vaios Koumaras (INF), Anastasius Gavras (EURE), Apostolis Salkintzis (LNV), Nikolaos Lazaropoulos (LNV), Jorge Sianes (OWO), Pablo Reyes (OWO), Adrián Bernet (OWO), David Artuñedo Guillén (TEL), Jesús Macías Portela (TEL), Arturo José Torrealba Ferrer (TEL), Fofy Setaki (COS), Ioanna Mesogiti (COS), Eleni Theodoropoulou (COS), Juan Torres (NOKIA), Hao Yu, Qize Guo, Mohammad Farhoudi, and Zhao Ming (OULU), Amine Taleb (ICTF), Rubén S. Montero (ON), Bruno Rodríguez (ON), Md Munjure Mowla (ISRD), Adam Flizikowski (ISRD), Bjoern Riemer (FOKUS)
Dissemination level	Public
Contractual date of delivery	30/06/2023
Status	Final
Version	v1.5
File name	6G-SANDBOX_D2.1_v1.5.pdf

Document History

Version	
V0.3	Edit of ToC
V0.4	Initial Contributions
V0.6	Updates on the facility requirements section
V0.8	Updates on the 6G-SANDBOX platforms section
V1.0	Updates on the KPIs section
V1.2	Full draft
V1.3	Final contributions
V1.4	Internal review
V1.5	Final

TABLE OF CONTENTS

List of FIGURES

List of TABLES

ABSTRACT

This document provides a comprehensive overview of the core aspects of the 6G-SANDBOX project. It outlines the project's vision, objectives, and the Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) targeted for achievement. The functional and non-functional requirements of the 6G-SANDBOX Facility are extensively presented, based on a proposed reference blueprint. A detailed description of the updated reference architecture of the facility is provided, considering the requirements outlined. The document explores the experimentation framework, including the lifecycle of experiments and the methodology for validating KPIs and KVIs. It presents the key technologies and use case enablers towards 6G that will be offered within the trial networks. Each of the platforms constituting the 6G-SANDBOX Facility is described, along with the necessary enhancements to align them with the project's vision in terms of hardware, software updates, and functional improvements.

KEYWORDS

KPIs, KVIs, Trial Networks, Testbed, Facility, reference architecture, functional requirements, non-functional requirements, experimentation lifecycle

DOCUMENT ACRONYMS AND ABBREVIATIONS

ATSSS	Access Traffic Steering Switching and Splitting
AMF	Access and Mobility Management Function
AUSF	Authentication Server Function
AI	Artificial Intelligence
AR	Augmented Reality
API	Application Programmable Interface
BBU	Baseband Unit
BS	Base station
CAPIF	Common API Framework
DWDM	Dense wavelength-division multiplexing
DVB	Digital Video Broadcasting
EIRP	Effective Isotropic Radiated Power
EC	European Commission
ESA	European Space Agency
EMF	Electric and Magnetic Fields
FP	False Positive
5G-EIR	5G Equipment Identity Register
GDPR	General Data Protection Regulation
IMU	Inertial measurement unit
KPI	Key performance indicator
KVI	Key Value Indicator
LEO	Low Earth Orbit
ML	Machine Learning
MSE	Mean Squared Error
MTBF	Mean Time Between Failure
MME	Mobility Management Entity
MEC	Multi Access Edge Computing
MTIP	Multi-connection Tactile Internet Protocol
MQUIC	Multi path Quick UDP Internet Connection
MTCP	Multi path TCP
NEF	Network Exposure Function
NFV	Network Function Virtualisation
NFVI	Network Function Virtualisation Infrastructure
NMS	Network Management System
NRF	Network Repository Function

NSSF	Network Slice Selection Function
NTE	Network Termination Equipment
O-RAN	Open Radio Access Network
PCF	Policy Control Function
P4	Programming Protocol-independent Packet Processors
PLMN	Public Land Mobile Network
QoE	Quality of Experience
QoS	Quality of Service
RU	Radio Unit
RIS	Reconfigurable Intelligent Surface
RRH	Remote Radio Head
RRU	Remote Radio Unit
RCS	Return Channel via Satellite
RIT	Radio Interface Technologies
RMSE	Root Mean Squared Error
SEPP	Security Edge Protection Proxy
SDN	Software Defined Network
SDU	Service Data Unit
SDO	Standards Development Organization
SLAM	Simultaneous Localization and Mapping
SDG	Sustainable Development Goal
SNS	Smart Networks and Services
SRIA	Strategic Research and Innovation Agenda
SMF	Session Management Function
SRIT	Set of Radio Interface Technologies
3GPP	3rd Generation Partnership Project
TSN	Time Sensitive Network
TA	Transnational Access
TND	Trial Network Descriptor
TNLC	Trial Network Lifecycle
TNLCM	Trial Network Lifecycle Manager
TP	True Positive
TRxP	Transmission Reception Point
UDM	Unified Data Management
UDR	Unified Data Repository
UE	User Equipment

UPF	User Plane Function
WAN	Wireless Access Network
vRAN	Virtualized Radio Access Network

1 INTRODUCTION

1.1 DOCUMENT STRUCTURE

The core part of the document is divided into the following sections:

- Section 2 6G-SANDBOX Ecosystem offers a synopsis of the project's vision, objectives, as well as the Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) that are targeted by the project.
- Section 3 6G-SANDBOX Facility Requirements offers an extensive presentation of the functional and non-functional requirements based on the proposed reference blueprint.
- Section 4 Overall Facility Design specifications contains a detailed description of the updated reference architecture of the 6G-SANDBOX Facility, based on the requirements presented in the previous section.
- Section 5 Experimentation Framework dives into the lifecycle of the experiments and the KPI and KVI validation methodology of the experiments.
- Section 6 Updates Toward 6G Technologies and Use Case Enablers presents the key technologies towards 6G that will be offered/exposed to create trial networks.
- Section 7 6G-SANDBOX Platforms describes each platform that constitutes the 6G-SANDBOX Facility, and explains the improvements necessary for their alignment with the vision of the project in terms of hardware, software updates and functional enhancements.
- Section 8 Summary of 6G-SANDBOX Testbeds and KPIs offers a comprehensive presentation of the technologies and KPIs supported by the four testbeds.

1.2 TARGET AUDIENCE

The release of the deliverable is public, with the intent of exposing the overall 6G-SANDBOX facility to a wide variety of research individuals and communities. From specific to broader, the various target audiences for D2.1 are described below:

- The Project Consortium to validate that all objectives and proposed technological advancements have been analysed and to ensure that, through the identified requirements (functional and non-functional), the next actions can be concretely derived. Furthermore, the deliverable sets to establish a common understanding among the Consortium with regards to: i) the Facility architecture to be set for reference, and ii) the technologies to be utilised, deployed and extended per platform.
- The Research Community and funding agency (the European Commission -EC) to: i) summarise the 6G-SANDBOX scope, objectives and intended project innovations, ii) detail the 6G-SANDBOX Facility and the four platforms as well as the targeted use cases that will be demonstrated and measure provided technological advancements, and iii) present the related requirements and associated KPIs that must be accomplished to achieve the expected results.
- Technology providers that may engage with the 6G-SANDBOX facility and provide own assets complementing the available infrastructure, either through open calls, or directly because they see a value in the collaboration.
- The vertical actors that will be engaged to the project with the process of the open calls and will utilise the 6G-SANDBOX facility to conduct their experiments.

- The general public for obtaining a better understanding of the framework and scope of the 6G-SANDBOX project.

2 6G-SANDBOX Ecosystem

The 6G-SANDBOX project introduces the concept of Trial Networks, which refers to fully configurable, manageable and controllable end-to-end networks (including slicing capabilities) which combine digital and physical nodes to validate new technologies and research advancements towards 6G. In principle, the validation capabilities provided by the 6G-SANDBOX Trial Networks are extensible in terms of the technologies and the component they incorporate, and flexible in terms of the experimentation processing and the target metrics.

2.1 6G-SANDBOX Vision

2.1.1 Objectives

The project ambition is to provide an experimental facility to validate technologies and use cases in the context of European Smart Networks and Services (SNS) program toward 6G. To achieve this high-level ambition, the project has identified the following three main technical objectives:

- The definition and implementation of the concept of Trial Networks as fully manageable and configurable end-to-end 5G/6G networks to be designed and created ad-hoc for experimentation. Target experimenters are mainly technology providers and developers of vertical applications that will have the opportunity to use an experimentation framework on top of the trial networks to automate the entire process for repeatability. A large number of experimenters will be selected as third parties in a competitive process using a cascade funding approach.
- The creation of several experimental platforms as part of the facility that will support the Trial Networks. Initial platforms are mature infrastructures available in Athens, Berlin, Malaga and Oulu. However, all of the developments in the project will be open and available to set up new sites.
- The creation, enhancement, and integration of new deployments toward 6G technologies to be part of the testbeds offering the Trial Networks. Initial areas for improvements considered by the consortium include experimentation techniques, O-RAN programmability, reconfigurable intelligent surfaces, integration of 5G with satellite, deterministic communications, artificial intelligence to control the network, security aspects, exposition of network capabilities though Application Programmable Interfaces (APIs), and advanced use cases in Internet of Sense. Again, contributions from third parties are expected with the open calls to complete the catalogue of technologies to be integrated in the testbeds.
- To validate a number of technologies toward 6G KPIs and KVIs thanks to the internal experimentation by the consortium and to the third parties engaging in the cascade funding process.

2.1.2 Overview of KPIs

Today, Standards Development Organizations (SDOs) (e.g., ITU-R and 3GPP) are in the process of setting the targets for the next generation of networks, while several stakeholder organizations are also focusing on identifying the high-level KPIs to be met by 6G networks along with feasible pathways. In this context, 3GPP working groups are focusing on identifying the requirements for the next generation of networks. For example, NetworldEurope 2022 Strategic Research and Innovation

Agenda (SRIA) defined a pathway to network evolution from the 2020-2030 timeframe, while EU's research communities (EU flagship projects, 5G PPP and recently 6G-IA) are working closely to align on a unified 6G networks vision.

Table 1. 6G-SANDBOX alignment with expected KPI values evolution based on SRIA 2021-2027

Target KPI	5G NR (Rel.16) 2020	Short-term Evo. ~2025	Medium-term Evo ~2028	Long-term Evo. ~2030
Spectrum	<52.6 GHz	<150 GHz	<300 GHz	<500 GHz
Bandwidth	<0.5 GHz	<2.5 GHz	<5 GHz	<10 GHz
Peak Data Rate	DL: >20 Gbps UL: >10 Gbps	DL: >100 Gbps UL: >50 Gbps	DL: >200 Gbps UL: >100 Gbps	DL: >400 Gbps UL: >200 Gbps
User Data Rate	DL: >100 Mbps UL: >50 Mbps	DL: >500 Mbps UL: >250 Mbps	DL: >1 Gbps UL: >0.5 Gbps	DL:>2 Gbps UL: >1 Gbps
Density	>1 device/sqm	>1.5 device/sqm	>2 device/sqm	>5 device/sqm
Reliability [BLER]	URLLC: >1-10-5	>1-10-6	>1-10-7	>1-10-8
U-Plane Latency	URLLC: <1 ms	<0.5 ms	<0.2 ms	<0.1 ms
C-Plane Latency	<20 ms	<10 ms	<4 ms	<2 ms
Energy Efficiency (Network/Terminal)	Qualitative	>30 % gain vs IMT-2020	>70 % gain vs IMT-2020	>100% gain vs IMT-2020
Mobility	<500 Km/h	<500 Km/h	<500 Km/h	<1000 Km/h
Positioning accuracy	NA (<1 m)	<30 cm	<10 cm	<1 cm

Among its objectives, 6G-SANDBOX aims to make significant contribution to KPIs definition and evaluation beyond the current state of research. To position 6G-SANDBOX contributions in the global 6G framework, in the process of capturing the 6G-SANDBOX view and capabilities on 6G KPIs definition and evaluation is necessary to align the 6G-SANDBOX view with the global 6G trends, vision and then to leverage on current research and standardization activities. To this end, the work done in the context of EU funded projects, 6G-IA Working Groups (WGs), ITU and 3rd Generation Partnership Project (3GPP) Standardization bodies as well as the targets set by the NetworldEurope SRIA 2022 [1] have been adopted as the KPIs baseline, to be further enriched.

To structure the view of 6G-SANBOX on KPIs and to provide a useful indexing of the addressed KPIs, these have been organized into the following KPI families, based on [2], [3], [4]:

Capacity: The "Capacity" KPIs category refers to metrics used to evaluate the amount of network resources available at network level or provided to end-users.

Latency: "Latency" is usually defined as the contribution of a network unit (physical layer segment or processing function) to the time from when the source sends a packet to when the destination receives it. This KPIs category includes those KPIs that refer to latency or to latency components (contribution) of various segments/functions/components, at various planes; namely user plane, control plane and orchestration plane in the performance of various application of network functionalities/processes.

Channel: The "Channel" KPIs family refers to KPIs specifically addressing the performance and the efficiency of the radio communication channel.

Electric and Magnetic Fields (EMF): This KPI family is related to Electric and Magnetic Fields (EMF) and in particular refers to measures of exposure to it.

Reliability: This KPIs family includes measures of assessing the correctness and trustworthiness of communication at various levels such as long/short-term, network/session/packet, etc.

Compute: This KPIs family refers to aspects of computing that can affect 6G implementation, usage, and performance following SDOs looking into communication and computing convergence.

Energy: This KPIs family refers to KPIs used for evaluating various aspects related to the energy efficiency of a system.

Security: This KPIs family covers KPIs related to security aspects.

Localization: This KPIs family addresses aspects of B5G/6G networks related to the localization accuracy.

Service Availability: This KPIs family covers KPIs related to service availability.

Artificial Intelligence (AI)/Machine Learning (ML): This KPIs family includes KPIs related to the capabilities and efficiency of AI/ML supported functions in 6G networks.

The KPIs identified at the initial stages of 6G-SANDBOX are shown in Table 2.

Table 2. TMV / ICT-52 KPIs targeted by 6G-SANDBOX

KPI Family	KPIs	Preliminary target values	Defined by
Capacity (Network)	Peak User data rate (network)	1 Tbps	5G PPP, SDOs
	Node Capacity	>1Tbps	5G PPP, SDOs
	RIS – Capacity enhancement	RIS capacity enhancement is targeted to be > 1 Gbps within the shadow region.	6G-SANDBOX
	Area Traffic Capacity	~ 1-10 Gbps/m3	5G PPP, SDO
	User density - Connection density	2 to 5 million /km²	5G PPP, SDO

Capacity (User)	User Experienced Data Rate	<1Gbps	5G PPP, SDO
Latency (Connectivity layer)	C-Plane latency (network)	latency in the order of 2ms round trip time	5G PPP, SDO
	U-Plane latency (network)	latency in the order of 0.1 to 1ms round trip time	5G PPP, SDO
	Delay deviation/jitter	Low delay jitter (e.g., in the order of 1μsec)	5G PPP, SDO
	RIS update rate	RIS update rate < 1μS	6G-SANDBOX
Latency (Orchestration)	Service Provisioning Time		5G PPP
	Slice Provisioning Time		5G PPP
Channel	Spectral efficiency	60b/s/Hz (5G: 30b/s/Hz)	5G PPP, SDO
EMF	Self EMF exposure		5G PPP, SDO
	Inter EMF exposure	WHO norm or more stringent national norms	5G PPP, SDO
Reliability	Operational Network Reliability	Up to the order of 10^{-9} measured at the end user level	5G PPP, SDO
	Session Reliability (frame error rate)	Up to the order of 10^{-9} measured at the end user level	5G PPP, SDO
	Packet loss rate	<<0.1%	5G PPP, SDO
	Frame loss rate	<<0.1%	5G PPP, SDO
Compute	Computational resource utilization/ optimization	~40% reduction/optimization of computation versus 5G	5G PPP
	Optimization periodicity	Optimization done in <1% with hour periodicity	6G-SANDBOX
Energy	Network energy efficiency Device energy efficiency	1 pJ/bit, target: an improvement of 10x compared to 5G.	5G PPP, SDO
	NFV energy efficiency	Not Applicable.	5G PPP
Security	Anomaly detection precision	Not Applicable.	
	Security Conformance	Passing all test vectors and robust against fuzzing.	
	Tenant data privacy	Passing all test vectors and robust against fuzzing.	
Localization	Localization accuracy Direction accuracy	<1 cm in 3D	SDO
Localization	Localization related delays & integrity (error)	Other aspects still to be defined	5G PPP, SDO
Service safety, integrity, and maintainability	Service safety, integrity, and maintainability	99,999% Towards 99,9999%	
AI Native capabilities	AI/ML accuracy (mean squared error (MSE), root Mean Squared Error (RMSE), etc)	> 0.95	6G-SANDBOX
	AI/ML Precision (Type-I errors)	Not a Number (NaN)	
	AI/ML training time	NaN	

	AI/ML training effectiveness	NaN	
	AI/ML processing times	< 0.15 ms	6G-SANDBOX
	AI/ML processing resources	NaN	
Sensing	Real Image	NaN	6G-SANDBOX
	Depth	NaN	6G-SANDBOX
	Pose	NaN	6G-SANDBOX
	Audio	NaN	6G-SANDBOX
	Velocity	NaN	6G-SANDBOX
	Object detection	NaN	6G-SANDBOX
	Egocentric segmentation	NaN	6G-SANDBOX
	Augmented Reality rendering	NaN	6G-SANDBOX
	Virtual Reality Rendering	NaN	6G-SANDBOX

The exact definitions of the enlisted KPIs are provided in the following paragraphs. It should be noted that standardized definitions used in previous generation networks are inherited and if necessary, set in the appropriate context, while new KPIs are identified, in order to define and assess new 6G capabilities, deployment contexts, and performance aspects at later stages.

2.1.2.1 Capacity KPIs Family Definitions

Capacity (Network)

In the context of 6G-SANDBOX, the Peak User Data Rate definition adheres to the definition given by ITU-R M.2410-0 [5].

Peak data rate is the maximum achievable data rate under ideal conditions (in bit/s), which is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilized (i.e., excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times).

Peak data rate is defined for a single mobile station. In a single band, it is related to the peak spectral efficiency in that band. Let W denote the channel bandwidth and SE_p denote the peak spectral efficiency in that band. Then the user peak data rate R_p is given by:

$$R_p = W \times SE_p \quad (1)$$

Peak spectral efficiency and available bandwidth may have different values in different frequency ranges. In case bandwidth is aggregated across multiple bands, the peak data rate will be summed over the bands. Therefore, if bandwidth is aggregated across Q bands, the total peak data rate is:

$W_i \times SEp_i$ (2)

where W_i and SEp_i (where i = 1,…Q) are the component bandwidths and spectral efficiencies respectively.

RIS – Capacity enhancement

In the context of 6G-SANDBOX RIS, Capacity enhancement KPI includes all essential KPIs that are responsible for capacity enhancement including signal reflection and manipulation, channel gain enhancement, coverage area, energy efficiency, reconfiguration speed, interference mitigation, scalability, and cost-effectiveness

Area Traffic Capacity

The 6G-SANDBOX definition of Area Traffic Capacity is that given by ITU-R M.2410-0 [5].

Area traffic capacity is the total traffic throughput served per geographic area (in Mbit/s/m^2). The throughput is the number of correctly received bits, i.e., the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time.

This can be derived for a particular use case (or deployment scenario) of one frequency band and one Transmission Reception Point (TRxP) layer, based on the achievable average spectral efficiency, network deployment (e.g., TRxP (site) density) and bandwidth.

Let W denote the channel bandwidth and ρ the TRxP density (TRxP/m^2). The area traffic capacity C_{area} is related to average spectral efficiency SE_{avg} as shown in the following equation:

$C_{area} = \rho \times W \times SE_{avg}$ (6)

If the bandwidth is aggregated across multiple bands, the area traffic capacity will be summed over the bands. The conditions for evaluation including supportable bandwidth are described in Report ITU-R M.2412-0[9] for the test environment.

User density - Connection density

The 6G-SANDBOX definition of Connection Density adheres to the definition provided by ITU-R M.2410-0 [5].

Connection density is the total number of devices fulfilling a specific Quality of Service (QoS) per unit area (per km^2). Connection density should be achieved for a limited bandwidth and number of TRxPs. The target QoS is to support delivery of a message of a certain size within a certain time and with a certain success probability, as specified in Report ITU-R M.2412-0 [6].

Capacity (User)

User Experienced Data Rate

In the context of 6G-SANDBOX, the User Experienced Data Rate definition adheres to the definition given by ITU-R M.2410-0 [5].

User experienced data rate is the 5% point of the cumulative distribution function (CDF) of the user throughput. User throughput (during active time) is defined as the number of correctly received bits, i.e., the number of bits contained in the service data units (SDUs) delivered to Layer 3, over a certain period of time. In the case of one frequency band and one layer of TRxP, the user experienced data rate could be derived from the 5th percentile user spectral efficiency through the following equation (3). Let *W* denote the channel bandwidth and SE_{user} denote the 5th percentile user spectral efficiency. Then the user experienced data rate, R_{user} is given by:

$$R_{user} = W \times SE_{user} \qquad (3)$$

If the bandwidth is aggregated across multiple bands (one or more TRxP layers), the user experienced data rate will be summed over the bands.

2.1.2.2 Latency KPIs Family Definitions

6G-SANDBOX adopts the definition of User and Control Plane Latency from ITU-R M.2410-0 [5].

C-Plane latency (network)

Control plane latency refers to the transition time from a most “battery efficient” state (e.g., Idle state) to the start of continuous data transfer (e.g., Active state).

U-Plane latency (network)

User plane latency is the contribution of the radio network to the time the source sends a packet to when the destination receives it (in ms). It is defined as the one-way time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 Service Data Unit (SDU) ingress point to the radio protocol layer 2/3 SDU ingress point of the radio interface in either uplink or downlink in the network for a given service in unloaded conditions, assuming the mobile station is in the active state.

Delay deviation/jitter

6G-SANDBOX uses as baseline the standardized definition of jitter given by ITU-T, as the short-term variations of the significant instances of a timing signal from their ideal positions in time. Considering as instances of the user-plane packets, jitter corresponds to the delay variation (i.e., jitter) in packet arrival times of user plane packets [7]. Adhering to [8], jitter can be quantified by metrics such as Root Mean Square (RMS) or peak-to-peak displacement, for example, of the delay variation in packet arrival times.

Reconfigurable Intelligent Surface (RIS) update rate

RIS update rate is the time it takes RIS to update the state of all control elements in a single RIS panel. Depending on a particular scenario, several updates will be necessary to find an optimal path between the RIS, Base Station (BS), and User Equipment (UE).

Latency (Orchestration Layer)

Service Provisioning Time

In the context of 6G-SANDBOX, Service Provisioning Time (considering the definitions provided in [2], [3], [4], and [9]) is defined as the total time it takes from submitting the request of creating a containerized service or function up to the actual deployment of such service/function and the provisioning of the service to the target user.

Slice Provisioning Time

In the context of 6G-SANDBOX, Slice Provisioning Time (considering the definitions provided in [2], [3], [4], and [9]) is defined as the total time it takes from submitting the request of creating a network slice up to the actual deployment of such slice and the provisioning of the slice to the target user.

2.1.2.3 Channel KPIs Family Definitions

Spectral Efficiency

6G-SANDOX adopts the definition of Spectral Efficiency from ITU-R [5]. To this end, we distinguish between the Peak Spectral Efficiency and the Average Spectral Efficiency.

Peak spectral efficiency is the maximum data rate under ideal conditions normalized by channel bandwidth (in bit/s/Hz), where the maximum data rate is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilized (i.e., excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times).

The following definition of Average Spectral Efficiency is from ITU-R M.2410-0 [5].

Average spectral efficiency is the aggregate throughput of all users (the number of correctly received bits, i.e., the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time) divided by the channel bandwidth of a specific band divided by the number of TRxPs and is measured in bit/s/Hz/TRxP.

The channel bandwidth for this purpose is defined as the effective bandwidth multiplied by the frequency reuse factor, where the effective bandwidth is the operating bandwidth normalized appropriately considering the uplink/downlink ratio.

