6G TWIN

Integrating Network Digital Twinning into Future AI-based 6G Systems

D5.1

Evaluation methodology, planning and coordination

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Executive Summary

Deliverable D5.1 is the first deliverable of **Work Package 5 (WP5): Evaluation, Reengineering, and Standardisation**. The objectives of WP5 are to: 1) specify the framework, requirements, and Key Performance Indicator (KPI) definitions for evaluating the performance and impact of the 6G Network Digital Twin (NDT) and the new AI-based communication paradigms (Task 5.1 - T5.1); 2) specify the test scenarios and test cases (T5.1); 3) process the test cases (Task 5.2 - T5.2); 4) propose new paradigms and solutions for the reengineering of network architectures (Task 5.3 - T5.3); and 5) propose solutions to support architectural standardisation efforts (Task 5.4 - T5.4).

Deliverable D5.1 is the outcome of Task 5.1 (T5.1), which aims to define the methodology, data, and requirements - including KPIs - for evaluating the performance and impact of the 6G NDT and the new AI-based communication paradigms. T5.1 serves as the foundation for the entire WP5 and is interconnected with all subsequent tasks within the work package. Its inputs include the preliminary definition of the use cases developed in WP4, while its outputs will inform both WP3 and WP4, both of which are supported by the KPIs developed in this task.

In this deliverable, we present the evaluation objectives that support the overall goals of the 6G-TWIN project and explain how they are addressed within the scope of Task 5.1. This includes the evaluation methodology, references to international standards, and both project-level KPIs (typically qualitative) and use-case-specific KPIs (quantitative), which are defined in detail together with the associated hardware and software components required for testing. The deliverable also introduces evaluation procedures covering both technical performance and social impact and discusses the interdependencies between this task and other parts of the project.

The project's solutions will be demonstrated through two complementary use cases: one focused on remote driving, and the other on energy efficiency in dense deployments. These use cases are aligned with the expected capabilities of future 6G networks and build on KPI frameworks established in previous research initiatives, including SNS JU STREAM C and D.

The document is structured as follows. Section 2 introduces the NDT architectural concept, including the notion of a 6G data space and the relevant state of the art. It also presents the ITU-T reference recommendation used to assess the maturity of the NDT. Section 3 describes the FESTA V-process adopted as the main evaluation methodology and explains how it maps to the 6G-TWIN tasks and work packages. It also classifies the KPIs into three categories: project-level KPIs, use-case-specific KPIs (with associated formulas, data, and system requirements), and KPIs for socio-evaluation. Sections 4 and 5 present the evaluation procedures for the two use cases, respectively. Each section outlines the use case objectives, the corresponding KPIs, the test scenarios and cases, and the hardware and software needed to perform the evaluations. Finally, Section 6 summarises the main findings, reflects on the deliverable's objectives, and highlights the contributions of the project partners.

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Abbreviations and acronyms

3GPP	Third Generation Partnership
5GC	5G Core
5GNR	5G New Radio
5GS	5G Systems
AaaML NF	Application AI/ML Assistance
ADS	Automated Driving Systems
AF	Application function
AI	Artificial Intelligence
AIaaS	AI as a Service
AIF	Artificial Intelligent Function
AIML-T	AI/ML Translator
AITM	AI Task Management
AMF	Access and Mobility Function
AR	Augmented Reality
ASM	Automotive Simulation Models
AV	Autonomous Vehicles
BER	Bit Error Rate
BLE	Bluetooth Low energy
BM	Beam Management
bps	bits per second
BS	Base Station
CACC	Cooperative Adaptive Cruise
CCL	Compute Continuum Layer
CCP	Connect-Compute platform
CCPA	California Consumer Privacy Act
CDR	Call Detail Record
CDT	City Digital Twin
CI/CD	Continuous Integration and
CN	Core Network
CNS	Complex Network Systems
COTS	Commercial off the shelf
CPU	Central Processor Unit
CSI	Channel State Information
CTGAN	Conditional Tabular Generative
CU	Centralized Unit
DAEMON	aDAptive and sElf-Learning MObile
DC	Data Collection
DDD	Domain-Driven Design
DES	Discrete Event Simulator
DL	Deep Learning
DNN	Deep Neural Networks
DRL	Deep Reinforcement Learning
DT	Digital Twin
DTC	Digital Twin Consortium
DTFV	Digital Twin Function Virtualization

DU	Distributed Unit
E2AP	E2 Application Protocol
E2E	End to End
E2SM	E2 Service Model
eMBB	Enhanced mobile broadband
ETSI	European Telecommunications
EVI	Ego Vehicle Interface
FMANO	Federated MANO
FR