Let R_i (T) denote the number of correctly received bits by user *i* (downlink) or from user *i* (uplink) in a system comprising a user population of *N* users and *M* TRxPs. Furthermore, let *W* denote the channel bandwidth and *T* the time over which the data bits are received. The average spectral efficiency, SE_{avg} is then defined according to the following equation.

$$\mathrm{SE}_{\mathrm{avg}} = \frac{\sum_{i=1}^{N} \mathrm{R}_i(T)}{T \cdot \mathrm{W} \cdot M}$$

2.1.2.4 EMF KPIs Family Definitions

A long-established aspect of mobile networks that has always been addressed is the Electromagnetic Field (EMF) exposure of people involved in the scenario and in particular the evaluation and measure of dosimetric quantities. 6G-SANDBOX considers the following two KPIs regarding EMF.

Self EMF Exposure

6G-SANDOX adopts the definition of Self EMF Exposure from IEC 62209 [10] (Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Human models, instrumentation, and procedures).

Inter EMF Exposure

6G-SANDOX adopts the definition of Inter EMF Exposure from IEC 62232 [11] (Determination of RF field strength, power density, and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure).

2.1.2.5 Reliability KPIs Family Definitions

Operational Network Reliability

6G-SANDBOX adheres to the definition of network reliability adopted by 3GPP TS 22.104 [12], according to which, reliability may be quantified using appropriate measures such as mean time between failures or the probability of no failure within a specified period of time.

6G-SANDBOX adheres to the definition of network reliability adopted by 3GPP TS 22.261 [13], according to which, in the context of network layer packet transmissions, reliability is expressed as a percentage of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the number of sent network layer packets. Measures of success of network layer packet transmission are packet/frame error and packet/frame loss rates.

Session Reliability (packet/frame error rate)

The packet loss and frame error rate represent the ratio of the number of erroneous packets or frames to the total number of sent packets or frames.

Packet /Frame loss rate

The packet loss and frame loss rate represent the ratio of the number of lost packets or frames to the total number of sent packets or frames, within specifically set timing constraints.

2.1.2.6 Compute KPIs Family Definitions

Computational resource utilization/ optimization

Computational resource utilization includes metrics (Average, Peak, Mean) of the cumulative usage percentage over the total computational resources of the hosts and data-centers used for 6G service provisioning - across 6G network domains.

Optimization thresholds/ Optimization periodicity

In the context of 6G-SANDBOX, a set of KPIs are used to define the targets of triggering optimization functionalities. Such triggers can be predefined periodicity parameters or utilization thresholds.

Resource utilization - Scale-out latency

In the context of 6G-SANDBOX, Scale-out latency (considering the definitions provided in [2], [3], [4] and [9]) is defined as the total time it takes from a trigger or request for scaling out of compute resources up to the actual deployment of such scaling out.

2.1.2.7 Energy KPIs Family Definitions

Energy Efficiency

6G-SANDOX adopts the definition of Energy Efficiency from ITU-R M.2410-0 [5].

Network energy efficiency is the capability of a Radio Interface Technologies (RIT)/ Set of Radio Interface Technologies (SRIT) to minimize the radio access network energy consumption in relation to the traffic capacity provided. Device energy efficiency is the capability of the RIT/SRIT to minimize the power consumed by the device modem in relation to the traffic characteristics. Energy efficiency of the network and the device can relate to the support for the following two aspects:

a. Efficient data transmission in a loaded case.
b. Low energy consumption when there is no data.

Efficient data transmission in a loaded case is demonstrated by the average spectral efficiency. Low energy consumption when there is no data can be estimated by the sleep ratio. The sleep ratio is the fraction of unoccupied time resources (for the network) or sleeping time (for the device) in a period of time corresponding to the cycle of the control signaling (for the network) or the cycle of discontinuous reception (for the device) when no user data transfer takes place. Furthermore, the sleep duration, i.e., the continuous period of time with no transmission (for network and device) and reception (for the device), should be sufficiently long.

Energy Efficiency in NFV

6G-SANDOX adopts the definition of Energy Efficiency in Network Function Virtualisation (NFV) from ETSI [14] and the metric is defined in 3GPP TS 22.261 [13].

Energy efficiency in NFV is calculated based on data transfer (KPIEE-transfer). The document specifies two variants of KPIEE-transfer (KPIEE-bit_transfer and KPIEE-packet_transfer) which are measures of the data volume transferred to and from the NFVI per unit of energy consumed by the Network Function Virtualisation Infrastructure (NFVI) as shown schematically below in Figure 1.

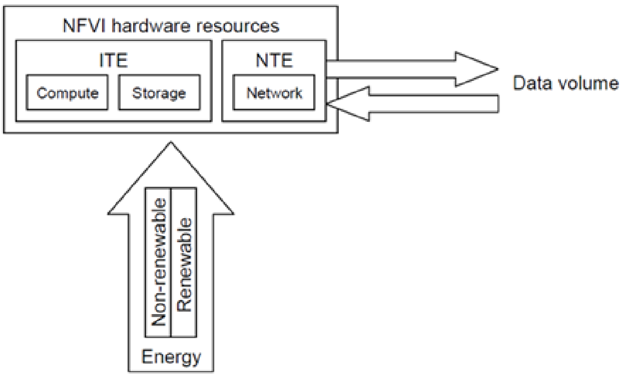


Figure 1. Energy efficiency in NFV based on data transfer [8]

The determination of the effectiveness of such NFVI in effecting a reduction of energy consumption depends upon knowledge of the energy consumption of the NFVI and data volume transmitted and received by the Network Termination Equipment (NTE) with the NFVI.

KPIEE-bit_transfer is based on the data volume defined by the arithmetic sum of Layer 2 payload content of the number of successfully transmitted and received bits.

KPIEE-packet_transfer is based on the data volume defined by the arithmetic sum of successfully transmitted and received packets.

KPIEE-bit_transfer and KPIEE-packet_transfer do not take account of:

- The energy consumption involved in the transport of the data to and from the NFVI beyond the physical interface.
- The energy consumption of any processing of the data (e.g., routing, etc.) beyond the physical interface.

2.1.2.8 Security KPIs Family Definitions

Anomaly detection precision

Anomaly detection refers to the process of identifying abnormal behavior as compared to an established pattern. Anything that deviates from an established baseline pattern is considered an anomaly.

Anomaly detection precision is a measure of the accuracy or correctness of the anomaly detection system in identifying true anomalies. It is calculated as the ratio of true positives (TP) to the sum of true positives and false positives (FP), given by:

$$\text{Precision} = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FP})}$$

The precision value ranges between 0 and 1, where a higher precision indicates a higher proportion of correctly identified anomalies relative to the total number of instances identified as anomalies.

Security Conformance

Security conformance testing in communication networks is a process that involves evaluating and verifying whether the security controls, protocols, configurations, and implementations within a network align with the specified security standards, guidelines, or regulatory requirements. It aims to ensure that the network infrastructure and its associated components conform to the defined security practices and exhibit the expected security behaviors.

In security conformance testing, the network's security measures are tested against established criteria to determine their compliance and effectiveness. The testing process involves assessing various aspects such as access controls, encryption mechanisms, authentication protocols, intrusion detection systems, firewalls, and other security components to ensure they meet the prescribed standards.

Tenant data privacy

Measuring and enhancing tenant data privacy effectiveness and maturity in terms of tenant customer trust, risk mitigation, and business enablement has become a top priority. Metrics are used to compare the maturity of their organization's privacy program to its strategy and goals and show how privacy supports both. A wide range of data points can be measured as data privacy metrics. Basic compliance and operational metrics track and enhance the effectiveness of processes by tracking actions taken by an organization, such as the quantity of data subject requests and data protection impact assessments. Advanced metrics, for instance, data sharing and email marketing, data subject requests and how many tenant customers are satisfied with the result, the number of privacy breaches and tenant customers impacted by them, show patterns in the data, such as the time taken to reply to requests. These metrics can be internally used to secure budgets and staffing, to measure performance, and to diagnose program status and needs, as well as externally to demonstrate accountability and enhance trust.

2.1.2.9 LOCALIZATION KPIS FAMILY DEFINITIONS

6G-SANDBOX adopts the definition of Localization provided by 3GPP TS 22.261 [13] and TS 23.271 [15] and TS 22.071 [16] in the following KPIs:

Localization accuracy - Direction accuracy

Accuracy is the difference between actual property or state and estimated property or state. Location may refer to the horizontal only or the 3D location (including the vertical location). The localization accuracy is a measure of the distribution of the localization error. The location error is the difference between the actual location of an entity and the estimated location of an entity in horizontal (XY) and vertical (Z) vector axis. Common statistics can be computed based on the 3D error or 2D error and include the MSE, the RMSE, the 99% localization error in meters (i.e., the error value such that 99% of the localization errors have smaller magnitude).

Localization related delays & integrity (error)

Considering the definitions provided in [2] and the deliverable D2.2 of RISE-6G [17], metrics to define and measure localization delays can include the following:

- First-time-to-fix, which is defined as the time required until a system provides the first location estimate of a device.
- Localization latency, which is defined as the time between a request for obtaining positioning information for a device and the time that the position is made available.
- Update rate, which is defined as the time between successive position estimates.

Localization Integrity

Considering the definitions provided in [2] and [17], metrics to define and measure localization integrity can include the following:

- Availability, which is measured as the mean-time between failures (MTBF) or the duration of the time the service is available.
- Reliability, which represents the ratio of the number of erroneous positioning estimates to the total number of positioning estimates.

2.1.2.10 SERVICE AVAILABILITY KPIS FAMILY DEFINITIONS

Service availability

6G-SANDBOX adheres to the definition of availability provided by ISO/IEC 27000 [18], which is the following: The property of being accessible and usable upon demand by an authorized entity.

In the context of 6G networks, the refinement provided in 3GPPP TS 22.261 [13] is considered as follows: Availability is the percentage of time during which QoS targets are met and service is offered during operation. In general, this metric provides a measure of the ratio of uptime to the sum of uptime and downtime, where uptime is the time the network service is available. It can be calculated using the following formula: Availability = (1 – (MTTR/MTBF)) x 100%, where MTTR is the mean time to repair, and MTBF is the mean time between failures.

2.1.2.11 AI NATIVE CAPABILITIES KPIS FAMILY DEFINITIONS

Each machine learning pipeline includes performance indicators that quantify the learning progress or the resource used on it, and put a number on it. All machine learning models require a metric to assess performance, whether they use linear regression or classification method. Similar to performance measurements, every machine learning activity may be divided into two categories: regression and classification. There are other metrics for these issues, however in this section we focus on the most common ones and the data they reveal regarding model performance.

AI/ML accuracy (mean squared error (MSE), root Mean Squared Error (RMSE))

AI/ML accuracy metrics are different from loss functions. Loss functions show a measure of model performance. They're used to train a machine learning model (using some kind of optimization like Gradient Descent), and they're usually differentiable in the model's parameters. For example, regression models have continuous output. So, we need a metric based on calculating some sort of distance between predicted and ground truth. In order to assess the performance of regression models, we'll usually evaluate these metrics in detail: Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), etc. For instance, the most common statistic applied to regression issues is MSE. The average of the squared difference between the target value and the value predicted by the regression model, which is differentiable, is essentially what is discovered.

AI/ML effectiveness improvement

AI/ML effectiveness refers to the efficiency for the AI training and inference. From the perspective of AI/ML training which needs huge amount of CPU/GPU capacities, the efficient training means using the minimum total cost, including the computing cost and communication cost if it comes with federated training, to reach the convergence of the model training or the minimum cost to reach a certain level of AI/ML accuracy. The AI/ML effectiveness improvement refers to the enhancement on effectiveness of the proposed optimized AI/ML task scheduling scheme.

2.1.2.12 Sensing KPIs Family Definitions

State of the art for eXtended Reality (XR) devices include multiple sensors: RGB and depth cameras, microphones, inertial measurement units (IMUs), controllers, etc. These sensors provide the necessary input data to the most relevant XR algorithms. And these XR algorithms provide a whole understanding of the scene where the devices are located. Semantic information of the scene are usually related to a 3D reconstruction that models, with different grades of accuracy depending on the final goal, the 3D morphology of the real scenario surrounding the user. It is a key algorithm in many Augmented Reality (AR) applications for generating realistic interactions between real and virtual objects.

Taking all this together, we define the following KPIs that match with the information that can be obtained:

- **Image of the real scenario**: it might be provided as a compressed video (using H264 or H265 codecs, for example) or a set of JPEG images.
- **Audio**: Provided by one or multiple microphones.
- **Depth**: With the same format of the image of the scene, the depth is usually provided by an additional camera and contains information of the distance from the camera to the objects of the scene.
- **Pose and orientation of the XR device:** XR devices must be able to accurately estimate its own pose in real-time using the available sensor data. This estimation is done using Simultaneous Localization and Mapping (SLAM) algorithms. In general, a robust XR-targeted SLAMs algorithm requires the combination of at least an RGB camera and Inertial measurement units (IMUs).
- **Velocity**: when the device is in movement this information is provided by the IMUs.
- **Object detection**: represented by the position, size and label of the bounding box of each detected object in the scene.

- **Egocentric segmentation**: This is related to the image of the body of the users that wear the XR devices, and it is useful for including it in the remote scenes. It is provided as as image mask that can be used to be rendered together with the remote image.
- **Augmented Reality rendering**: In ARs applications it is the image that is displayed in the devices. It has a format such as the image of the real scenario described in the first bullet.
- **Virtual Reality rendering**: In VRs applications it is the image that is displayed in the devices. It has a format such as the image of the real scenario described in the first bullet.

2.1.3 Overview of KVIs

The technological advancements and the proliferation of technology in modern societies has impacted and is continually impacting human and animal life as well as the environment in numerous ways. Thus, the impact assessment of technology even before its development and proliferations is in the spotlight of discussions at global, EU and local level. To this end, research and development activities not only focus on the results of research on the technology domains, but also on how these activities address societal needs and how they impact value creation. The need to align technology domain aspirations with society needs and values is driven by a large set of commitments from global, European and country-wide organizations, such as the UN Sustainable Development Goals (SDGs) [19], the European Green Deal and technological sovereignty reflecting European values. These values are in turn channelled to the funding programs, regulation, and society expectations. To this end, late phase 5GPPP projects (e.g. the preliminary work of the Hexa-X project in its deliverable D1.2 [20] and D1.3 [21]), 6G Flagship projects and organisations/associations formulating the 6G vision have made an effort to align the 6G vision with value creation. In the context of 6G-SANDBOX, these efforts are taken into consideration and also the methodology defined by 6G-IA Sub-Working Group Societal Needs and Value Creation –on how to identify the impact on Key Values and Key Value Indicators to evaluate the impact from the proliferation of use cases addressed by R&D activities- is adopted. According to 6G-IA SNVC, «KVIs are all about understanding the context within which technologies must operate, and identifying the resulting societal value these developments offer. » [22].

SNS R&I Work Programme 2021-2022 [23] identification of certain key values, grouped in three categories as follows:

Table 3 SNS R&I Work Programme 2021-2022 key values' categories

• Democracy	• Ecosystem	• Innovation
• Privacy	• Sustainability	• Safety
• Fairness	• Business value	• Security
• Digital inclusion	• Economic growth	• Regulation
• Trust	• Open collaboration	• Responsibility
	• New value chain	• Energy consumption

However, the identified values are reflecting the aforementioned global and European targets and are formulated for states, thus they need to be interpreted and further nailed down to KVs for the ICT industry to identify its impact.

Therefore, also the SNS R&I Work Programme 2023-2024 does not explicitly specify KVIs, but rather refers to the Sustainable Development Goals (SDGs) of the UN. Where it is more explicit it refers to the work of the vision expert work group of the 6G IA on the societal values 6G will address.

To this end, although it is stated that the 2021-2022 work programme states that these KVIs should be adapted to the goals of the SNS projects, it is still a challenge to qualify and even less to quantify relevant KVIs for this project.

In the case of UN SDGs, the SNS work programme provides examples such as:

- SDG 8: Promote sustained, inclusive, and economic growth: achieve higher levels of economic productivity through diversification, technological upgrading, and innovation.
- SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, upgrade infrastructure and retrofit industries to make them sustainable with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.
- SDG 11: Make cities and human settlements inclusive, safe, resilient, and sustainable.
- SDG 13: Climate Action. Support smart low carbon lifestyles, monitoring emissions, and shaping demand in transport and energy, enabling resilient mission critical communications in extreme weather (vertical markets: transport, health, and public safety). Furthermore, it provides for complementary societal values in ethics issues related to privacy and EMF (electric and magnetic fields) awareness and reduction.

The 6G IA vision WG provides a KVI analysis framework as a series of steps:

1. Identification of societal pain points.
2. Identification of relevant, positively affected key values.
3. Identifying indicators for key values to measure the scale of effect.
4. Determining the enablers of usage.
5. The quantification of KVIs with KPIs, which effectively means the derivation of network performance parameters (KPIs) from agreed KVIs.

The current methodology is rather abstract and not yet suitable to execute a mapping of key value indicators to network performance parameters.

2.1.3.1 Assessment of general KVI categories

Adopting the 6G-IA SNVC methodology and identifying the Key Values mandated by the programme, the project brief/proposal and a study of the 6G-SANDBOX deliverable products and outcomes, at a first approximation the work of 6G-SANDBOX is centred around the key values of (i) resilience, (ii) sustainability, and (iii) inclusiveness.

The 6G-SANDBOX project considers the key societal value of **resilience** as the ability to adapt and recover from challenging and unforeseen situations. In the context of a multi-stakeholder and open experimentation facility for 6G, resilience can be related to the ability of the facility to withstand unexpected events and continue to function effectively. This involves developing robust and secure operational protocols that can handle unexpected disruptions and attacks on the facility, by designing algorithms that can dynamically adjust to disruptions or deploying a fault-tolerant architecture that can automatically detect and recover from failures. Although fault-tolerance is not explicitly addressed by the project the overall design considers these aspects, since highly distributed systems such as the

6G-SANDBOX facility being a multi-stakeholder environment must inherently incorporate measures to mitigate failures of nodes or network parts, caused by attacks or other reasons.

On the other hand, a multi-stakeholder and open experimentation facility for 6G has the potential to demonstrate how we can improve the resilience of critical infrastructures such as transportation systems, emergency response networks, or healthcare facilities. For example, by demonstrating secure real-time communication and trusted data sharing among systems and stakeholders in any 6G environment, 6G-SANDBOX can help improve the response time and effectiveness of services in the event of disruptions of communication infrastructure or other crisis. Emphasizing resilience in the design and implementation of an environment such as 6G-SANDBOX, future networks can continue to function effectively even in the face of unforeseen disruptions and attacks, thus contributing to the overall well-being and safety of society.

We consider the key societal value of **sustainability** as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs. In the context of an open experimentation facility like 6G-SANDBOX, sustainability is related to the development of network capabilities that are environmentally responsible, energy-efficient, and economically viable. In 6G-SANDBOX, we incorporate the value of sustainability by focusing on economically viable technologies and practices. The aspects of environmental responsibility and energy-efficiency are only indirectly affected; namely by exposing energy consumption metrics to the experimenter and customer of the facility, which facilitates the consideration of such aspects.

On the other hand, 6G-SANDBOX can support the growth of sustainable industries and practices. For example, by fully exposing relevant energy metrics during experimentation, 6G-SANDBOX can enable secure and trusted real-time monitoring and control of energy usage in factories and other industries. It can therefore contribute in the longer term to improve energy efficiency and reduce resource waste in industry and society. Emphasizing sustainability in the design and implementation of the 6G-SANDBOX facility contributes to the long-term well-being and prosperity of society, while reducing its impact on the environment, and supporting sustainable development and economic growth.

The key societal value of **inclusiveness** is the recognition that every member of society should have equal access to opportunities, resources, and services in the context of 6G networks. In the context of a multi-stakeholder and open experimentation facility, inclusiveness is related to ensuring that services are accessible and available to everyone, regardless of their location, income, or other factors. In our research we incorporate inclusiveness, taking note of the European Accessibility Act[1] (in effect June 2025), which establishes accessibility requirements for several key products and services and ensures services are accessible and usable for most members of society. With respect to usability, the capabilities of 6G-SANDBOX aim to be transparent for the experimenter, however, delivering services for everyone, including persons with impairments or disabilities, is not within the scope of the 6G-SANDBOX experimental facility. Additionally, the services should be affordable; however, this aspect cannot be reasonably assessed in 6G-SANDBOX. Finally for the inclusion of people across all geographic locations including rural and remote areas, we argue that the architecture facilitates an easy and efficient extension though deployment of additional nodes on demand and the inclusion of edge computing capabilities.

6G-SANDBOX can, however, support the needs of under-represented or marginalized communities, by enabling for example experimentation with trusted real-time translation services or access to

[1] https://ec.europa.eu/social/main.jsp?catId=1202

remote civic services through trusted and advanced 6G network capabilities. This will help improve the accessibility and quality of services for people who may face barriers to accessing traditional services. The consideration of inclusiveness aspects in the design and implementation of such a 6G system ensures that the network services benefit and are secure for everyone. This helps to promote social equity, reduce disparities, and improve the overall well-being and prosperity of society.

2.1.3.2 Relevance of KVIs in the Context of Use Cases and Open Calls

As indicated in the 6G IA white paper by its vision work group, it is currently appropriate to analyse KVIs in the context of each use case and attempt to derive related KPIs following a five steps methodology. In this sub-section we will briefly elaborate on this methodology in order to provide guidance to experimenters using the 6G-SANDBOX facility to systematically derive KPIs enabling identified key values.

The 6G IA vision WG provides a KVI analysis framework in steps; namely:

(0) Identification of the scenario and the relevant use cases that are addressed by the R&D activity/ solution, including the societal pain points that lie in these use cases;

(1) Identification of relevant, positively affected key values; at this point the affected key values are searched in the programme mandate, the description of the use case (problem statement and solution) and in the global and European normative frameworks.

(2) Identification of indicators for key values to measure the scale of effect, stemming from the proliferation of the use cases. At this point, it is useful to mention that there are two forms of impact: a direct impact and an indirect impact; both forms can have positive and adverse effects caused by the usage of R&D outcomes.

(3) Formulating of KVIs for the quantification of the impact on KVs ; i.e. metrics, absolute or relative measures of the impact assessment on KVs. KVIs will need to capture KVs that are both benefitted as well as those that are harmed. This step includes multiple iterations over the various maturity phases of the R&D activity and sets specific targets based on societal values. The formulation of KVIs shall be tailored to the specific Use Case and reflect the following:

- Stakeholders addressed in the real deployment of the use case
- Scale of proliferation of the use case (global, continental (EU), local, organisational (e.g. specific industry, stakeholder entities), personal)
- Aspects of the use case that are addressed by the specific activity (i.e. domain such as: environmental, socio-economic, personal, etc.)
- And last but not least any targets/ KVIs inherited by the programme/ project mandate.

(4) Identification of key enablers (technology features, capabilities, KPIs) that are necessary for the adoption and proliferation of the use cases in order to achieve the targeted impact.

As an example, at these initial stages of 6G-SANDBOX project, following the 6G-IA SNVC methodology on the aforementioned key values we consider the following KVIs deriving from the use case of «providing 6G-SANDBOX facilities as platforms where researchers, experimenters and other entities (from industry and academia) can access through the open calls».

Table 4 KVIs targeted by 6G-SANDBOX

KV	KV classification	KVIs	Enablers
Resilience	Stakeholder: Entities that can access 6G-SANDBOX to test and adopt resilience capabilities of network solutions (e.g., critical infrastructures such as transportation systems, emergency response networks, or healthcare facilities, smart cities) Scale: EU, country-wide, local Domain: socio-economic KV as outcome: Improved safety of society.	KVI1: Improved response times for critical and emergency service providers represented by various stakeholders. KVI2: Improved effectiveness of services in the event of disruptions of communication infrastructure or another crisis.	Open access to infrastructure Resilience related capabilities incorporated in the testbeds
Sustainability	Stakeholder: Environment Scale: Global, EU Domain: Environment KV as outcome: Network capabilities are environmentally responsible, energy-efficient.	KVI1: Reduction of the energy footprint of telecommunication solutions KVI2: Reduction of materials usage of telecommunication solutions KVI3: Environmentally neutral materials lifecycle of telecommunication solutions	Energy Efficient Solution Technologies with neutral environmental footprint
Sustainability	Stakeholders: Industry (involved in solution development) Scale: Organisational Domain: socio-economic; Process/ Human Activity KV as outcome: Economically sustainable solution for Industry to manufacture and provision	KVI1: Affordable Cost for industry stakeholders to manufacture and provide the solution KVI2: High Benefit vs Cost ratio - for Industry to manufacture and proliferate/commercialise the solution	Low CAPEX/ OPEX solution
	Stakeholders: Service providers, Service customers Scale: Organisational, personal Domain: socio-economic; Process/ Human Activity KV as outcome: Provide economically sustainable solution to stakeholders – users of the solution & services	KVI1: Affordable service/ Cost of service for service customers. KVI2: Affordable service/ Cost of solution for provisioning the relevant services	Low CAPEX/ OPEX solution
Inclusiveness	Stakeholder: Experimenters, researchers Scale: personal	KVI1: Accessibility of infrastructure from remote locations with no	Remotely accessible facilities

	Domain: socio-economic; Innovation; KV as outcome: Services are accessible and available to everyone, regardless of their location, income, or other factors	6G facilities (for experimentation and testing). KVI2: Accessibility of infrastructure to under-represented or marginalized communities	High availability of facilities High reliability testing High reliability of obtained results.

Similarly, this methodology can be followed for the identification of KVs and KVIs as well as the technology enablers, in the context of use cases to be tested and demonstrated within the 6G-SANDBOX open calls.

2.1.4 Stakeholders and Actors

The following section presents an initial analysis on the Stakeholders and Actors that are expected to be of particular interest in the 6G-SANDBOX Ecosystem. This analysis takes as its starting point the analysis presented in the 5G Ecosystem whitepaper [24] of the 5G Infrastructure Association. Even though the document describes the ecosystem on a 5G environment, it is still considered as the recommended foundation in documents published as recently as May 2023 by the 6G IA [25].

From this initial analysis, a large number of stakeholders are identified and associated in different groups and sub-groups. This initial organization has been further refined for the context of 6G-SANDBOX, resulting in the selection of the following stakeholders:

- **Research and Innovation**: This group includes any research institution that can produce scientific results, and other research projects, such as those coming from the SNS JU programs or equivalent international initiatives. Included in this category are also experimental platforms that provide support to third parties during experimentation.
- **Vertical**: This stakeholder includes both the Verticals and Vertical Association in the 5G PPP stakeholders' picture and glossary [26]. It includes any company or association of companies involved in the development, manufacturing, and marketing of products and media content and services to end users at a commercial scale. Both SMEs and large enterprises are considered Verticals. This is a large group that includes, among others:
    - Technology, connectivity, and digital services providers.
    - System integrators.
    - Healthcare, energy, public safety.
    - Logistics and transport, Smart Cities.
    - Agriculture and Industry, Factories of the Future.
- **End Users**: End users represent the customers that buy products or services provided by a Vertical, or citizens in general. They are of special interest for the definition and assessment of KVIs.
- **Regulation and Standardization bodies**: This group includes regional and national authorities, regulators, and policy makers, as well as standardization organizations.

This initial analysis has been complemented with a set of discussions in the context of the sessions organized by the project to promote the open calls at national and European levels, as well as events like EUCNC 2023.

3 6G-SANDBOX Facility Requirements

3.1 6G-SANDBOX Approach and Requirements Gathering Methodology

The 6G-SANDBOX facility will be developed with the goal of supporting the Trial Networks throughout their lifecycle. To this end, it builds upon a well-established architecture that has evolved from the experience gained through previous 5GPPP projects and is structured into three layers, each serving a specific purpose, as shown below in Figure 2.

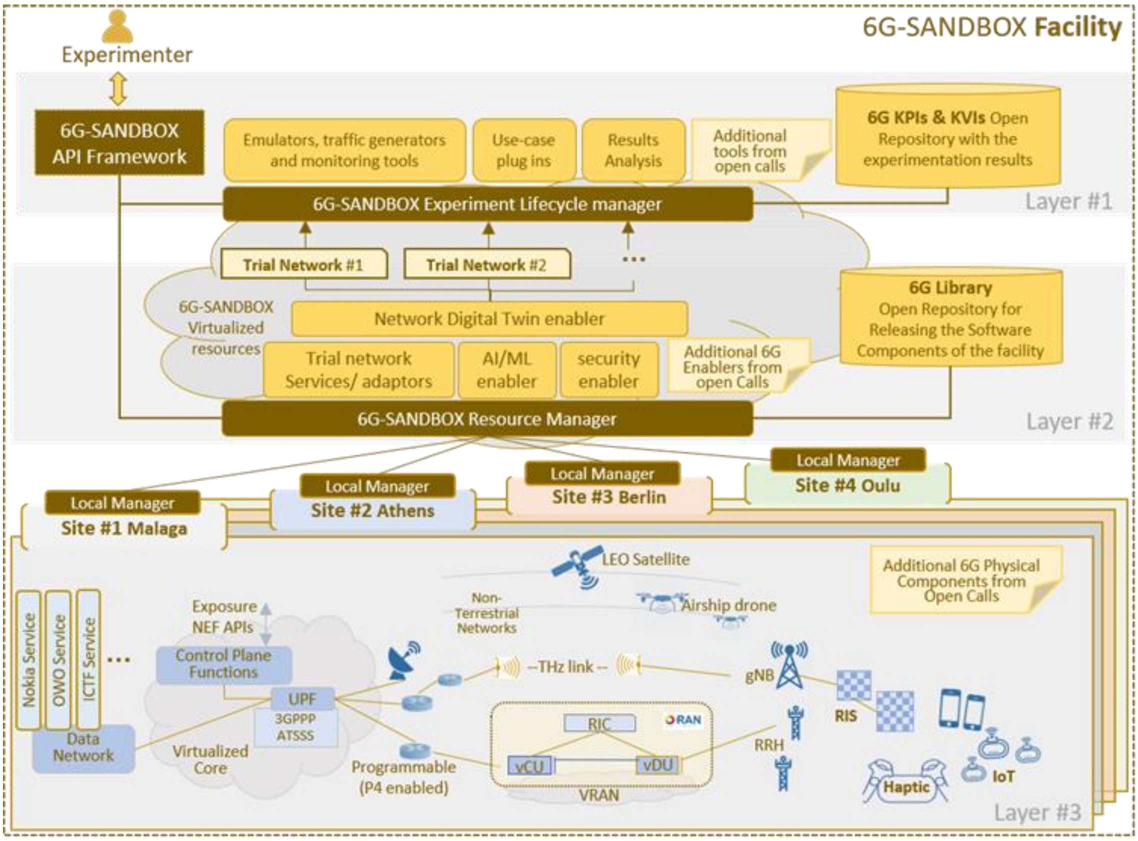


Figure 2. 6G-SANDBOX Facility Blueprint

Following a bottom-to-top approach, the first layer (Layer #3) known as the **Physical Connectivity Infrastructure** layer, consists of the four diverse, in terms of capabilities yet fully interoperable, platforms. This layer focuses on establishing the physical connectivity required for the Trial Networks. The second layer, called the **Resource Management** layer (Layer #2), is responsible for efficiently managing the virtualized resources within the facility. It hosts software components that enable an "Infrastructure as Code" (IaC) approach. This approach supports the creation and programmability of the Trial Networks by providing the necessary infrastructure. The third layer, known as the **Experimentation Lifecycle** layer (Layer #1), manages experiments conducted within the facility. It serves as the primary interface for interacting with the experiments and acts as a centralized entry point for experiment-related activities.

To evolve from the blueprint to the initial design of the architecture, it was deemed mandatory to drill into the specific functional requirements and in some cases, capabilities per component. The definition of the functional requirements plays a crucial role in fulfilling the expected functionality of the 6G-SANDBOX facility. Due to their diverse nature, it is important to adopt a constructive approach for organizing, processing, and presenting these requirements. The most effective method has been to group them according to the layering directives outlined in Figure 2 above. The requirements' description was analytically defined as shown below in Table 5. The target of this work has not been to provide an exhaustive and unmanageable list of technical details, but rather to determine the key demands to stir the design phase to identify the proper means to address them.

Table 5 Requirements Description Template

Field	Description
REQ-ID	A unique ID, in the form of REQ-TYPE-#, TYPE=INFRA/RM/EXP • INFRA: Infrastructure Layer • RM: Resource Management Layer • EXP: Experimentation Layer
Priority	• Mandatory • Desirable • Optional
Description	A brief text explaining the requirement, including the objectives where necessary
Type	TYPE=FUNC/NONFUNC • FUNC: Functional • NFUNC: Non-Functional

3.2 Functional Requirements

3.2.1 Infrastructure Layer

This section presents the requirements that are relevant to the infrastructure layer components, focusing on the core network, the backhaul network, the mobile edge platform and the radio heads, as well as the end-user equipment. These components originate from: i) the four (4) mature experimentation testbeds utilised within 6G-SANDBOX (Malaga, Berlin, Athens, Oulu), ii) components from commercial public networks, and iii) emulation/twinning components (mainly offered by Keysight toolbox). It is also important to note that during the lifetime of the project, the infrastructure layer will be enhanced with additional components that will be provided by externals open callers. These enhancements and updates in the framework of the infrastructure layer will be described in the final deliverable of T2.1 namely “D2.2: Final overall Framework Design and requirements”, due at M24.

Table 6. Infrastructure Layer Functional Requirements

REQ-INFRA-FUNC-1	**5G RAN and Core Coexistence**
Priority	Mandatory
Description	The facility shall provide 5G RAN and core components to experiment with use cases involving aggregation of technologies, standalone mode, and other interworking capabilities
REQ-INFRA-FUNC-2	**Modes of operation**
Priority	Mandatory
Description	The 5G system (core network, RAN, and UE) shall support standalone modes of operation
REQ-INFRA-FUNC-3	**Flexible Configuration of User Equipment**
Priority	Mandatory

Description	The platforms shall provide both commercial and experimental UEs with open APIs to allow flexible configuration
REQ-INFRA-FUNC-4	**Utilisation of Edge nodes for experiments**
Priority	Mandatory
Description	The edge nodes of the infrastructure layer shall allow deployments that will support the use cases
REQ-INFRA-FUNC-5	**Integration of measurement probes and tools**
Priority	Mandatory
Description	The infrastructure layer shall enable the deployment of measurement tools and probes. It shall also encompass the mechanisms for gathering relevant metrics required to validate the corresponding KPIs for the scenarios to be tested.
REQ-INFRA-FUNC-6	Resource Isolation
Priority	Mandatory
Description	The Infrastructure layer shall facilitate resource sharing and support multiple accesses. Additionally, it will incorporate suitable mechanisms to ensure resource usage isolation when necessary.
REQ-INFRA-FUNC-7	**Virtualised Computing Environment**
Priority	Mandatory
Description	The Infrastructure layer shall utilize virtualized computing infrastructure to enable function virtualization using virtual machines and/or containers
REQ-INFRA-FUNC-8	**Infrastructure as a Service**
Priority	Mandatory
Description	The deployed virtualized infrastructure shall provide interfaces and APIs that enable resource management and orchestration by Coordination layer
REQ-INFRA-FUNC-9	**NTN integration**
Priority	Mandatory
Description	The infrastructure layer shall encompass the integration of fixed/RAN and Non-Terrestrial Network (NTN) with EDGE/MEC, and the utilization of satellite for mobile backhaul. It shall also include the emulation of satellite communication systems.
REQ-INFRA-FUNC-10	**Different Access Technologies integration**
Priority	Mandatory
Description	Access technologies, including fixed (mostly optical fiber), beyond 5G radio e.g., O-RAN and RIS, shall be integrated.
REQ-INFRA-FUNC-11	**Support of 5GNR mmWave**
Priority	Mandatory
Description	The infrastructure layer shall support beyond 5G and 6G spectrum. This should include licensed, unlicensed, or licensed-shared access. It also includes novel spectrum at THz bands.
REQ-INFRA-FUNC-12	**Spectrum use**
Priority	Mandatory
Description	Regulatory constraints with respect to 5G spectrum use must be abided
REQ-INFRA-FUNC-13	**Management Interface**

Priority	Mandatory
Description	The infrastructure layer shall provide an interface for the vertical applications/experimenters to be able to control the execution of their experiment

3.2.2 Resource Management Layer

The Resource Management layer is responsible for managing computational and network resources of the facility and will be a single reference coordination layer for the physical infrastructure as part of the four experimentation sites. The main components of this layer are: i) the Digital Twin enabler for interaction with the Experimentation lifecycle layer, ii) the Trial Network lifecycle manager, and iii) 6G-enablers for AI. The functional requirements concerning the components of the Resource Management layer are provided in Table 7 below.

Table 7. Resource Management Layer Functional Requirements

REQ-RM-FUNC-1	**Interaction with the Experimentation Layer**
Priority	Mandatory
Description	The Resource Management layer shall expose APIs for discoverability and secure access through the Common API framework (CAPIF), to its different functionalities
REQ-RM-FUNC-2	**Provision of scalable networking tools**
Priority	Mandatory
Description	Integration with digital twin platforms namely QualNet and EXata shall be considered for network modelling and simulation
REQ-RM-FUNC-3	**Trial Network descriptor definition**
Priority	Mandatory
Description	The Resource Management layer shall support the definition of a Trial Network Descriptor, including commands for the execution of actions such as the creation, modification, suspension, closure, and twinning of instances of the Trial Networks
REQ-RM-FUNC-4	**Management of the trial network**
Priority	Mandatory
Description	The Trial Network lifecycle manager shall handle the translation of the contents of a Trial Network Descriptor to the actions and configuration values necessary for the instantiation, modification of the Trial Networks
REQ-RM-FUNC-5	**Inter platform distribution of resources**
Priority	Mandatory
Description	The Trial Network lifecycle manager shall handle the management of the lifecycle of the Trial Network, from creation until decommission and the upkeep of their status, as well as the distribution of resources between the different Trial Networks
REQ-RM-FUNC-6	**Flexibility towards the IaC**
Priority	Mandatory

Description	The Resource Management layer shall support Infrastructure-as-code, including the creation of any required modifications, or the development of additional components that interface with IaaS provider to deliver additional functionalities
REQ-RM-FUNC-7	**Utilisation of various Infrastructure managers**
Priority	Mandatory
Description	The Resource Management layer shall be able to support other infrastructure managers as well. The infrastructure managers will allow to maintenance of an up-to-date report of the usage of the resources
REQ-RM-FUNC-8	**RAN profiles**
Priority	Mandatory
Description	The Resource Management layer shall expose a list of possible RAN configurations to be utilized by the experimenters
REQ-RM-FUNC-9	**Support of traffic steering**
Priority	Mandatory
Description	The Resource Management layer shall support connectivity configuration and traffic steering for slices located on separate platforms with the purpose of creating one end-to-end slice
REQ-RM-FUNC-10	**Load balancing of traffic**
Priority	Mandatory
Description	The Resource management layer shall support intelligent traffic load balancing for traffic across multiple access networks
REQ-RM-FUNC-11	**Coexistence of multiple slices**
Priority	Mandatory
Description	The Resource management layer shall allow the co-existence of multiple slices running concurrently over the same infrastructure

3.2.3 EXPERIMENTATION LIFECYCLE LAYER

The 6G-SANDBOX Experimentation Lifecycle layer encompasses a powerful software suite which will include i) a standardized API framework and ii) a powerful experimentation toolbox to support the experimentations. All of the results (experimentation methodology, KPI/KVI definitions, and values from the measurement campaigns) will be hosted in an open repository, namely the KPIs/KVIs repository. Based on the information provided above, Table 8 below outlines the requirements specific to the experimentation layer.

Table 8. Experimentation Layer Functional Requirements

REQ-EXP-FUNC-1	**Exposure of APIs towards the experimenter**
Priority	Mandatory
Description	The Experimentation layer shall expose open APIs enabling the Vertical experimenter to access the Facility, define and conduct experiments as well as retrieve the results
REQ-EXP-FUNC-2	**Support of specific plugins for modularity**
Priority	Mandatory

Description	The manager of the Experimentation layer shall support the development, execution, and analysis of test plans by utilizing an architecture with plugins for any additional extensions
REQ-EXP-FUNC-3	**Dashboard for visualisation**
Priority	Mandatory
Description	The Experimentation layer shall provide visual representation of the experiment execution results through a graphical user interface, as well as automated reporting to the experimenter
REQ-EXP-FUNC-4	**Monitoring of the experiments**
Priority	Mandatory
Description	The Experimentation layer shall provide to the experimenter monitoring information in relation to the execution of the experiment
REQ-EXP-FUNC-5	**KPIs collection and validation**
Priority	Mandatory
Description	The Experimentation layer shall provide a repository for data gathering as well as processing of all experimental data to calculate and validate the target KPIs
REQ-EXP-FUNC-6	**Profiling configurations**
Priority	Mandatory
Description	The Experimentation layer shall expose to the experimenters predefined options for components’ configuration that can be provisioned at a given time for experimentation
REQ-EXP-FUNC-7	**Inventory list and technologies per platform**
Priority	Mandatory
Description	The Experimentation layer shall provide an Inventory listing the experimental capabilities per platform
REQ-EXP-FUNC-8	**Provision of experimentation toolbox**
Priority	Mandatory
Description	The Experimentation layer shall provide to the experimenter a set of tools for monitoring and simulation to facilitate the experiments
REQ-EXP-FUNC-9	**Experiment definition**
Priority	Mandatory
Description	The Experimentation layer shall provide an experiment descriptor template to allow experimenters to describe their experiments. The descriptor could be part of the open API specification.
REQ-EXP-FUNC-8	**Provision of experimentation toolbox**
Priority	Mandatory
Description	The Experimentation layer shall support the deployment of past experiment settings (e.g., platform’s configuration) and the repetition of the experiment
REQ-EXP-FUNC-9	**Common API Framework**

Priority	Mandatory
Description	The Experimentation layer shall provide a common API framework for any interaction needed among the architectural layers

3.3 Non-Functional Requirements

Non-functional requirements encompass a wide range of qualities and characteristics that significantly impact the overall performance, usability, security, reliability, and sustainability of a system. In the context of developing the 6G-SANDBOX facility, both functional and non-functional requirements are crucial to meet the expectations of experimenters and the specific use cases that will be tested. While 6G networks are still in the early stages of definition and development, based on anticipated advancements and expectations, some envisioned non-functional requirements include security and privacy, NTN integration, deterministic communications, sustainability, and O-RAN. A summary of these requirements can be found below in Table 9.

Table 9. 6G-SANDBOX Non-Functional Requirements

REQ-NFUNC-1	**KPI & KVI Validation**
Priority	Mandatory
Description	The trial networks and all its components shall be able to measure and validate the target KPIs/KVIs and store them in 6G KPI and KVI repository
REQ-NFUNC-2	**Security & Privacy**
Priority	Mandatory
Description	The trial network shall implement robust security measures to protect experimenter's data, prevent unauthorised access, and mitigate potential threads
REQ-NFUNC-3	**NTN seamless integration**
Priority	Mandatory
Description	The 6G-SANDBOX facility is expected to seamlessly integrate satellite networks in the existing testbeds (i.e., Malaga, Athens, Berlin) for enhanced coverage and improved connectivity
REQ-NFUNC-4	**E2E Experiment Automation**
Priority	Mandatory
Description	The 6G-SANDBOX facility will need to provide an end-to-end trial network including fully automated lifecycle management tasks (e.g., creation, maintenance, resource management, and deletion)
REQ-NFUNC-5	**Network Openness**
Priority	Mandatory
Description	The 6G-SANDBOX facility should support Open APIs to enable communication between the experimenters and the facility, as well as among the various components of the system
REQ-NFUNC-6	**Network Slicing**
Priority	Mandatory
Description	Each platform should support network slicing, allowing the creation of customized virtual networks to meet the specific requirements of the experimenter (i.e., trial networks should support multiple slices)
REQ-NFUNC-7	**Intelligent Resource Management**
Priority	Mandatory
Description	The 6G-SANDBOX facility should incorporate advanced AI capabilities within the trial network enhancing overall network efficiency and reliability

REQ-NFUNC-8	O-RAN and RIS
Priority	Mandatory
Description	The 6G-SANDBOX facility should support Open RAN solution with open interfaces and integrate RIS solution one of the existing testbeds
REQ-NFUNC-9	Time Sensitive Networking (TSN) support
Priority	Mandatory
Description	The 6G-SANDBOX facility should have the capability to support TSN features, ensuring precise time synchronization and deterministic low-latency communication for time-critical use cases
REQ-NFUNC-10	Sustainability
Priority	Optional
Description	The 6G-SANDBOX facility should prioritize energy efficiency, aiming to reduce power consumption and environmental impact. Innovations in network hardware, algorithms, and power management techniques should be implemented to achieve sustainable and green network operations.

3.3.1 Use case requirements

For an extensive and full-range utilization of the 6G-SANDBOX facility, use case specific services and enablers are targeted with a focus on the Xtended Reality concept. Table 10 below shows the non-functional requirements that the facility should accomplish and are purely related to the Xtended Reality use case.

Table 10. 6G-SANDBOX Use Case Requirements

REQ-NFUNC-1	XR Quality – High Bitrate
Priority	Mandatory
Description	The 6G-SANDBOX facility should support the transmission of high bit rates for assuring the transmission of 360 equirectangular video with minimum resolutions of UHD at 20 Mbps
REQ-NFUNC-2	XR Quality – Low latency
Priority	Mandatory
Description	The 6G-SANDBOX facility should support maximum end-to-end latency between video/audio/XR data of 5s
REQ-NFUNC-3	Media storage
Priority	Mandatory
Description	The 6G-SANDBOX facility should support the storage of videos that will be served as Video-On-Demand for remote users
REQ-NFUNC-4	GPU processing
Priority	Optional
Description	The 6G-SANDBOX facility should support the computation of high demanding algorithms (IA such as deep-learning tools) that analyse and provide information about the real-world images captured by XR apps

REQ-NFUNC-5	Remote application control access
Priority	Mandatory
Description	The 6G-SANDBOX facility should provide remote access to control and manage the XR apps

3.3.2 Cross platform requirements

During the requirements analysis phase, specific non-functional requirements that hold value across all the testbeds of the 6G-SANDBOX facility, have been also identified and are presented below in Table 11.

Table 11. Cross Platform Requirements

REQ-NFUNC-1	Security and Privacy
Priority	Mandatory
Description	The testbeds shall implement processes to ensure experimenter privacy and obtain consent to comply with General Data Protection Regulation (GDPR) requirements
Reference layer	All
REQ-NFUNC-2	**Authentication and Authorization**
Priority	Mandatory
Description	The Experimentation layer shall provide means for authentication and authorization of experimenters accessing the Facility
Reference layer	Experimentation layer
REQ-NFUNC-3	**Operational Stability and availability**
Priority	Mandatory
Description	The testbeds shall offer continuous, uninterruptable operation during experimentations
Reference layer	All
REQ-NFUNC-4	**Repeatability of the Results**
Priority	Mandatory
Description	Each testbed shall guarantee that the results of the experiments are repeatable achieving evaluation of the experiment and the selected configuration status
Reference layer	All

4 OVERALL FACILITY DESIGN SPECIFICATIONS

4.1 REFERENCE ARCHITECTURE DESIGN PRINCIPLES

The Reference Architecture of the 6G-SANDBOX facilities has been designed according to the extensive experience of the Consortium partners in previous H2020 research projects, including the EU Wireless [27], 5Genesis [28], and 5G-VINNI [29]. This previous experience has given the Consortium partners knowledge on the requirements and expectations for experimental platforms, as well as insights on solutions for the management of such systems. In addition to this experience, special emphasis has been placed in five key characteristics that improve the long-term support and continuous evolution of the 6G-SANDBOX facilities. These characteristics are Modularity, Openness, Reusability, Innovation, and Sustainability, which are reflected in the approach and architecture of 6G-SANDBOX as described in more detail below.

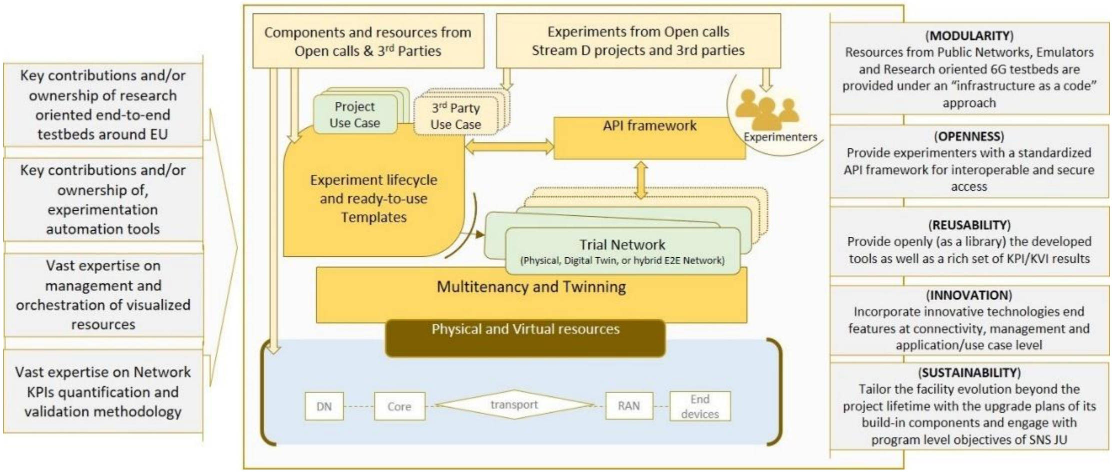


Figure 3. Overall Project Approach

Modularity is achieved by the creation of a layered architecture and implementation of well-defined standardized APIs for the communication of the components. Additionally, an "Infrastructure as Code" approach will be applied to many of the components and functionalities provided.

Openness is achieved by the usage of the 3GPP CAPIF, which is the base of the 6G-SANDBOX API Framework, guaranteeing access to the functionality though unified and standardized interfaces. Additionally, software components created within the project will be released as open-source software whenever possible, as well as made available as part of the 6G Library, which is a main component of the Reference Architecture.

Reusability is achieved, in part, due to the Consortium's approach to Openness, but is also supported by the creation of reusable patterns, such as Trial Network templates that can support pre-defined use cases and provide the foundation for more specialized goals. The concept of Trial Networks also introduces a separation between actual experimentation and the configuration of the underlying resources. This enables the same Trial Network to be seamlessly instantiated in different experimentation platforms, even for situations where physical components may not be available due to the usage of Digital Twins.

Innovation The definition of the Trial Network should lead to an increase in innovation, reducing the complexity in experimentation and trials management and allowing platforms to move to a zero-touch management approach. In line with the approach to modularity, the usage of standardized APIs and a layered design implies that innovative technologies can be more easily adopted by the 6G-SANDBOX platforms in the future.

Sustainability is achieved by providing the best support for emerging 6G experimentation. The Reference Architecture has been designed with the needs of experimenters coming from Open Calls and future SNS JU programs as a main input. Additionally, the Consortium will be actively involved in related Working Groups to provide insights and guide the conversations to reach the most favorable conclusions for the community.

4.2 Reference Architecture Model

The 6G-SANDBOX Reference Architecture is a layered architecture, where each layer abstracts and encapsulates part of the functionality while making use of the abstractions provided by the layers below. By using this approach, it is possible to reduce the perceived complexity of the system, offering to end-users a simplified interface that does not require extensive knowledge of the inner workings of the system, while also separating the real complexity into smaller, more manageable pieces. The reference architecture shown below in Figure 4 is composed of three different layers.

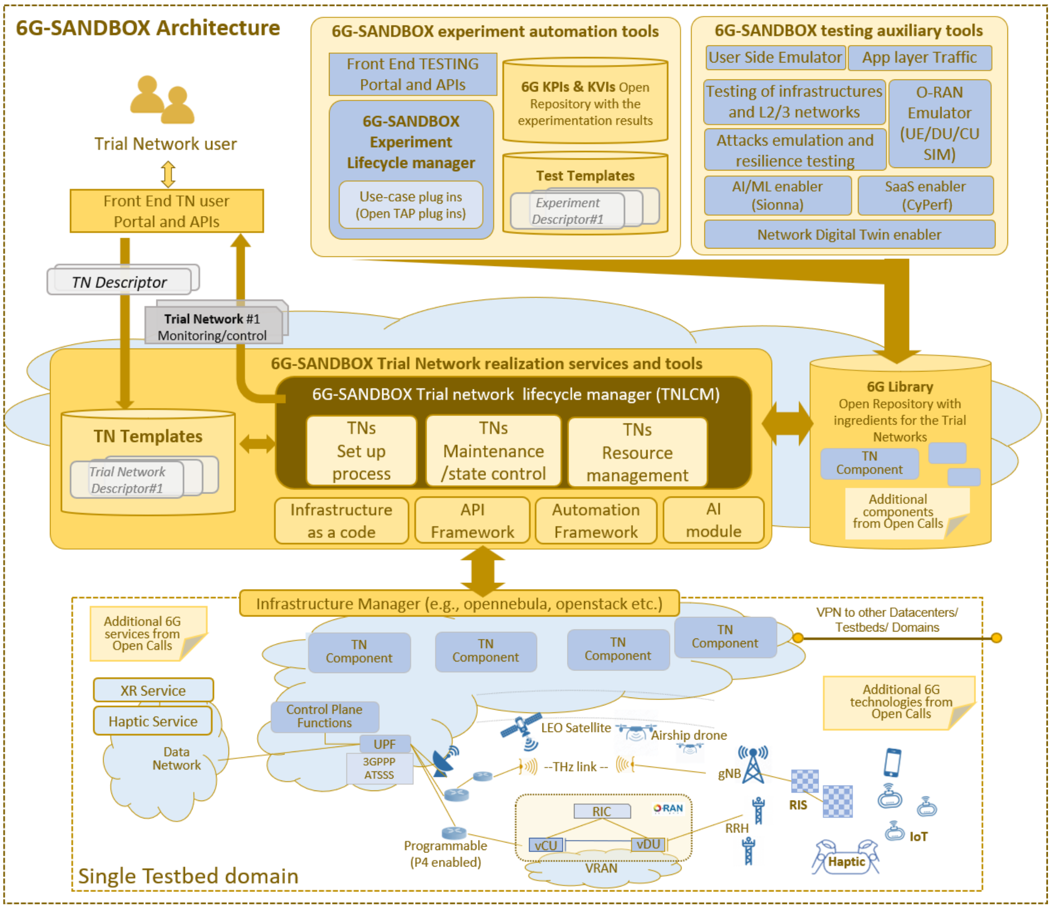


Figure 4. 6G-SANDBOX Updated Architecture

From bottom to top the layers are as follows:

- The **Physical Infrastructure Layer** contains all the physical components that form: (i) the 5G/6G network, (ii) the computational resources, (iii) the measurement equipment, (iv) the end user devices, and (v) any additional devices necessary for a particular experiment that need to be integrated into the testbed. This layer can be extended with external resources from other Testbed Domains, the premises of the experimenters or the public cloud, by the usage of VPN connectivity.

- The **Resource Management Layer**. On top of the Physical Infrastructure layer, each Testbed Domain makes use of Infrastructure Managers (such as OpenNebula, OpenStack, PROXMOX, etc.) that allow the management of the heterogeneous capabilities in the testbeds from a single point of entry.
- The **Experimentation Lifecycle Layer** acts as an interface between Experimenters (the users of a Trial Network) and the underlying Resource Management layer. Its main task is to manage the lifecycle of the different Trial Networks, which encapsulate the resources from the testbed that are made available to the experimenter.

Access to the functionality is provided to Trial Network users mainly in the form of standardized RESTful APIs. These APIs may be complemented with one or more Web Portals that ease the usage of parts of the API, but which are not mandatory and do not replace the APIs. This architecture gives support to an undetermined number of Trial Networks, which can co-exist inside the testbed, sharing the available underlying resources but isolated from each other so that no experimenters can have access to data or computational resources that have not been reserved for their use case. An alternative view of the 6G-SANDBOX reference architecture is illustrated in Figure 5 below. This figure provides a more simplified perspective on the 6G-SANDBOX reference architecture, which is more in line with the architectural diagrams found in various standardization bodies.

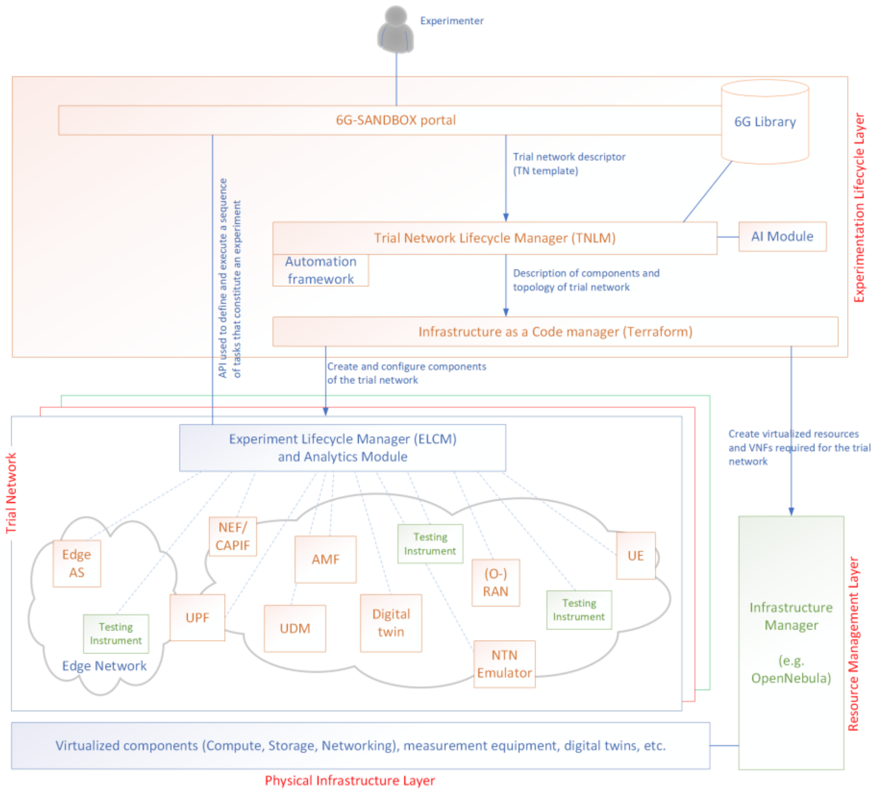


Figure 5. Alternative View of 6G-SANDBOX Architecture

The following sub-sections provide additional details for each of the layers and the Trial Networks.

4.2.1 Physical Infrastructure Layer

The Physical Infrastructure Layer is composed by all the heterogeneous devices and equipment that ultimately support the features and capabilities of an experimentation platform. This includes:

- The computational capabilities in the platforms, usually in the form of servers that host different virtualization or containerization frameworks or provide storage to virtual machines and containers.
- The 5G and 6G radio deployments, as well as the network that interconnects the elements within the platform and provides access to the Internet. This includes any radio access technologies that can give service to commercial or experimental user equipment, possibly including non-terrestrial interconnection.
- Any measurement equipment that can obtain raw measurements, which can be used for the calculation of KPIs and KVIs. Measurements can be obtained from any of the components of the platform or the devices under test.
- Any equipment that can alter the conditions in which an experiment is performed in a controlled and repeatable way, which can lead to the creation of a successful scenario in which the devices under test are studied.
- Commercial or experimental user equipment, which can be instrumentalized with different probes to extract information about their performance and usage during an experiment.
- Any other devices, either located physically on the platform or accessible via VPN connectivity that can take part in an experiment execution.

4.2.2 Resource Management Layer

The Resource Management Layer contains the Infrastructure Manager of the testbed, which is used for controlling the computational capabilities located in the Physical Infrastructure Layer of the Testbed. The goal of this component is to provide an abstraction layer between the different clusters that can be part of the Testbed, effectively creating a unified entry point that can be exposed to the layer above.

The preferred option within the 6G-SANDBOX umbrella is OpenNebula[2], however, Testbeds are free to choose a different Infrastructure Manager as long as compatible Infrastructure-as-Code providers exist for their selection. In the case of 6G-SANDBOX, Terraform[3], an open-source Infrastructure-as-Code management tool, acts as the interface between the Resource Management Layer and the Experimentation Lifecycle Layer, which is located above.

4.2.3 Experimentation Lifecycle Layer

The Experimentation Lifecycle Layer provides the following functionality:

- Acts as interface between the Experimenter and the underlying Testbed, allowing the definition, creation, management, and removal of Trial Networks that the Experimenters can use.
- Controls the lifecycle of the Trial Networks, keeping track of status and resource usage for each individual Trial Network. It is expected that this layer will be able to act autonomously, for example, suspending unused Trial Networks if resources need to be freed, or stopping them if malicious behavior is detected.
- Provides a collection of Trial Network templates, which can be used by Experimenters for deploying pre-defined Trial Networks for common usages or used as a base for defining new Trial Networks better tailored for their needs.

[2] https://opennebula.io/

[3] https://www.terraform.io/

- Housing the 6G Library, which is a collection of components that can be deployed as part of a Trial Network. These components can be physical devices that are made available to Experimenters (in this case, most likely being assigned to a single Trial Network at a time), or software components that can be instantiated on multiple Trial Networks independently and concurrently.

The necessary logic for the management of the Trial Network's lifecycle is implemented in the Trial Network Life Cycle Manager (TNLCM). It is envisioned that this component performs the following functions:

- Translating the contents of the Trial Network Descriptors into directives for the layers below. These directives will be handled either by the **Infrastructure –as Code** manager (which will be ultimately executed by the Infrastructure Manager) or by the **Automation Framework**. The Automation Framework is composed by the set of tools that allow the management and configuration of heterogeneous hardware and software components, and that may require additional interactions that cannot be performed directly by the Infrastructure Manager.
- Giving information to Experimenters on how to gain access to the components deployed inside their Trial Networks.
- Controlling the status of each Trial Network, as well as tracking the usage of resources using information provided by the layers below. This information is to be exposed though an API to trusted entities, for example, the **AI Module**.
- Allowing trusted entities (Experimenters of the AI Module) to control and modify the state of the Trial Networks that they have access to.

4.2.4 TRIAL NETWORKS

A Trial Network can be defined as a sub-set of the capabilities of a Testbed that Experimenters can use for the validation of 6G technologies and the measurement of KPIs and KVIs. Trial Networks are isolated from each other, in a way that guarantees the availability of the reserved resources for each Experimenter and avoids unwarranted access to data belonging to other parties.

Trial Networks are defined as Trial Network Descriptors, which are data entities that detail the components, which are catalogued in the **6G Library**, that must be instantiated or made available during the lifecycle of the Trial Network, as well as their interconnections. Trial Networks Descriptors can request only a basic infrastructure that Experimenters can further configure and use or include more advanced functionality for measurement or experiment automation that can be pre-configured before giving access to the Experimenters for its use.

Considering that there are no limits imposed to Trial Networks in terms of resource allocation, scope of usage or experimentation and persistence in time, it is possible to conceive the creation of Trial Networks that provide service to complete research projects, such as those coming from the SNS Stream D.

4.2.5 LIFECYCLE OF THE TRIAL NETWORKS

A Trial Network, as described above, can be seen as an abstraction of a full experimentation platform (composed by a sub-set of the real platform's resources) that can persist for an initially undetermined amount of (possibly non-continuous) time. For this reason, it is necessary to have access to the tools necessary for the automated management of the life cycle of multiple Trial Networks within the same platform. Within the context of 6G-SANDBOX, this tool, the Trial Network Lifecycle (TNLC), resides in the Experimentation Lifecycle Layer, and provides access to both Experimenters and Platform Owners for direct management of individual Trial Networks. At the same time, the TNLC is capable of autonomously ensuring the availability of the different Trial Networks and the correct usage of resources, either by following a pre-defined logic or based on decisions made by machine learning and AI algorithms which can have access to a sub-set of the Trial Networks in the platform.

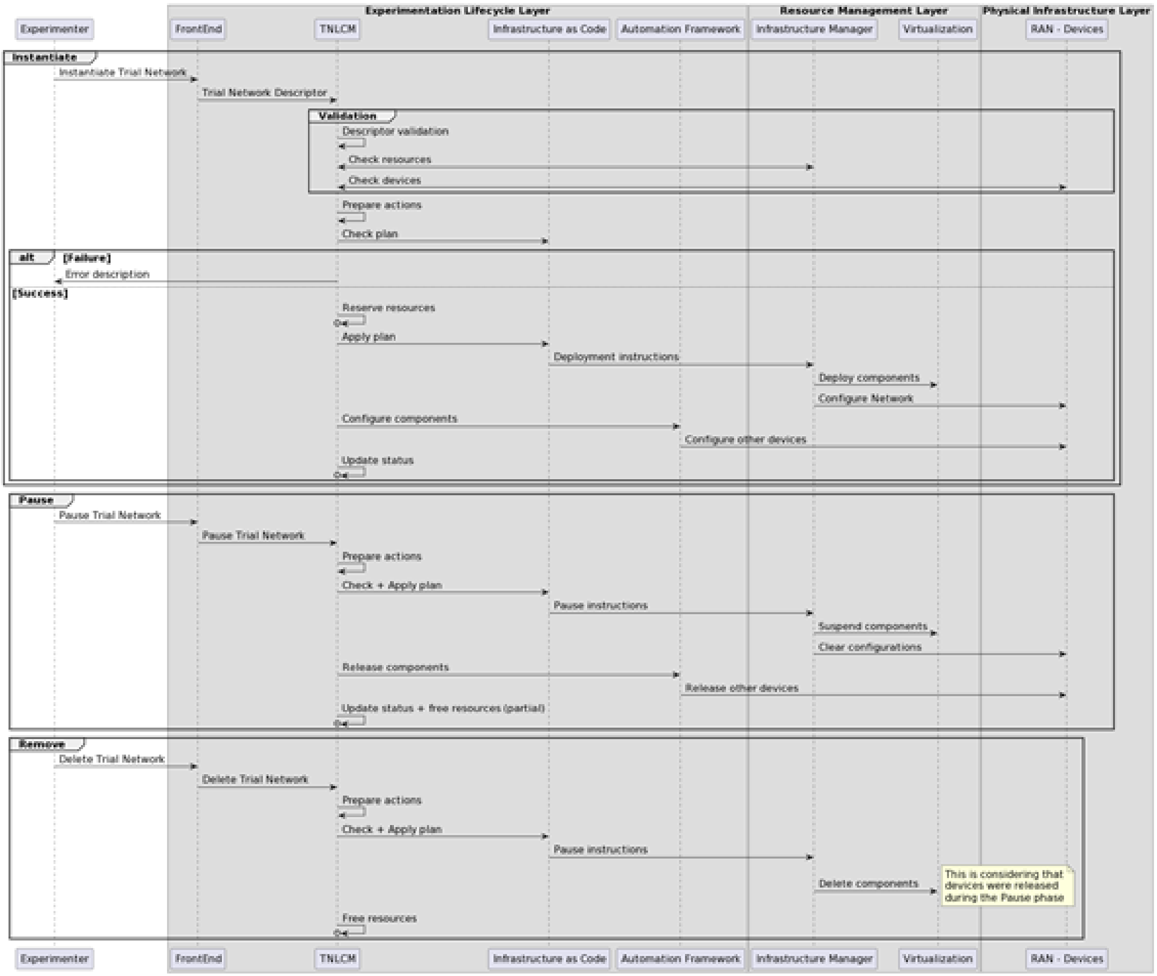


Figure 6. Simplified Trial Network Lifecycle Example

An example of the management of the lifecycle of a Trial Network by the Trial Network Life Cycle Manager (TNLCM) as well as the coordination with the other components of the 6G-SANDBOX architecture can be seen above in Figure 6. The lifecycle of a Trial Network starts with the creation of a Trial Network Descriptor (TND), which includes information about the elements that must be accessible or instantiated as part of a Trial Network and their configurations, the topology of the network and the expected interconnection between the elements, and any other information that further describe the behavior and details of the Trial Network. A catalog of pre-defined TNDs for common use cases will be made available as part of the 6G Library; these can be used as a base for further customization or instantiated directly as ready-to-use Trial Networks.

An important part of the lifecycle is the Validation of the TND, which gives the Experimenter the possibility of assessing the correctness of their descriptor before the actual instantiation and configuration of the components of the Trial Network inside the actual experimentation platform. This allows them to identify problems or inconsistencies that can lead to errors during the usage of the Trial Network. Once the Validation has been successfully completed, the TNLCM makes use of both the Infrastructure –as Code manager (mainly for the creation of the computational resources and the network topology) and the Automation Framework (for all components and configurations that cannot be managed directly by the Infrastructure Manager) for the deployment of all the components that belong to the requested Trial Network. Once this process is finished, the TNLCM reports back to the Experimenter the completion of the task and information on how to access the components created.

By default, an instantiated Trial Network can persist in time indefinitely, as long as no severe issues are detected which can lead to a failed TN that should be deactivated. At any time, both Experimenters and Platform Owners can interact with the Trial Network to modify its status. The following is a partial list of actions that are expected to be possible during the lifecycle of a Trial Network:

- Modify: An existing Trial Network can be modified, by adding or removing components or altering the configuration of existing ones. The system should be able to update the existing instance without a full re-deployment of the components.
- Suspend/Pause: An active Trial Network can be deactivated, releasing most of the resources but keeping information on the status of each component so that they can be reactivated at a later stage. After the reactivation, the state of each component and of the TN as a whole should be as similar to the status prior to the suspension as possible.
- Save/Restore: It should be possible to create and keep different snapshots a Trial Network's status, allowing Experimenters to restore stable configurations at any time.
- Twining: By making use of digital twins of the components in a Trial Network, it should be possible to alter an existing Trial Network so that some or all components migrate from their physical version to their digital counterpart.
- Stop/Remove: An active Trial Network can be stopped, releasing all resources. In this case, the necessary information for easily reactivating the Trial Network would not be stored, requiring a complete re-deployment of the components, if necessary, but keeping generated logs or results that can be useful to Experimenters. A Trial Network could also be Removed, clearing all information.

It is expected that the TNLCM will autonomously perform the minimum set of actions over an existing Trial Network that are required for ensuring the availability of the components and the integrity of the system; however, Experimenters can configure their Trial Networks so that they can be managed by the AI Module. In this case, the AI Module may alter certain aspects or the status of the Trial Network to guarantee the requested performance or to make better use of the resources autonomously. The AI Module may also measure the consumed energy (through TNLCM exposed APIs), proceed to data aggregations, and perform correction/recommendation actions based on prediction/classification algorithms. Energy saving is a key KPI in 6G networks and even slight modifications of configuration parameter values can lead to energy savings, if this is the outcome of a well posed AI/ML model. Such models are incorporated in the AI module.

5 EXPERIMENTATION FRAMEWORK

Experimentation support on 6G-SANDBOX is based on the methodology defined during the course of the 5Genesis H2020 Project (with improvements that come from the EVOLVED-5G project), and makes use of the Open5Genesis Framework, which is a set of open-source components that aim to ease the automation of experiments and the acquiring of KPIs and KVIs. This methodology and framework will be adapted and extended according to the needs and learnings during 6G-SANDBOX. It should be noted that the methodology described in this section is the default provided to experimenters in 6G-SANDBOX; however, experimenters may decide to make use of other tools and are free to install them in their Trial Networks, or a third party may provide alternative solutions to other experimenters by taking part in the Open Call process.

5.1 EXPERIMENTATION METHODOLOGY

The default experimentation methodology in 6G-SANDBOX is based on the methodology defined as a result of the 5Genesis Project. This methodology is based on the definition of three components (Test Cases, Scenarios, and Slices) and these components can be mixed, leading to a particular Experiment. A description of the information and intended role of each of these components are listed below.

Test Cases are documents, usually following a pre-defined template, that describe the general goals and process to follow for the acquiring of a certain set of KPIs or KVIs. Usually, a Test Case template includes the following information:

- A textual description of the target KPIs and KVIs expected to be measured as a result of the implementation of the Test Case, providing some context related to the goals and reasons that motivate the creation of the Test Case.
- A description of the methodology to follow (e.g., minimum number of iterations, measurement rate and duration, etc.).
- Information related to the methods for calculating the outputs (e.g., KPI calculation methods from the obtained raw measurements), possibly including remarks regarding complementary measurements that can be easily obtained from the same Test Case.
- Expected preconditions that need to be ensured for a correct usage of the Test Case, or information about the applicability of the process.
- The sequence of steps to be followed during the execution of the Test Case. These steps should be defined as generally as possible, avoiding specific implementation details whenever possible to improve the reusability of the Test Case in different experimentation platforms.

The details contained in the Test Case are used as a guide for different Test Case Implementations, which are specifically tailored to the conditions and capabilities of a particular experimentation platform. Each implementation can be different; however, a successful implementation will meet the general conditions and procedure describes in the Test Case, allowing replicability and the comparison of KPIs obtained in different experimentation platforms.

Scenarios are a guideline for the configuration of the network conditions to be present during the execution of an experiment. For example, a Test Case may be executed multiple times under different conditions such as low or high coverage, different network congestion, with UEs in a static position or under different mobility patterns, etc. The information on the scenario is used to configure different values in the real or emulated network in order to obtain the requested network conditions in the experimentation platform.

With regards to the Scenario, it is expected that as part of the results and measurements provided to experimenters, a description of the effective scenario (e.g., network configuration over time, available resources allocated, etc.) as well as records of every event (such as, modifications on the Trial Network's description or status, either coming from the experimenters themselves or automatically executed by the testbed or AI modules, when allowed) that may affect the KPIs measured in the Trial Networks will be provided. This is to ensure that experimenters have the required visibility of the conditions where the measurements have been obtained and can correlate these conditions with their results.

Complementary to the Scenarios, **Slices** specify the end-to-end resources allocated for an experiment execution (or Trial Network). This includes the computational capability reserved to each component of the Trial Network as well as the resources reserved in the emulated or real network made available to the experimenters. Resources reserved in virtualized environments to instantiate components of the Trial Network will be reserved and dedicated to this trial network exclusively and will be allocated until the trial network is suspended or deleted. Therefore, having dedicated resources allocated to trial networks will ensure that KPIs and KVIs calculated during the experiment are not affected by other trial networks activity.

An **Experiment** is defined as the combination of Test Case, Scenario, and Slice that is then executed in an experimentation platform in order to obtain a set of KPIs and KVIs. In the case of 6G-SANDBOX, Experiments are executed inside a Trial Network, where in most cases a set of tools (based on the Open5Genesis Framework and enhanced with additional automation and measurement tools) have been automatically deployed and configured during the provisioning phase of the Trial Network. Experiment's implementation and execution is further detailed in Section 5.2 below.

5.2 Lifecycle Of The Experiments

The 6G-SANDBOX Library will give Experimenters access to a ready-to-use experimentation framework, that can be automatically deployed as part of their Trial Networks and allows them to automate their experiments, obtaining and processing KPIs and KVIs. This set of tools is based on the open-source components that are part of the Open5Genesis Framework, with enhancements and adaptations coming from the 6G-SANDBOX Consortium that will also be publicly released.

The Open5Genesis Framework follows an architecture described in Deliverable D2.4 of the 5Genesis Project [28], which within the context of 6G-SANDBOX can be adapted and simplified to the architecture shown below in Figure 7. This architecture has similarities with the 6G-SANDBOX reference architecture but it should not be confused. The main differentiation is that an adaptation of the 5Genesis architecture can be seen inside each Trial Network, while the 6G-SANDBOX reference architecture describes the organization of the components that support the existence of several Trial Networks in a single platform.

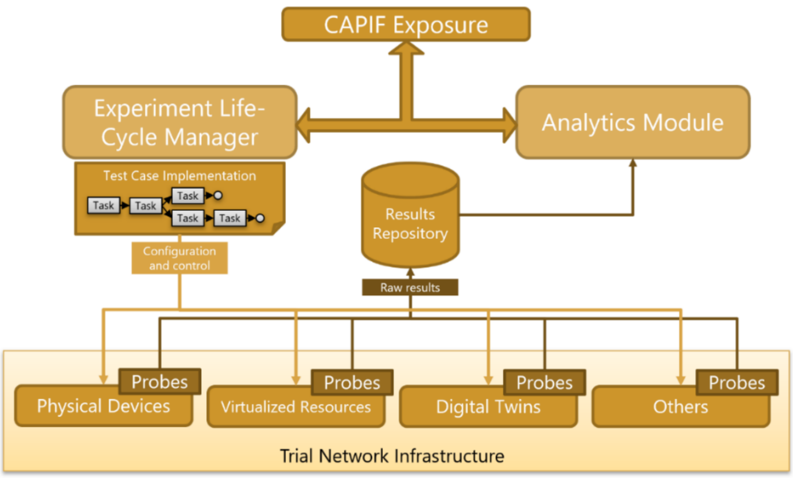


Figure 7. Simplified Trial Network Architecture

In each Trial Network, we find an isolated set of physical and virtual components from a platform (and possibly other external components accessible via VPN connectivity). These components, which can include user equipment, measurement tools, and probes, etc., form the infrastructure of the Trial Network. On top of this infrastructure, we find several components that can be used for the automation of experiments and the measurement of KPIs and KVIs. These are the Experiment Life Cycle Manager (ELCM) and the Analytics Framework.

The **Experiment Life Cycle Manager** (ELCM) is the component that allows the implementation and execution of Test Cases, as well as configuring the network conditions specified in the Scenario. This component can be made available to experimenters who can then define their own Test Cases or make use of existing templates from the 6G Library. The implementation of Test Cases in the ELCM is based on the creation of a set of Tasks, that will be executed sequentially or following a pre-defined logic (that can contain loops and conditional execution of branches). Each Task can execute different actions, including but not limited to:

- Creating and modifying the value of certain variables within the Experiment. These values can then be queried and used by other Tasks.
- Making use of heterogeneous scripts, that can be used for controlling or configuring different components and devices in the Trial Network infrastructure.
- Delegating the execution of actions to other orchestrators, such as OpenTAP[4] or Robot Framework[5].

For 6G-SANDBOX, the ELCM will be adapted and updated according to the needs of the project. For example, it is expected that the ELCM will be integrated with CAPIF, so that experimenters can access the provided functionality through a unified interface.

5.3 KPIs AND KVIs VALIDATION

The 5Genesis Framework defines and supports a specific methodology for the management of results and the validation of KPIs and KVIs, in the form of the **Analytics Framework**. This gives a standardized solution for the management of raw results and provides both a dashboard and REST API for KPIs and KVIs calculations.

This solution is based on the usage of a single Results Repository (effectively an InfluxDB database), which is populated with data generated by a set of heterogeneous probes distributed in the infrastructure of the Trial Network. Each probe can generate measurements independently, requiring only that these measurements are tagged following a particular format and that specifies a timestamp centered in UTC.

The Analytics Module can make use of this metadata for filtering of stored measurements, for example, to perform calculations only on results that belong to a particular Experiment execution or that were generated during a specific period of time.

It should be noted that the description above applies to the results generated within a single Trial Network when using the default Experimentation framework. There are two considerations that are of importance:

[4] https://opentap.io/
[5] https://robotframework.org/

- Experimenters are always able to install alternative solutions that can generate results that are not handled following this methodology.
- Experimenters will also need access to measurements generated outside of their Trial Network, for example, events generated as part of the Trial Network's lifecycle management or from shared components.

Regarding the second point above, it is expected that this data will be made available, though filtered, in order to guarantee the privacy and security of other Trial Networks running in the same platform. The specific solution to be used has not been decided at the time of this writing but some possibilities include:

- Automatically injecting new entries in the internal Results Repository of the Trial Network.
- Giving access to experimenters to a global Result Repository where they can retrieve a limited sub-set of the data contained.
- Considering that the Analytics Framework can work with multiple *data sources*, configure both the internal and global Result Repositories.

As is the case with the ELCM, it is expected that the Analytics Framework will be extended and adapted during the course of 6G-SANDBOX.

6 UPDATES TOWARD 6G TECHNOLOGIES AND USE CASE ENABLERS

This section discusses the evolution of key technologies toward 6G that will be made available and accessible for the creation of trial networks of 6G-SANDBOX. To ensure interoperability and openness, these components will be exposed through Open APIs (Application Programming Interfaces). By adopting Open APIs approach the flexibility and freedom to integrate, customize, and build upon these technologies, is guaranteed.

6.1 DISRUPTIVE WIRELESS TECHNOLOGIES

With the use of the wireless technologies within the project, the first aim is to improve the industry-level, disaggregated, and O-RAN-based virtualized Radio Access Network (vRAN). It involves the development of software components (offered as Containerized Network Functions) that allow flexible deployment of disaggregated vRAN elements (O-CU, O-DU, O-RU) on top of virtualized Kubernetes or Docker Swarm platforms. These components include the Placement Agent and Prediction Agent. Secondly, an optimization framework will be developed to determine the optimal placement of vRAN in edge-cloud and edge-multi-cloud deployments, considering specific performance goals and limitations. For this purpose, the framework will provide templates and examples of how to allocate resources for three different types of systems: edge resource schedulers, federated joint radio/computing schedulers, and multi-cloud systems.

It will also include information on how to use CAMEL descriptors to define deployment goals. In addition, improvements will be made to the cognitive plane definition, which ensures the utilization of AI/ML techniques for acquiring knowledge and modifying vRAN settings based on the current environment conditions and feedback. These solutions will enable customization of the vRAN deployment to align with the anticipated use cases in the project, especially those that demand specific functional divisions (such as guaranteeing latency limits or achieving high data rates). This task will also investigate the different types of tools and evaluate the system performances by using these tools for O-RAN components, RIC, xApps, and AI/ML. The Malaga platform will be leveraged as a testbed by using test and measurement tools for O-RAN deployment debugging and troubleshooting.

Another part of the relevant activities will be to define the API for RIS to be able to dynamically modify settings of the RIS HW for multiple use cases available in the project. A synergy of lensing and reconfigurable meta surfaces is being explored to extend the field of view beyond the state of the art as well as enable open software APIs for independent control and optimization of a beamforming solution. The RIS modeling in the mmWave outdoor scenario will be designed and associated RF tests of RIS components will be executed. The output of this task will create a 6G-SANDBOX Library v1 which will describe the technology enablers incorporated in the 6G-SANDBOX Library such as Open RAN, Time Sensitive Networks (TSN), XR, etc.

6.2 Deterministic Networking Enablers

The project targets to develop Programming Protocol-independent Packet Processors (P4) modules to provide deterministic communications over the 6G network as shown in Figure 8. This type of connectivity will be key at the data plane, such as the backhaul (5G core - CU), fronthaul (DU-RU) and User Plane Function (UPF).

First, the P4 modules can be part of the trial networks and can be used in the project to demonstrate the KPIs improvement (e.g., latency, reliability, security, and energy consumption). The first planned developments will be the implementation of UPF (Rel. 16) and non-invasive telemetry at interfaces such as N3, N5, or F1. The P4 modules will be exposed to other modules (i.e., through APIs), for example, to improve the performance of the Zero-Touch Management of the 6G network. In addition, the intention is that the P4 modules can continue to be used and improved in open calls.

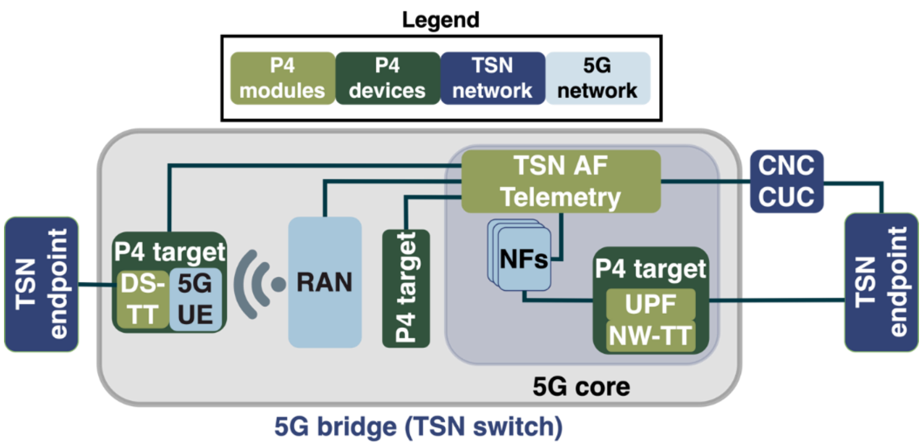


Figure 8. P4 Modules and TSN Over 5G Architecture at University of Malaga Platform

Secondly, the AI/ML framework for DetNet will also be designed and demonstrated to enable intelligent deterministic network and service management. From the perspective of end-to-end performance guarantee within the DetNet, the AI/ML capacity should span from the radio access networks to the transport networks to facilitate the deterministic network connection in a large-scale trial network. The AI/ML framework will include several entities, i.e., monitoring system, analysis engine, decision engine, and API for users. The monitoring system will collect the network metrics and user dynamics and feed them to the analysis engine for further analysis. Based on the network statistic from the underlying network through e.g., netconf, the analysis engine will provide advanced insight on how to configure, operate, and manage the trial networks to ensure the end-to-end deterministic performance. After that, the decision engine will determine how to configure, maintain, or control the trial network infrastructure based on some pre-defined objectives by users using e.g., reinforcement learning. An AI/ML-based deterministic network and service close management loop will be supported by this framework and demonstrated on the trial network testbed.

6.3 Fixed, 5G and NtN Integration

The integration of 5G with Satellite communications is one of the hot topics in research and standardization toward 6G. In that direction, 3GPP is considering NTN integration in Release 17 and 18 and subsequent releases, SNS has already funded projects ETHER and 6G-NTN in the same call where 6G-SANDBOX and European Space Agency (ESA) is promoting collaboration. In this context, one 6G-SANDBOX ambition is to enhance the experimental platforms in the project with the capability to offer such 5G/NTN integration as part of the trial networks. The 5G/NTN enablers that are addressed by 6G-SANDBOX in this domain, include the integration of satellites with terrestrial mobile networks starting with satellite backhauling, satellite-assisted multi-connectivity, as well as gNBs in space and the utilization of 5G/6G compliant satellite systems. On top of the resources committed by the partners, the project has signed a MoU with ESA to access their capabilities and the implementation of these enablers.

The Integration of these features will consider several scenarios, which are described below starting with the currently available resources and closing with the most innovative flying satellite onboarding 5G and Edge capabilities. The project will implement both field deployments and emulation capabilities to conduct relevant studies.

- Scenario 1 includes the use of commercial satellites services like Starlink or Oneweb to connect standard ground terminals to create a data path. This scenario can support the use of satellite as backhaul for 5G gNB as well as a second data path for multi-connectivity.
- Scenario 2 consists in the interconnection of 6G-SANDBOX testbeds with ESA labs in UK and Netherlands (not flying equipment) to reproduce specific behaviors with a mixed of physical and software equipment.
- Scenario 3 consists in the use of a new Low Earth Orbit (LEO) regenerative satellite to be launched under ESA umbrella in 2024 to act as a gateway between NR UE and NR gNB.
- Scenario 4 consists in the use of another LEO satellite with gNB on board to be launched in middle 2025 by ESA, that will be later enhanced with onboard computing capabilities.
- Scenario 5 provides emulation of the satellite to replace any of the previous scenarios as part of a trial network without the need of additional hardware support.

All these scenarios will be part of trial networks to allow internal experiments by the 6G-SANDBOX consortium as well as experiments by third parties. More details on the actual features, integration in the project platforms and experiments will be reported in deliverables D3.1, D4.1, and D5.1. However, to provide some examples, we present now some works planned in Athens, Malaga, and Berlin in that direction.

To enable multi-connectivity (e.g., in scenario 1), the implementation of an Access Traffic Steering Switching and Splitting (ATSSS) proxy will be considered as shown below in Figure 9. The ATSSS proxy will support multiple access paths with an ATSSS client (including a satellite path) and will be able to route data traffic across these paths according to the routing preferences provided by the experimenter. This will enable experimenters to evaluate the performance of different routing strategies for different types of data flows.

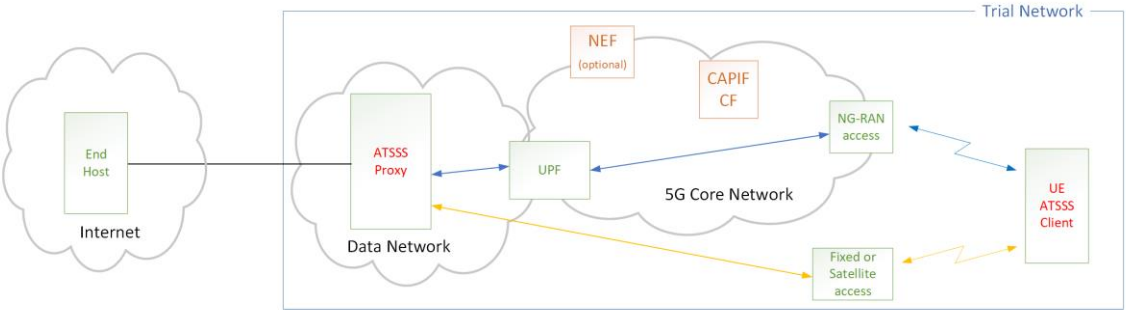


Figure 9. Multi-Connectivity Support Using an ATSSS Proxy

One activity in Malaga will be the evaluation of multi-connectivity protocols, including Multipath TCP (MPTCP), Multipath Quick UDP Internet Connection (MPQUIC), Multi-connection Tactile Internet Protocol (MTIP), and potentially others sourced from cascade funding opportunities. These protocols will be complemented with AI/ML support for enhanced adaptability. Figure 10 represents the full path and equipment involved in multi-connectivity using Satellite to backhaul 5G plus a fixed connection. The satellite to backhaul 5G connection consists of a user station located at the University of Málaga, which connects to the OneWeb satellite constellation. The satellite then relays the data to an NTN ground control in Teleport Portugal, from where the data is transmitted to Telefónica premises via the London OneWeb headquarters.

The combination of the satellite connection, along with the fixed UMA-Telefónica connection, forms the topology where multi-connectivity is expected to be evaluated in Scenarios 1 to 4.

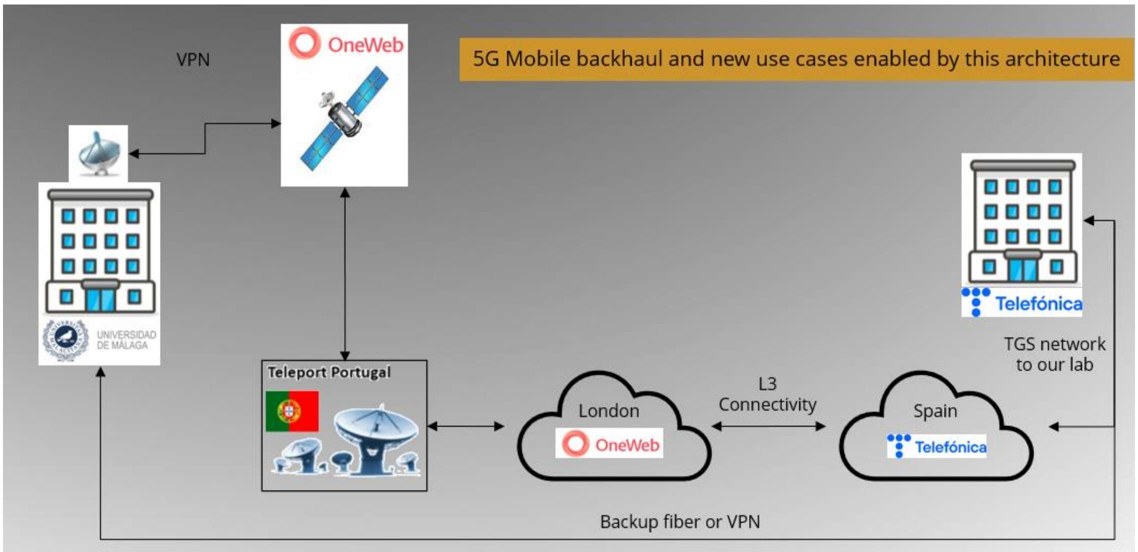


Figure 10. Example Deployment of a Satellite Backhaul Connectivity in Malaga

Athens platform plans the incorporation of satellite backhauling and the implementation of scenario 1 as shown in Figure 11 for the case of 5G NSA.

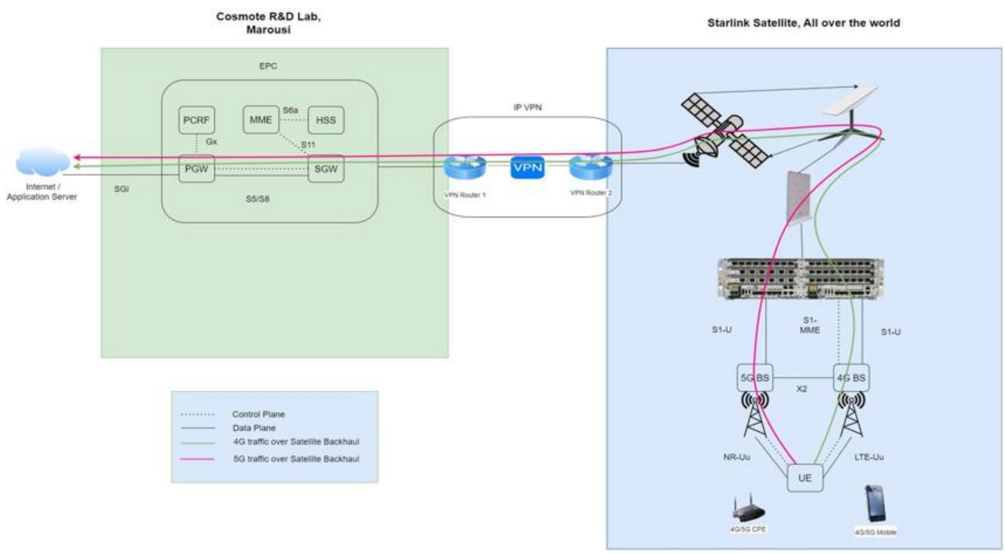


Figure 11. Satellite Backhauling for Athens Platform

The Athens platform also aims, through scenario 5, to evaluate performance and validate innovative access and network techniques through emulated Digital Video Broadcasting - Return Channel via Satellite (DVB-RCS2)/DVB-S2 satellite communication systems that can interconnect with real equipment as shown in Figure 12. These systems will be able to support the emulation of multigateway and multispot topologies as well as mesh and star configuration schemes. Performance evaluation will focus on the use of Software Defined Networking (SDN)-based techniques, such as acceleration, congestion control, and the use of multiple paths. Multi Access Edge Computing (MEC) nodes will be equipped with E2E protocol optimization methods, while providing service developers with easy-to-use APIs.

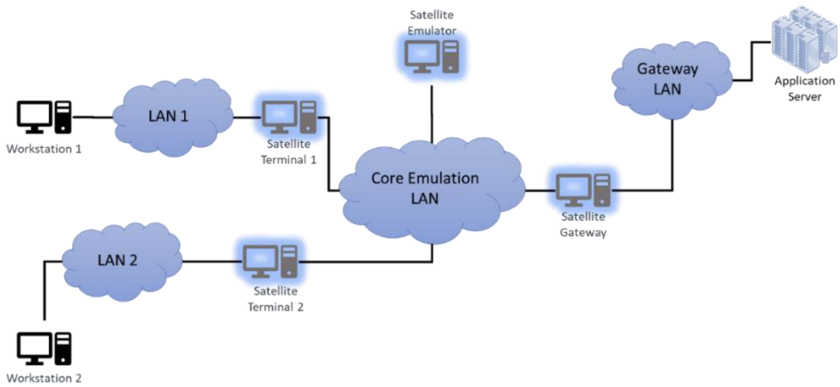


Figure 12. Example of Emulated Satellite Communication System Planned in Athens

6.4 Internet of Sense Enabling Services

The primary objective of applying Internet of Sense services within the project, is to explore and integrate multiple devices that enhance the sensations of immersive technologies. So, multiple eXtended Reality (XR) applications will be developed and served through testbeds. These applications will use more common XR devices, such as 360 cameras and microphones, and new haptics devices such as the OWO vest, that will deliver an enhanced sensorial experience. In addition, using novel AI/ML tools, bodies and objects will be teleported between remote places. Video streaming (Video on Demand and real-time) will be done using IoT gateways developed using Dockerized micro-services and deployed in Kubernetes architectures. Furthermore, a XR apps API will be developed to be able to control the applications that will use these devices and tools. Together with the required functions, metrics about the Quality of Experience (QoE) will be also exposed through the API. These metrics will be checked and considered to perform an analysis of the human response to the XR apps. This API will be CAPIF compliant and accessible in the Málaga testbed.

6.5 NETWORK INTELLIGENCE AND OPENNESS

In the project the openness guarantee is introduced in multiple levels, from the data and results to the strategic approach to release innovative software developments and integrations to an open repository, named open 6G Library. Several advanced 5G/6G components will be introduced to the Library, incorporating new capabilities in access and transport networks, edge resources, and enablers for deterministic communications, among others. To expose these capabilities to applications and services, the 3GPP has established the CAPIF as the reference framework for exposing, discovering, and consuming APIs. CAPIF includes common aspects applicable to any northbound service API. As such, it is a complete API framework that covers the functionality needed to smoothly integrate the components of the Library to the 6G-SANDBOX Facility.

More precisely, as part of the network intelligence and openness the project will focus on identifying the components that can be integrated with CAPIF, discovering their capabilities, and developing the necessary intermediate layers to expose these components through CAPIF. This integration will enable applications and services to seamlessly integrate with these capabilities in an open and standard-compliant format. The CAPIF Core function from Release 17 will be deployed as part of the 6G-SANDBOX project, and it will incorporate a Certification Authority to expedite the issuance of certificates required for mutual authentication in the TLS transport layer. The inclusion of the Certification Authority in the deployment of the CAPIF Core function will streamline the authentication process and enhance the security of communications within the 6G-SANDBOX environment.

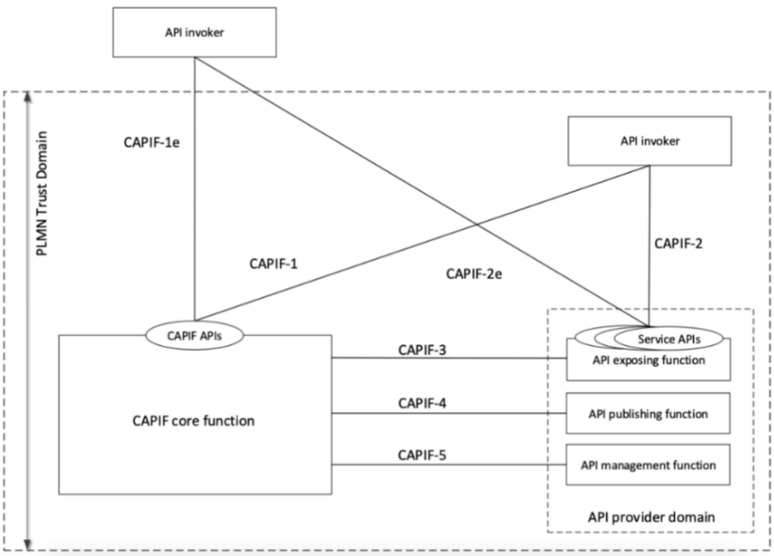


Figure 13. CAPIF Architecture

By making the components of the 6G-SANDBOX Library compliant to CAPIF, application developers and service providers will have standardized access to the advanced 5G/6G components. They will be able to leverage these capabilities in an open and compliant manner, enabling interoperability and facilitating the development of innovative services and applications. At the network core domain, the focus will be on the APIs exposed through the Network Exposure Function (NEF) Emulator to support

5G programmability. The NEF Emulator implements the standardized NEF APIs in a configurable emulated environment, where the user can define specific simulation environments. Such specifications include the number and type of user devices and the position of gNBs. The reference architecture of the NEF emulator is shown in Figure 14 below.

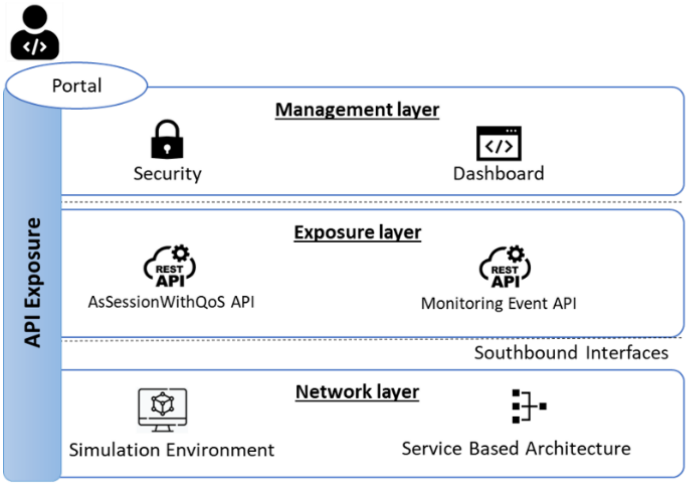


Figure 14. Reference Architecture of NEF Emulator

In addition to network openness, a network intelligence module that will monitor Trial Networks (assembled in 6G-SANDBOX) status generated from the Infrastructure as Code manager and will predict and detect changes in the network status using AI algorithms to prevent on failures, being able to automatically take pre-correction actions. This module will gather information from the Infrastructure as Code manager to detect and predict changes in the network status. To achieve this, AI algorithms will be employed to analyze network data and identify potential failures or issues. The network intelligence module will be able to automatically take pre-correction actions, in order to prevent network failures and maintain the network's optimal performance. The network intelligence module will also monitor energy consumption and proceed to correction/recommendation actions that target energy saving.

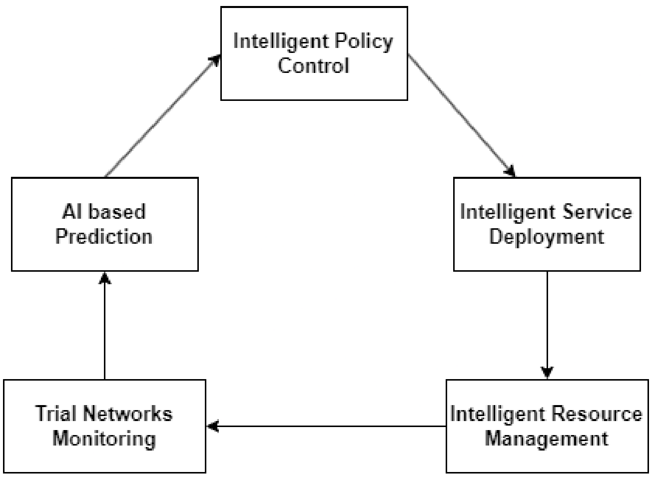


Figure 15. Network Intelligent Module

One of the objectives will be to design the necessary infrastructure and technological stack to deploy the different components of the network intelligence module and its integration with the rest of the platform systems to gather metrics for training artificial intelligence models. The following aspects should be addressed:

- Infrastructure: Design the infrastructure that will be required to deploy and operate the network intelligence module. It should be virtual: servers, storage, and processing resources to run the artificial intelligence algorithms.
- Technological stack: Select the appropriate technologies to implement the network intelligence module:
    - Programming languages
    - Machine learning frameworks
    - Databases
    - Data processing and analysis tools
    - Virtualization and container technologies
- Integration with other systems: The network intelligence module needs to be integrated with other existing systems and platforms to obtain the necessary metrics for training the artificial intelligence models. This may involve configuring connections and APIs to retrieve real-time data from network monitoring systems and other relevant systems.
- Data collection and preparation: To train the artificial intelligence models, relevant data needs to be collected and prepared. This may involve extracting metrics from existing systems, cleaning and transforming the data, as well as identifying and handling missing or inconsistent data.

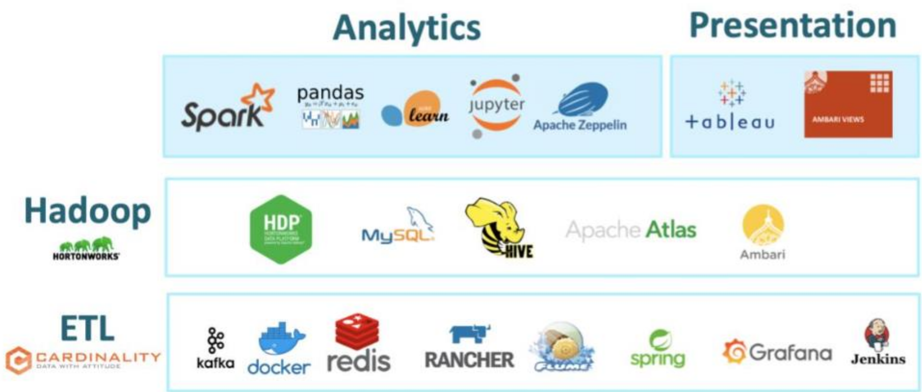


Figure 16. Network Intelligent Tech Stack

Another significant effort will be the development of automations that make modifications to the platform and network based on decisions made by the network intelligence module.

To achieve this, the following aspects should be addressed:

- Decision-making process: The network intelligence module, using AI algorithms, will analyze the network status, identify potential issues or optimizations, and make decisions based on predefined rules or machine learning models.
- Automation triggers: Based on the decisions made by the network intelligence module, triggers will be set up to initiate the necessary actions or modifications. These triggers can be based on specific thresholds, events, or time-based schedules.
- Automated actions: Once the triggers are activated, the automation system will execute the predefined actions. These actions can include making configuration changes to network

devices, provisioning, or reallocating network resources, adjusting network parameters, or initiating other relevant processes.

- Monitoring and feedback: The automation system will continuously monitor the effects of the executed actions and gather feedback from the network. This feedback will be used to evaluate the effectiveness of the decisions made by the network intelligence module and to refine the AI models or rules if necessary.
- Error handling and rollback: To ensure the stability and reliability of the network, appropriate error handling mechanisms should be implemented. In cases where the automated actions result in undesired outcomes or issues, the system should have the ability to roll back the changes or trigger corrective actions.

The automation system should implement proper security measures and fail-safe mechanisms to prevent unintended consequences or unauthorized modifications. Regular testing, validation, and monitoring of the automation system will also be crucial to ensure its effectiveness and performance.

7 6G-SANDBOX PLATFORMS

The 6G-SANDBOX facility consists of four distinct, geographically dispersed platforms that work together to achieve its stated objectives. While Section 3 analysed the requirements per layer for realizing the Facility's capabilities, this section provides a detailed overview of each platform that follows a common style/format, including a diagram and description of the underlying technology and topology status. It also outlines the necessary enhancements that will be integrated into each platform and the innovative advancements that will be achieved. By presenting this information, the section offers a comprehensive understanding of the current status of each platform and the anticipated developments required to enhance their functionalities and contribute to the overall objectives of the 6G-SANDBOX facility.

7.1 MALAGA PLATFORM

7.1.1 PLATFORM OVERVIEW

Malaga platform is represented by Victoria Network, which includes a wide variety of mobile networks and other technologies set in different locations. The current status is highlighted in green in Figure 17. The main site of the platform is the University of Málaga (UMA) campus, where outdoor and indoor 5G deployments are available. Outdoors, two solutions based on Nokia cells are provided: one with 10 microcells working on FR1 (b7 and n78) and another one with two cells for mmWave FR2 (n257 and n261). Indoors, a Nokia picocells based deployment is available, with two cells in FR1 (n78). In addition, a full O-RAN solution is provided in the same band (n78).

In addition, Victoria Network includes other locations with RAN deployments not belonging directly to UMA, but to associated entities, and that are also linked to its infrastructure through a MOCN split.

Firstly, the Police control Center is connected to a RAN deployment in downtown Malaga using a radio link. Other RAN locations from Telefónica, like Malaga Harbor and Torremolinos, are also part of the network.

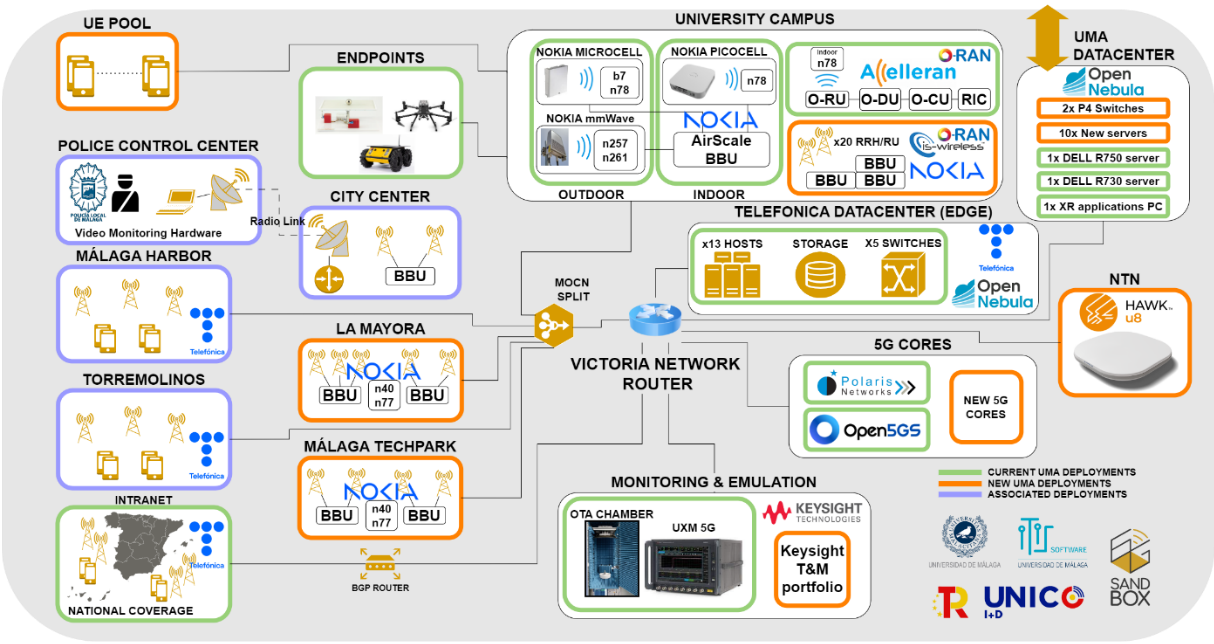


Figure 17. Malaga Platform

Regarding 5G cores, the following two options are provided:

- Polaris 5GC Unicorn is a lightweight 5G Core suitable for private enterprise networks and emergency networks. It is a scalable, cloud-native architecture that can be used to deliver 4G and 5G services. Unicorn includes all Core Network Functions (CNFs) - Access and Mobility Management Function (AMF), Mobility Management Entity (MME), Authentication Server Function (AUSF), Network Slice Selection Function (NSSF), Unified Data Management (UDM), Unified Data Repository (UDR), Session Management Function (SMF), Policy Control Function (PCF), NF Repository Function (NRF), User Plane Function (UPF), SEPP (Security Edge Protection Proxy), along with a Network Management System (NMS), a web-based Console to manage and operate the 5G core network.
- Open5GS is a C-language Open-Source implementation of 5GC. It includes Release-17 compliance and contains the following functions: NF Repository Function (NRF), Service Communication Proxy (SCP), Access and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Authentication Server Function (AUSF), Unified Data Management (UDM), Unified Data Repository (UDR), Policy and Charging Function (PCF), Network Slice Selection Function (NSSF), and Binding Support Function (BSF). As it is an open-source solution, many instances can be provided based on experimenters' requirements.

Another important element currently available is the Intranet, which is a service provided by Telefónica. Through the Intranet, any user registered in the system and owning a commercial SIM card from Telefónica can connect to Victoria Network infrastructure. This is a very valuable feature as it provides coverage to experimenters in any location in Spain.

Victoria Network also provides 5G networks in controlled and emulated environments. Currently, an OTA chamber and a 5G emulator (Keysight E7515B UXM 5G Wireless Test Platform) are available, together with a set of software tools for testing and measurement that will be extended during the project. This equipment is provided by Keysight.

Finally, the testbed includes the following two datacenters:

- UMA datacenter: This is the main datacenter that includes the routers, switches, firewalls, storage systems, servers, etc. to support all services and applications in Victoria Network. An important element allocated here is the Infrastructure Manager, based on OpenNebula.
- Telefónica datacenter: This is an additional datacenter acting as Edge with another OpenNebula deployment to provide virtualized resources to experimenters.

7.1.2 Enhancements and Innovations

Victoria Network will be enhanced during the lifetime of 6G-SANDBOX with the following features and innovations (highlighted in orange in Figure 17):

First, the University campus RAN deployment will be extended with both traditional and distributed solutions. Mainly, traditional RANs will be based on Nokia equipment and O-RAN implementations will be provided by IS-Wireless. However, additional approaches not coming from these entities can also be expected. In total, about 20 new Remote Radio Head (RRH)/Radio Units (RUs) will be available.

In addition, two new RAN locations will be added to the network. One in La Mayora, which is a public institute that owns a property where it leads international studies on the production of subtropical and Mediterranean fruits, as well as the introduction of new varieties of exotic fruits. And another one in Malaga TechPark, which is a business park specializing in the ICT sector and where the new RAN deployment will cover different areas.

On the other hand, regarding 5G cores, new commercial ones are expected. However, specific information about the solutions/providers is not available yet. It is important to note that some solutions can come directly from Open Calls.

About the Monitoring and Emulation features, as introduced in section 7.1.1, the Keysight's Testing and Monitoring portfolio will be extended and made available for experimenters. This is a vast set of more than 20 tools. These are mainly software applications, but new hardware equipment will be also available in Malaga. In addition, Victoria Network will soon have a Non-Terrestrial Network (NTN), as a LEO satellite receiver will be installed on the University campus. This will allow testing of multipath connectivity between different endpoints, including a connection with ESA facilities, with whom a MoU for this undertaking has already been signed.

To conclude, all these enhancements require more computing and storage capacity. This is why UMA datacenter will be expanded with about 10 new servers to allocate the coming services. In addition, two new P4 switches will be acquired to improve data transport and include telemetry in Victoria Network.

7.2 Athens Platform

7.2.1 Platform Overview

The Athens platform is an advanced large-scale 5G SA experimental facility, which is spread across two different locations within the metropolitan region of Athens, namely the COSMOTE/OTE Academy campus and the NCSR Demokritos campus, which are interconnected with a dedicated 10G dark fiber, and are operating two fully operational 5G SA networks. The current status of the platform is highlighted in green color in Figure 18 below.

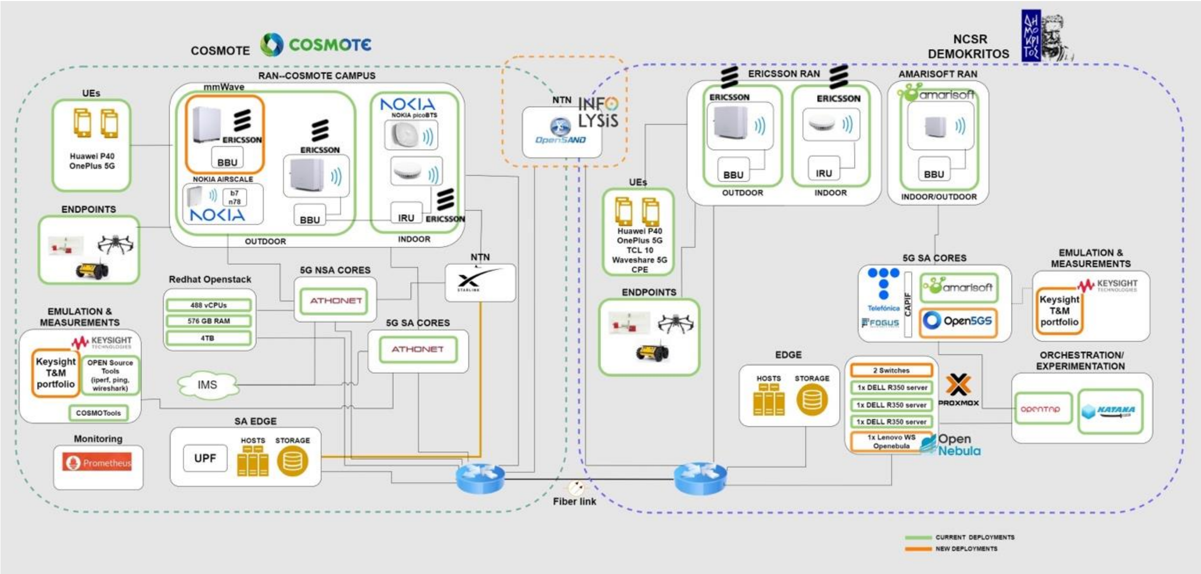


Figure 18 Athens Platform

The first 5G SA network is based on ATHONET 5G SA Core and ERICSSON Baseband Unit (BBU) /Remote Radio Unit (RRU)/RAN, being deployed both at the COSMOTE and NCSR Demokritos campuses. More specifically, the ATHONET 5G Core is located in COSMOTE/OTE Academy premises and is used to drive two ERICSSON BBU units, one deployed at COSMOTE campus and one deployed at NCSR Demokritos campus. Each of these two BBUs is controlling three ERICSSON RRU/RAN units at each domain, therefore realizing a large scale 5G network with six indoor/outdoor cells/RAN units in total for both sites.

The latter 5G SA network is deployed only at NCSR Demokritos campus and is based on Amarisoft 5G RAN and a variety of potential 5G SA Core implementations, such as Amarisoft, Open5GS and Athonet, which are supporting a different level of openness (e.g., NEF/CAPIF). Thus, the NCSRD campus site includes two radio access networks that are connected to different 5G cores, which enable further research in inter-PLMN handover and roaming scenarios. A scenario for the realization of the inter-PLMN capabilities could be a UE moving from the coverage area of one PLMN to another PLMN while maintaining its ongoing session, from Operator A (e.g., COSMOTE) to Operator B (e.g., NCSRD).

As far as the Core Networks are concerned, the supported options are as follows:

- Amarisoft 5G SA Core: The Amarisoft 5G Core network solution provides essential network functions for the operation of a 5G network, Access and Mobility Management Function (AMF), Authentication Server Function (AUSF), Session Management Function (SMF), User plane Function (UPF), UDM (Unified Data Management), and 5G Equipment Identity Register(5G-EIR) all integrated within the same software component.
- Athonet 5G SA Core: ATHONET 5G Stand Alone (SA) core network includes two UPFs (User Plane Function) to emulate the edge and core 5G network data plane. The network also features 3GPP (3rd Generation Partnership Project) Control Plane Network Functions, including the Access and Mobility Management Function (AMF), Session Management Function (SMF), Authentication Server Function (AUSF), and User Data Management (UDM)

Function. These functions enable the management and control of the network. Additionally, the network supports 3GPP interfaces, including N1, N2, N3, N4, and N6, which enable communication between network functions. This setup is hosted at COSMOTE Cloud facilities, providing a secure and reliable infrastructure.

The Radio Access Network (RAN) is based on the Ericsson BBU 6630 which is a baseband unit that provides high-performance connectivity for mobile networks. The unit is compatible with various radio units, including the 4408, which is designed to provide high-capacity and low-latency connectivity for outdoor deployments. In addition to the radio unit, the system also includes the Indoor Radio Unit (IRU) 8848 and Dot 4479 B78L, which are essential components for the indoor deployment of a 5G network. The GPS system is used for synchronization purposes and ensures accurate timing and location data for network operations. Together, these components form a powerful and reliable radio access network that delivers high-speed connectivity and low latency. In addition, Nokia Airscale and 5G Small Cell (RRH) deployments are also supported.

At the NCSRD site, the Amarisoft 5G NR which is also supported, can operate in FDD/TDD frequency bands below 6 GHz with up to 50 MHz of bandwidth. It supports various subcarrier spacing options for both data and synchronization signals and can operate in MIMO configurations up to 4x4 in DL. The MIMO layers can be also complemented either in one 5G cell with 50 MHz bandwidth and 2x2 MIMO configuration, or three 5G cells with 20 MHz bandwidth and 2x2 MIMO configuration each.

7.2.2 Enhancements and Innovations

The planned integration activities during the lifetime of the project, involve several improvements aiming at the enhancement of the platform. These enhancements including the expansion of the existing functionalities and upgrading or replacing components supporting state-of-the-art technologies. The following enhancements are anticipated.

7.2.2.1 NTN

On top of the terrestrial dedicated dark fiber link between the two sites in Athens platform, a satellite/NTN-emulator is currently under deployment, which will enable multi-operator and multi-access scenarios, such as inter-Public Land Mobile Network (PLMN) hybrid-access and dual-connectivity, with agility and low cost. ATSSS enables efficient use of multiple RATs in a multi-connectivity scenario. The emulated satellite opens this field for further research into custom solutions where different PDU sessions per access can run in parallel. Specifically, the solution supported by the Athens platform involves the use of MPTCP to combine multiple network paths (i.e., the terrestrial and the emulated satellite/NTN) in a single TCP connection. The satellite emulated based approach of the Athens testbed can emulate a complete DVB-RCS2 – DVB-S2 system in a realistic and flexible way and its ability to interconnect with real equipment and applications provides excellent experimentation means. It is a distributed platform, which is composed of a satellite network on the operator side and Satellite Terminals (STs) at the client side. The satellite operator part is composed of a backbone network between satellite Gateways (GWs), capable of being interconnected to external networks, providing satellite network access on each terminal and gateway. The offered emulation platform allows the experimenter to emulate mesh and star configuration schemes as well as multi spot and multi gateway topologies. It provides configuration and monitoring (real-time and offline) tools to evaluate the performance of the emulated scenarios, supporting IPv4, IPv6 and Ethernet connectivity.

7.2.2.2 Ericsson mmWave

The Athens platform and more specifically COSMOTE site, is set to undergo an enhancement in the RAN outdoor segment through the integration of Ericsson mmWave technology, specifically the AIR5322 antenna radio module. This enhancement aims to optimize and strengthen the platform's ability to provide reliable and efficient wireless connectivity, enhanced coverage, increased network capacity, and improved performance in the outdoor environment due to its ability to provide a high Effective Isotropic Radiated Power (EIRP) value of up to 62 dBm. The n258 band will cover the frequency range from 26700 to 27100 MHz.

7.2.2.3 KEYSIGHT TEST AND MEASUREMENT TOOLS

All pertinent 6G test and measurement software tools provided by Keysight will be deployed on the Athens platform, with the objective of boosting and augmenting the capabilities of the platform. These tools will be integrated seamlessly into the existing infrastructure, equipping the Athens platform with advanced functionalities for comprehensive testing and measurement in the context of 6G technology. This strategic deployment aims to enhance the platform’s potential and enable efficient evaluation and optimization of 6G networks, thereby supporting the experimenters.

7.2.2.4 OPENNEBULA

OpenNebula will be installed in the Athens platform, serving as an additional infrastructure manager within the broader infrastructure of the 6G-SANDBOX facility. By leveraging OpenNebula in the Athens platform, users/experimenters will benefit from its robust features and capabilities, since the platform enables the expansion of multi-cloud environments to the edge, combining the utilization of virtual machines (VMs) and containers. This allows for increased flexibility in application deployment, catering to diverse requirements. Furthermore, OpenNebula's ability to leverage public cloud and edge resources ensures that the Athens platform can tap into a wide range of infrastructure providers. By utilizing resources from different providers, the Athens platform can effectively harness the power of hybrid and edge environments, providing enhanced performance and scalability.

7.2.2.5 OPEN5GS

As of the time of this document’s writing, a “clean” installation of Open5GS core network is currently underway aimed at advancing the capabilities of Athens platform. Moreover, the Amarisoft RAN will be seamlessly integrated with the Open5GS core. Open5GS is an open-source 5G core network and a highly suitable option for the Athens platform due to its support for distributed NF deployments, which aligns with the evolution toward the distributed 6G architecture. One of the key advantages of using Open5GS is the ability to deploy UPF in different locations within the testbed, such as at the edge site and the core site, and associate them with different network slices (e.g., S-NSSAI). Overall, this approach allows for greater flexibility and enables the support of multiple user planes in three dimensions, including network slicing, traffic steering, and Application Function (AF) traffic influence.

7.3 BERLIN PLATFORM

7.3.1 PLATFORM OVERVIEW

Fraunhofer FOKUS operates the 5G Playground in its location in Berlin. The Playground is used in multiple projects to implement and validate various use cases for 5G and upcoming 6G. It is also used for the implementation of the Open5Gcore Platform. The Playground has a long history in the mobile communication field and has constantly evolved from older technologies such as 3G and 4G The overall architecture of the platform can be seen in Figure 19.

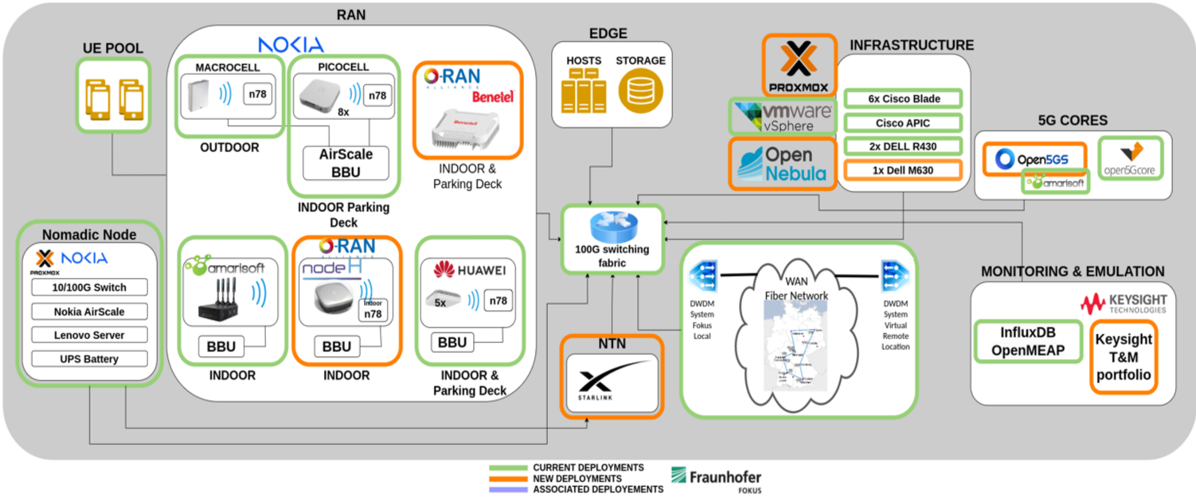


Figure 19. Berlin Platform

In its current state, it consists of outdoor and indoor 5G cellular equipment from various vendors utilizing mainly the Private network spectrum 3.7 to 3.8 GHz band n78.

Indoor coverage includes a distributed MIMO cell installation from Huawei and Nokia covering the entire underground parking deck, which is also used by other departments for autonomous driving activities. Another Nokia Macro cell is located on the roof to provide outdoor coverage in the vicinity of the building. Throughout the laboratory floor, Huawei micro remote radio heads are installed providing coverage to the lab environment. In addition to the "big" vendor RAN we also have SDR based gNodeB from Amarisoft and ETTUS USRP supporting OpenAir and srsRAN software stacks. To cover O-RAN use cases, the USRP based setups can be used in addition to small cells from NodeH. The networks are configured as 5G SA with Slicing and RAN Sharing enabled to support multiple core networks at the same time. As core network the Fraunhofer FOKUS developed Opene5GCore is used most of the time. Open5GCore supports very flexible NF deployment models that range from classic all-on-one cloud models to very distributed setups, which include multiple UPF at various network locations. The Standard 3GPPP interfaces are exposed due to the modular design of the Open5GCore, thus experimenters can access or intercept these interfaces. However, other (open source) cores are also available and can be activated for specific PLMN (MCC/MNC). The Playground basically operates multiple standalone Operators, each with its own pool of sim cards, which can be produced on demand. For the UE side, the playground has mobile phones from several vendors interconnected to multiple indoor locations and accessible via ADB remote control software. In addition to the consumer mobile phones embedded modem M.2 cards and CPE Devices are available. In addition to the fixed installed RAN components, so-called Nomadic Nodes are available. These refrigerator-sized mobile racks include compute, network, and storage resources together with RAN equipment from Nokia or Huawei and power supplies. These Nodes can be used to implement and validate nomadic ad-hoc private network scenarios.

From the infrastructure side, the playground components are interconnected with operator grade 100 Gbit switches that operate in a redundant leaf-spine architecture. Dedicated Isolated network setups can be created by management software and further delegated to individual projects. Compute and Storage resources are managed by VMware hypervisor which provides virtual machines to the projects utilizing the Playground. In addition to the six VMware servers bare-metal servers can be added to the infrastructure to support special use cases which rely on direct hardware access. The nomadic nodes rely on a single server with the Proxmox hypervisor to host VM and container-based services. In addition to the redundant 1 Gbit internet uplink via the DFN, the testbed also has a direct fiber connection to a German-wide Wireless Access Network (WAN) fiber loop. By using a 96-channel Carrier grade Dense wavelength-division multiplexing (DWDM) system from Nokia, this WAN link can be used to connect remote locations across Germany. By using two of these DWDM systems, a 900 Km loop is configured which can be used to simulate remote locations in the same testbed. To cover NTN use cases, a Starlink antenna is also available in the playground. This allows the experimentation with different spilt scenarios where some components of a 5G system are moved into a various edge (virtual) data centers. These (virtual) edge data centers can be interconnected using the Satellite or long-range WAN links to simulate different distances.

7.3.2 Enhancements and Innovations

In the framework of the enhancements planned for Berlin's platform in the upcoming months, the following technology aspects and components are targeted.

7.3.2.1 Keysight Test and Measurement tools

All pertinent 6G test and measurement software tools provided by Keysight will be deployed on the Berlin platform, with the objective of boosting and augmenting the capabilities of the platform. These tools will be integrated seamlessly into the existing infrastructure, equipping the platform with advanced functionalities for comprehensive testing and measurement in the context of 6G technology. In addition to the software only tools, the Berlin platform is already equipped with Keysight energy Measurement devices to measure the energy efficiency of RAN components.

7.3.2.2 OpenNebula

OpenNebula will be installed in the Berlin platform as a cloud-management solution to provide the experimenters a unified interface into the platform compute resources. A single bare-metal server will be assigned exclusively to be managed by OpenNebula using the KVM hypervisor. In addition to this, the integration of the shared VMware resources into OpenNebula is planned. This would provide a unified interface to control the combined compute resources of different hypervisors via a single interface.

7.3.2.3 O-RAN Components

In addition to the research targeted SDR solutions that are used for O-RAN support in the Platform, the installation of state-of-the-art O-RAN radio heads from Benetel is planned. The Radio-Head units will operate in the n78 Frequency band and can be used by various O-RAN software stacks as part of the RAN.

7.3.2.4 NTN

The current integration of the Starlink satellite connectivity allowed a very static use of the Satellite resources. To extend the usability of the Satellite connection services by experiments, an update of the VPN system that provides the isolated NTN links via Starlink is planned. In addition to this software-based enhancement, a secondary Antenna is planned to arrive soon.

7.4 Oulu Platform

7.4.1 Platform Overview

University of Oulu has a 5G Test Network (5GTN) with a campus-wide small cell, macro-cell, and distributed antenna based cellular network to be complemented by NFV based EPC and 5G backhauling solution (http://5gtn.fi/). Figure 20 provides a comprehensive overview of the platform's architecture.

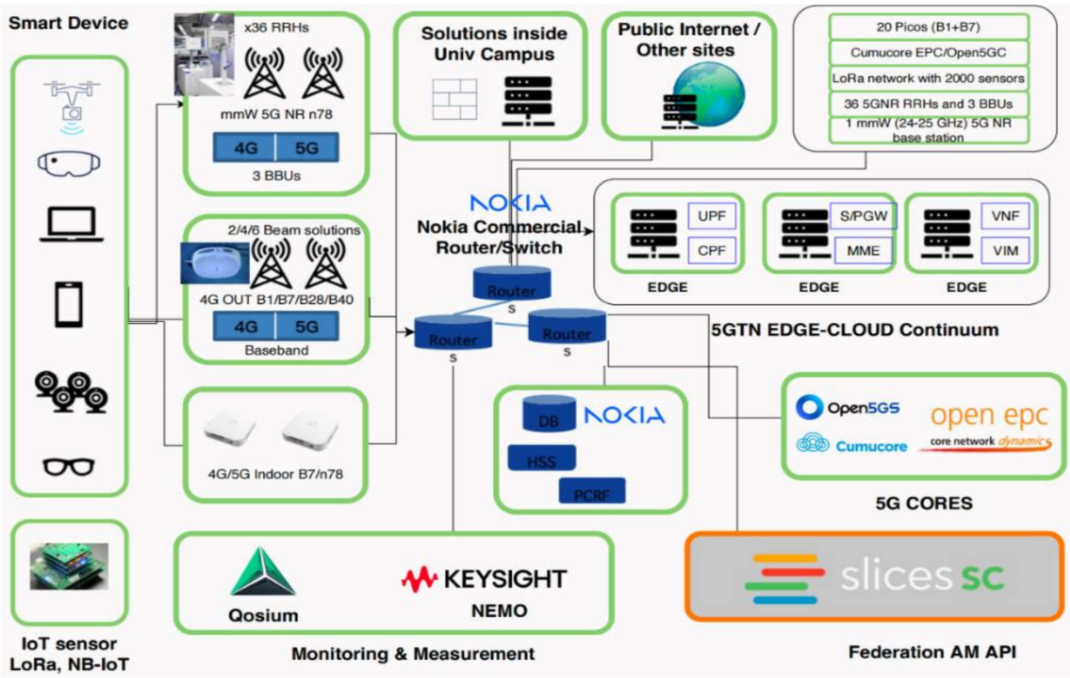


Figure 20. Oulu Platform

Full-scale 5G test network supports using 5G devices, higher frequency bands, cognitive management functionalities, system testing tools for new solutions. The 5G Test Network feature evolution follows 5G research and standardization progress, acting as verification platform for theoretical 5G research. The cellular devices part of the network is composed of 30 LTE small cells (700 MHz, 2.1, 2.3, 2.6, 3.5 GHz) and 2 macro cells (2.3 GHz). The network has two 5GNR base stations (3.5 GHz) complemented with User Equipment from MediaTek (10) that are easily integrated to any device, and 5G enabled mobile phones from several vendors. The network is currently being complemented by mmWave (24-28 GHz) 5G NR base stations as well as with 36 remote radio head (RRH) based cloud RAN 5G NR devices. For research purposes, we have also pre-standard 5G capable NOKIA proof-of-concept (PoC) devices at 26-28 GHz. Early 2023, NOKIA Open edge system will be deployed allowing the use of RAN Intelligent Controller (RIC) with xApps.

Open air interface (OAI) 4G and 5G NR protocol stacks with USRP radios is supported as well. The network is controlled by operator grade EPC (Evolved Packet Core), thus making OULU in practice a network operator with own SIM production for mobile devices. The current operational EPC version is 5G NSA compliant, but for research purposes 5G standalone (SA) core is also available. The network within the campus is complemented by wireless sensor network (IoT, internet of things) extension with an estimated 2,000 different kinds of sensors with wireless connectivity through NB-IoT, LTE-M, and LoRa. Furthermore, the network has big data computing servers for network data analytics purposes. Some of these servers are distributed within the network thus allowing MEC as well as caching services. The NOKIA EPC has open application programming interfaces (virtualized EPC) that make it possible to integrate new services to e.g., network management.

7.4.2 Enhancements and Innovations

OULU platform will include SLICE-SC to facilitate full control over the parameters of an experiment and enable the repeatable experiments regardless of the physical infrastructures, i.e., different sites within the Consortium, and conduct valid experimental results, which are easy to cross-reference and replicate. SLICE-SC provides Transnational Access (TA) to its available infrastructures, which means free of charge, transnational access to research infrastructures for selected user groups. The access includes the logistical, technological, and scientific support and the specific training that is usually provided to external researchers using the infrastructure. TA can be Physical Access and Remote Access. OULU will facilitate the open call through the TA enabled by the SLICE-SC.

8 SUMMARY OF 6G-SANDBOX TESTBEDS AND KPIS

This section offers a comprehensive presentation of the technologies and Key Performance Indicators (KPIs) supported by the four testbeds. It adopts a two-fold approach. Subsection 8.1 provides an overview of the current capabilities of each platform while subsection 8.2 highlights the measurable KPIs at the current stage, along with an outline of the additional KPIs that will be supported in the future. These insights are derived from the project's detailed time plan, providing a comprehensive understanding of the existing features of the platforms and the anticipated developments to further enhance their functionalities.

8.1 SUMMARY OF PLATFORM FEATURES

Section 7 provides a comprehensive description of the main characteristics of the four platforms, accompanied by architectural diagrams for each one of them. The purpose of this subsection is to summarize the individual features offered by the platforms in their current state and to present the envisioned technologies and components. In this summary, the features are categorized into six groups: Core Network, RAN outdoor, RAN indoor, Infrastructure Managers, NTN technologies, and tools related to Emulation and Measurement for facilitating experiments. In order to signify the deployments that are currently supported (see Table 12 below), a checkmark symbol '✓' is used, while the technologies intended for deployment in a later phase are represented by the letter 'o'.

Table 12. Technologies Per Platform

	Technologies	**Malaga**	**Athens**	**Berlin**	**Oulu**
Core Network	Open5GS	✓	o	o	
	Open5GCore			✓	
	Amarisoft		✓		
	Open EPC				✓
	Athonet		✓		
	Polaris	✓			
RAN outdoor	Nokia Microcell	✓		✓	
	Nokia mmWave	✓			
	Ericsson mmWave		o		
	Ericsson 4408		✓		
	Nokia Airscale		✓		
	Nokia Macrocell			✓	
	Amarisoft		✓		
RAN indoor	Nokia picocell	✓	✓		
	Amarisoft		✓	✓	
	Huawei			✓	
	OpenRAN			o	

	OpenRan Acceleron	✓			
	OpenRAN Nokia	o			
Infrastructure Manager	OpenNebula	✓	o	o	
	vmWare			✓	
	Openstack		✓		
NTN	Starlink		✓	✓	
	Hawk	o			
	OpenSand emulator	o	o	o	
Emulation and Measurements	Keysight tools**	o	o	o	o
	OTA chamber	✓			
	5G UXM emulator	✓			
	NEF emulator		✓		
	Cosmotools		✓		
	Prometheus		✓		
	OpenMEAP			✓	
	Opensource tools (iperf, ping)	✓	✓		
Orchestration tools	Katana		✓		
	OpenTap	✓			

8.2 Summary of Current KPIs

An overview of the measurement capabilities from the four testing platforms with respect to the KPIs defined in Section 2.1.2 is summarized in Table 13, with a '✓' denoting for the KPIs that are currently measurable, and an 'o' denoting for the KPIs that are planned to be measurable at a later phase. As can be seen from the table, most of the KPIs have or will be covered by the four testing platforms, depending on the scope of the projects, the definition of the addressed scenarios and use cases, and the nature of the applications/services under test. The uncovered KPIs are mainly in the category of EMF, security, and localization testing at the current stage, given the fact that the development of the four testing platforms is still in progress. Some of the KPIs measurable by different Keysight test and measurement tools are provided in Annex 1.

Table 13. Overview of KPI Measurement Capabilities in Four Testing Platforms

Category	KPI Name	Malaga	Berlin	Athens	Oulu
Capacity	Peak Data Rate	✓	✓	✓	✓
Capacity	User Experienced Data Rate	✓	✓	✓	✓
Capacity	Bandwidth	✓	✓	✓	✓
Capacity	Area Traffic Capacity	o		o	
Capacity	Connection Density	o		o	
Capacity	Network Capacity	o		o	

Latency (Connectivity)	User Plane Latency	✓	✓		✓
Latency (Connectivity)	Control Plane Latency	✓	o	✓	✓
Latency (Connectivity)	Delay deviation / jitter	✓	✓	✓	✓
Latency (Connectivity)	E2E Service Latency	✓	✓	✓	✓
Latency (Connectivity)	E2E Application Latency	✓	✓	✓	✓
Latency (Orchestration)	Service Provisioning Time	✓	o	✓	
Latency (Orchestration)	Slice Provisioning Time			✓	
Channel	Spectral Efficiency	o		o	
Channel	Received Signal Quality (SINR)	✓			✓
Energy	Energy Efficiency	o	o		o
Energy	NFV Energy Efficiency	o	o		o
Energy	Network Energy Efficiency	o	o		o
Energy	Device Energy Efficiency	o	o		o
Reliability	Packet Error & Frame Error Rate		✓	✓	✓
Reliability	Packet Loss & Frame Loss Rate	✓		✓	✓
Reliability	Session reliability			o	
Service availability	Service availability	✓		✓	
Service availability	Service safety, maintainability	✓		✓	
Compute	Edge computational resource usage	o			
Compute	RAM Usage	✓	o	✓	
Compute	CPU Usage	✓	o	✓	
Compute	Availability	✓	o	✓	
Compute	Resource utilization	✓	o	✓	
Localization	Availability		o		
Localization	Localization acquisition time		o		

9 CONCLUSION

This document summarizes the outcomes of the activities involved in gathering, harmonizing, and prioritizing requirements based on the proposed blueprint, which sets the foundation for the updated reference architecture of the 6G-SANDBOX facility. The goal is to provide a focused and balanced set of demands in an agile manner, rather than an exhaustive and disorganized list of technical details. These demands will guide the final design phase, leading to the ultimate architecture of the 6G-SANDBOX facility, which will be presented in D2.4 at M24.

Additionally, the deliverable provides comprehensive information about the experimentation blueprint, which serves as the basis for analysing and specifying the desired functional architecture. It explores each individual platform in detail, including their underlying technology, current topology status, and planned enhancements throughout the project's duration. The document emphasizes the innovative aspects that each platform aims to achieve and delves into the specific Key Performance Indicators (KPIs) that will be measured by each platform.

As the initial technical deliverable of the 6G-SANDBOX project, this document offers a concise overview of the project's scope, objectives, and overall approach. It is intended to serve as a crucial reference guide for specifying the 6G-SANDBOX Facility, informing subsequent implementation work that will be documented in forthcoming technical deliverables.

References

[1] "Strategic Research and Innovation," https://bscw.5g-ppp.eu/pub/bscw.cgi/d511515/SRIA%202022%20-%20White%20paper%20-%20for%20public%20consultation.pdf.

[2] Nielsen, Lars, Gavras, Anastasius, Dieudonne, Michael, Mesogiti, Ioanna, Roosipuu, Priit, Houatra, Drissa, & Kosmatos, Evangelos. (2022), "Beyond 5G/6G KPIs and Target Values," Zenodo. https://doi.org/10.5281/zenodo.6577506, 2022.

[3] 5G PPP phase II KPIs , "Annex to Programme Management Report".

[4] K.X. Du, B. Sayadi, G. Carrozzo, F. Lazarakis, A. Kourtis, M.S. Siddiqui, J. Sterle, O. Carrasco, R. Bruschi, "Definition and Evaluation of Latency in 5G:A Framework Approach," URL: http://www.jkjmanagement.com/5gwf19-4/papers/p135-du.pdf, 2019 IEEE 5G World Forum.

[5] ITU-R M.2410-0, "Minimum requirements related to technical performance for IMT 2020 radio intefrace(s)," https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2017-MSW-E.docx, 2017.

[6] ITU-R M.2412-0, "Guidelines for evaluation of radio interface technologies for IMT-2020," https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2412-2017-PDF-E.pdf, 2017.

[7] ITU-T, G.810 , "Definitions and terminology for synchronization networks," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.810-199608-I!!PDF-E&type=items .

[8] ITU-T G.1020, "Performance parameter definitions for quality of speech and other voiceband applications utilizing IP networks," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.1020-200607-I!!PDF-E&type=items.

[9] Dieudonne, Michael, Wang, Hua, Mesogiti, Ioanna, & Kosmatos, Evangelos, "Beyond 5G/6G KPI Measurements," Zenodo. https://doi.org/10.5281/zenodo.7963247, 2023.

[10] IEC/IEEE 62209-1528, "Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Human models, instrumentation and procedures (Frequency range of 4 MHz to 10 GHz," https://webstore.iec.ch/publication/62753, 2020.

[11] IEC 62232, "Determination of RF field strength, power density and SAR in the vicinity of base stations for the purpose of evaluating human exposure," https://webstore.iec.ch/publication/28673 , 2022.

[12] "3GPP TS 22.104 "Service requirements for cyber-physical control applications in vertical domains"," https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3107.

[13] "3GPP TS 22.261 "Service requirements for the 5G system" Rel 18".

[14] "ETSI EN 303 471 "Energy Efficiency measurement methodology and metrics" v1.1.1," https://www.etsi.org/deliver/etsi_en/303400_303499/303471/01.01.01_60/en_303471v010101p.pdf, 2019.

[15] "3GPP TS 23.271 "Functional stage 2 description of Location Services (LCS)" Rel 17," https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=834.

[16] "3GPP TS 22.071 "Location Services (LCS); Service description; Stage 1" Rel 16," https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=584.

[17] "RISE-6G Deliverable D2.2, "Metrics and KPIs for RISE wireless systems analysis: First results," https://rise-6g.eu/Pages/DELIVERABLES/Livrables.aspx, June 2021.

[18] "ISO/IEC 27000," https://www.iso.org/standard/63411.html, 2014.

[19] United Nations, "Sustainable Development Goals," http://www.un.org/sustainabledevelopment/sustainable-development-goals.

[20] "D1.2 Expanded 6G vision, use cases and societal values," https://hexa-x.eu/wp-content/uploads/2022/04/Hexa-X_D1.2_Edited.pdf, 2021.

[21] "D1.3 Targets and requirements for 6G - initial E2E Architecture," https://hexa-x.eu/wp-content/uploads/2022/03/Hexa-X_D1.3.pdf, 2022.

[22] Wikström, Gustav, Schuler Scott, Arianna, Mesogiti, Ioanna, Stoica, Razvan-Andrei, Georgiev, Georgi, Barmpounakis, Sokratis, Gavras, Anastasius, Demestichas, Panagiotis, Hamon, Marie-Helene, Hallingby, Hanne-Stine, & Lund, David, "What societal values will 6G address?," Zenodo. https://doi.org/10.5281/zenodo.6557534, 2022.

[23] "SNS R&I Work Programme 2023-2024," https://smart-networks.europa.eu/wp-content/uploads/2022/12/sns_ri_wp_2023-24.pdf.

[24] Hallingby, Hanne Kristine, Fletcher, Simon, Frascolla, Valerio, Gavras, Anastasius, Mesogiti, Ioanna, & Parzysz, Fanny, "5G Ecosystems," Zenodo. https://doi.org/10.5281/zenodo.5094340, 2021.

[25] Hallingby, Hanne-Stine, Gavras, Anastasius, Mesogiti, Ioanna, Bledow, Nona, Darzanos, George, Frizzell, Ronan, Breuer, Henning, Rokkas, Theodoros, & Fernandez Vega, Luis, "5G and Beyond 5G Ecosystem Business Modeling," Zenodo. https://doi.org/10.5281/zenodo.7640478, 2023.

[26] "5G PPP stakeholders picture," https://5g-ppp.eu/revised-5g-ppp-stakeholders-picture-and-glossary, 2021.

[27] "D2.2-Final EuWireless Architecture," https://euwireless.eu/wp-content/uploads/2020/04/EuWireless_D2.2_v1.0.pdf.

[28] "D2.4 - Final report on facility design and experimentation planning," https://5genesis.eu/wp-content/uploads/2020/07/5GENESIS_D2.4_v1.0.pdf .

[29] " D1.4 "Design of infrastructure architecture and subsystems"," https://zenodo.org/record/4066381, 2020.

ANNEX 1

KPI list from Keysight measurement tools

Keysight tool	KPI family	KPI name
BreakingPoint	Capacity	TCP/HTTP Connections Per Second
BreakingPoint	Capacity	HTTP Transaction per Second
BreakingPoint	Capacity	HTTP Throughput
BreakingPoint	Capacity	Concurrent TCP/HTTP Connection Capacity
BreakingPoint	Capacity	TCP/HTTPS Connections per second
BreakingPoint	Capacity	HTTPS Transaction per Second
BreakingPoint	Capacity	HTTPS Throughput
BreakingPoint	Capacity	Concurrent TCP/HTTPS Connection Capacity
BreakingPoint	Latency	TCP/HTTP Transaction Latency
BreakingPoint	Latency	HTTPS Transaction Latency
BreakingPoint	Security	Cipher RSA 2K/4K key size – CPS performance
BreakingPoint	Security	Cipher ECDHE-RSA 256-P/512-P curve size – CPS performance
BreakingPoint	Security	Cipher ECDHE-ECDSA 256-P/512-P curve size – CPS performance
BreakingPoint	Security	Cipher TLS1_3 EC CPS Performance
BreakingPoint	Security	Block Cipher AES128/AES258 -CBC – Throughput Performance
BreakingPoint	Security	Block Cipher AES128/AES258 -GCM – Throughput Performance
BreakingPoint	Security	Block Cipher Cha-Cha-Poly – Throughput Performance
Cloud Peak	Compute	CPU cache Hit / Miss / Ratio
Cloud Peak	Compute	CPU performance score
Cloud Peak	Compute	Memory latency (ns)
Cloud Peak	Compute	Memory bandwidth (GBps)
Cloud Peak	Network	Packet loss (PPM)
Cloud Peak	Network	Packet latency (RTT)
Cloud Peak	Network	Packet latency (TCP / UDP)
Cloud Peak	Network	Packet jitter (µs)
Cloud Peak	Network	Packet TX rate (Mbps)
Cloud Peak	Network	Packet RX rate (Mbps)
Cloud Peak	Network	CPU utilization (%)
Cloud Peak	Network	Memory utilization (RAM)
Cloud Peak	Storage	BW / IOPS / Latency (read)
Cloud Peak	Storage	BW / IOPS / Latency (write)
Cloud Peak	VIM	Noisy neighbour success rate
Cloud Peak	VIM	Noisy neighbour resource usage
Cloud Peak	VIM	VM deployment success rate
Cloud Peak	VIM	VM deployment speed
CyPerf	Capacity	Total number of client and server agents in a test
CyPerf	Capacity	Throughput
CyPerf	Capacity	Connection per second
CyPerf	Capacity	Simulated users
CyPerf	Security	Total count of attacks allowed / blocked
CyPerf	Security	Total applications success / failed
CyPerf	Latency	Connect time
CyPerf	Latency	Time to first byte (TTFB)
CyPerf	Latency	Time to last byte (TTLB)
Hawkeye	Capacity	Throughput
Hawkeye	Capacity	Transactions per sec
Hawkeye	Packet Loss	Packet loss rate
Hawkeye	Packet Loss	Packet loss burst
Hawkeye	Packet Loss	Total bytes lost
Hawkeye	Latency	One way delay (ms)
Hawkeye	Latency	Jitter (ms)
Hawkeye	Latency	max jitter (ms)

Hawkeye	Latency	Max delay variation (ms)
Hawkeye	Latency	Response time (ms)
Hawkeye	Voice	Voice MOS score
Hawkeye	Video	Video MDI scores
Hawkeye	Video	Avg Video Playback Rate (bps)
Hawkeye	Video	Avg Video Pre-buffering duration (ms)
Hawkeye	Video	Video Playback Downshifts
Hawkeye	Video	Video Playback Upshifts
Hawkeye	Video	Video Quality
Hawkeye	Video	Video Stopped Count
Hawkeye	Video	Video Stopped Duration (ms)
IxLoad	Capacity	Simulated users
IxLoad	Capacity	Throughput
IxLoad	Capacity	Connections/sec
IxLoad	Capacity	Layer 7 transactions/sec
IxLoad	Capacity	Concurrent connections/sessions
IxNetwork	Frame Loss	Tx frames
IxNetwork	Frame Loss	Rx frames
IxNetwork	Frame Loss	Frame loss
IxNetwork	Frame Sequency	last sequence number
IxNetwork	Frame Sequency	duplicate frames
IxNetwork	Frame Sequency	sequence gaps
IxNetwork	Frame Sequency	reverse error
IxNetwork	Capacity	Tx frame rate
IxNetwork	Capacity	Rx frame rate
IxNetwork	Capacity	Rx rate
IxNetwork	Latency	MEF frame delay
IxNetwork	Latency	forwarding delay
IxNetwork	Latency	delay jitter
IxNetwork	Latency	inter-arrival time
IxNetwork	Capacity	Tx frame rate
IxNetwork	Capacity	Rx frame rate
IxNetwork	Capacity	Rx rate
IxNetwork	Latency	MEF frame delay
IxNetwork	Latency	forwarding delay
IxNetwork	Latency	delay jitter
IxNetwork	Latency	inter-arrival time
LoadCore	Latency	One way delay (ms)
LoadCore	Latency	delay jitter
LoadCore	Packet Loss	Packet loss

ANNEX 2

Glossary

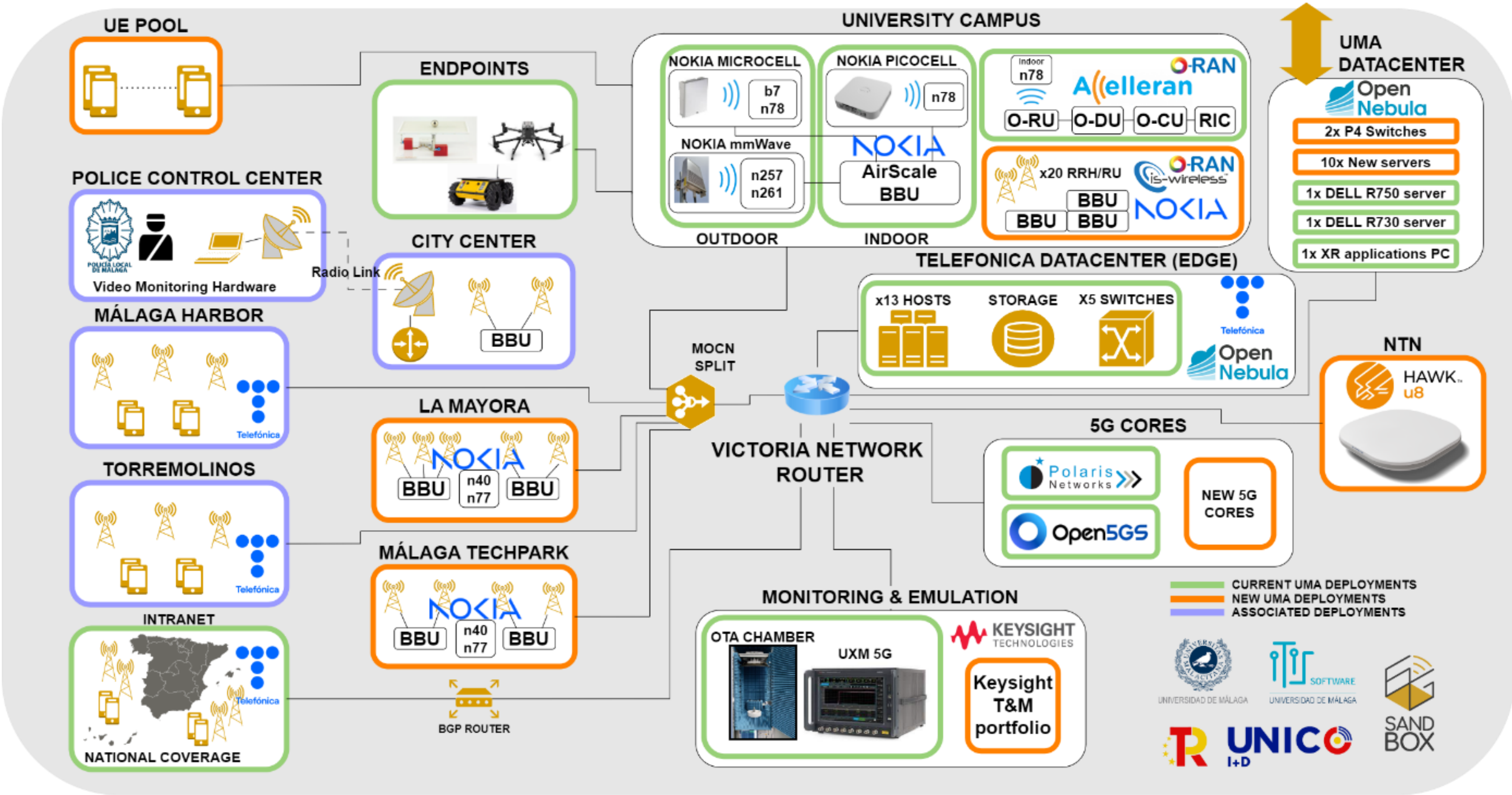
Term	Description
Facility (or the 6G-SANDBOX facility) (or 6G-Experimentation facility)	The full set of 6G-SANDBOX components that are offered as a pan-European testbed for experimenting. The testing procedures can be for 6G technology validations and for 6G KPI measurements. The facility is expected to include the implementation of all the components that will be structured around a 6G-SANDBOX reference architecture.
Experimentation platform (or Platform)	An End-to-End platform (a system with integrated Radio Access Network, Network Core, Transport and services) that include 6G-enabled components/features and experimentation services as well as local cloud infrastructure capabilities. Four platforms support the 6G-SANDBOX project, namely the Malaga platform, the Athens Platform, the Berlin platform, and the Oulu platform.
Site (or Platform's Site) (or Experimentation platform's Site)	A location-dependent part of an experimentation platform. The various sites of a platform should be well interconnected and interfaced, but this interconnection and interfacing is not necessarily exposed to platform externals. Example: the Athens platform of 6G-SANDBOX is composed of parts that are located in the COSMOTE premises (i.e., parts that define the COSMOTE site of the platform, e.g., the 5G core) and parts at the NCSRD campus (i.e., parts that define the NCSRD site of the platform, e.g., the 5G access); these two sites are well-connected with an optical fiber link.
Node	It refers to every physical or virtual component that can be identified individually, i.e., it has specific purpose (provides a kind of service) and it encompass one or multiple technological features. Examples are a 5G-NR antenna, a RIS system, an IoT end-device, a network application, a network function, a set of network functions that compose network core, an experimentation tool, etc.
Trial Networks	Fully configurable, manageable and controllable network which combines digital/virtual and physical nodes and provides services for 6G technology validation and 6G KPI measurements. Instances of Trial Networks might be offered targeting specific network domains and technologies. End-to-end Trial Networks will be offered by the four experimentation platforms that support the 6G-SANDBOX project.
6G Library	To support reusability, openness, and long-term evolution a meaningful set of software components -that will be provided to and/or developed for the 6G-SANDBOX **facility-** will be packed and offered in a relevant repository (e.g., GitHub) together with the required documentation in order to create an open reference software library, which will not only be under continuous enhancement by the project partners, but it is also meant to serve as an index and sink point for other developments (during and beyond the project lifetime).
6G KPI and KVI repository	To maximize the contribution towards a 6G experimentation ecosystem, all the results of the experimentation processes performed on the 6G-SANDBOX facility will be stored in an open 6G KPI & KVI repository following a common and structured format (based on the SNS JU work in the related WGs) and they will be accessible by other projects/stakeholders, and thus, subject to external analysis.
Technology validation test (or 6G Technology validation)	Tests using the 6G-SANDBOX facility targeting to assess whether a component/node operates and interacts properly, and also provide expected results. The Technology validation tests target the assessment of components/nodes within an overall system. E.g., the tests to validate that the API framework of 6G-SANDBOX is well integrated in the overall testbed.
KPI measurement campaigns (or 6G KPI measurements)	Tests using the 6G-SANDBOX testbed targeting the quantification (selection of values) for well-defined KPIs (e.g., KPIs defined in the 6G-

	SANDBOX proposal/DoA, or selected ones from the related SNS JU work group).
Architecture (or Reference Architecture)	The main representation of the 6G-SANDBOX **facility**. It can be provided in various levels of detail (abstractions) or viewpoints (e.g., functional, topology, implementation etc.). A first version of the 6G-SANDBOX Reference Architecture is in the proposal/DoA. Based on the components, the interfaces, the technologies, the tools, and the structure that might be depicted in the Reference Architecture, the development teams should be able to implement the relevant functions, processes, and services.
Physical Infrastructure Layer	The lower layer of the 6G-SANDBOX **Reference Architecture**. It includes the functions and the components needed for providing end-to-end 6G-enabled connectivity (each of the 4 6G-SANDBOX platforms are included here)
Resource Management Layer	The mid layer of the 6G-SANDBOX **Reference Architecture**. It manages computational and network resources and forming them as Trial Networks to be offered for experimentation. It may operate in a cross-platform manner / above the local (platform specific) controllers and managers. It may also include functions and components needed for optimizing the Trial Networks, e.g., with AI capabilities and Security guarantees.
Experimentation lifecycle Layer	The upper layer of the 6G-SANDBOX **Reference Architecture**. It includes the functions and the components needed for controlling the experimentation process and providing the required access to the experimenters.

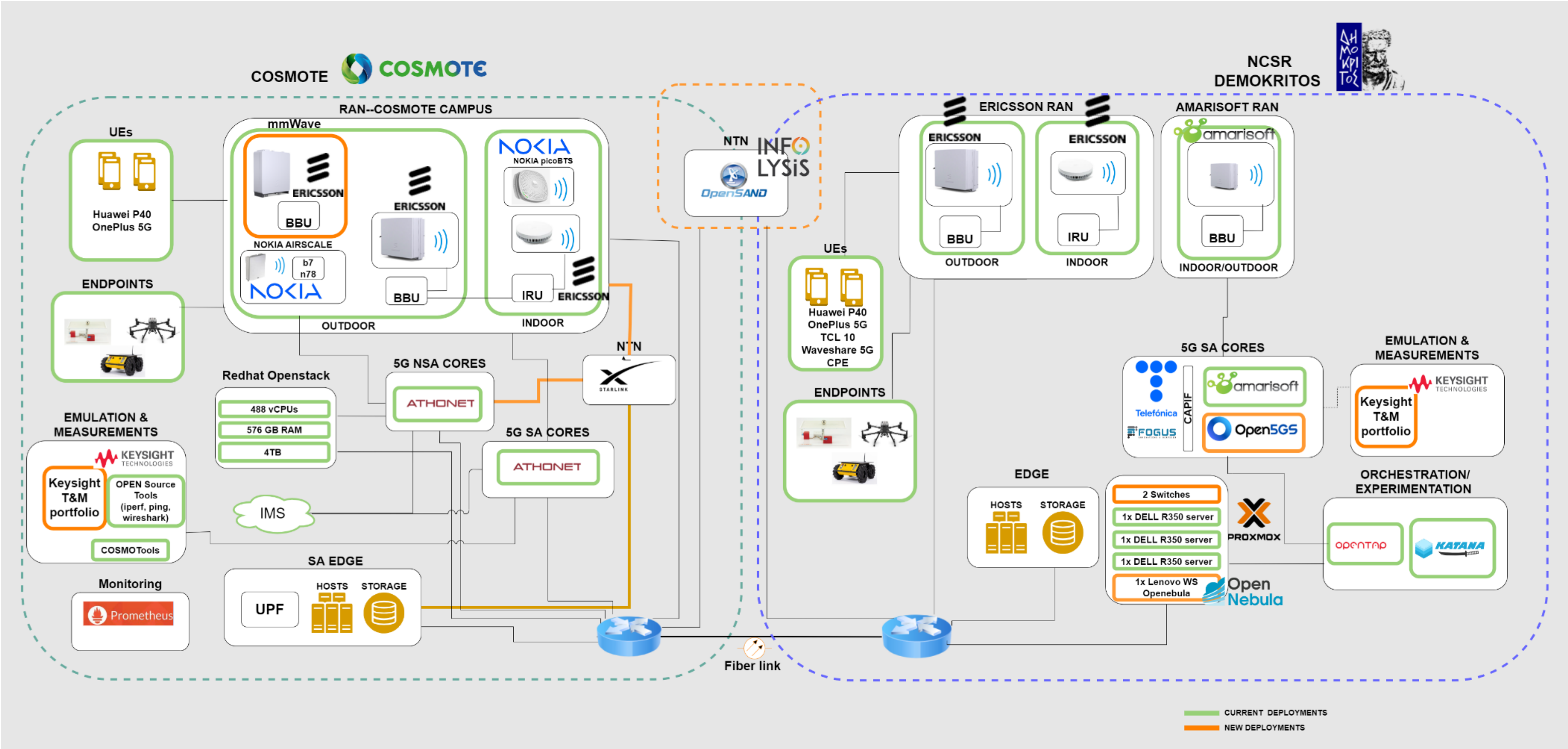
ANNEX 3

6G-SANDBOX platforms

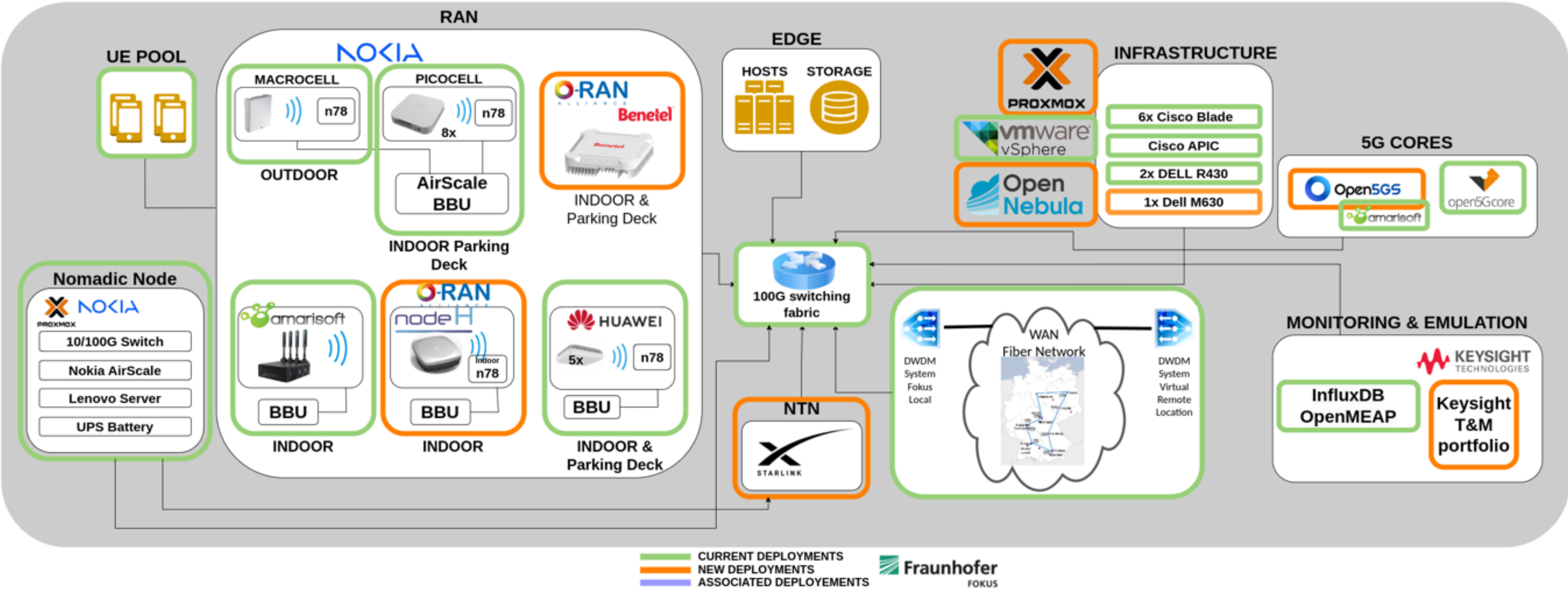
Malaga Platform



Athens Platform



Berlin Platform



Oulu Platform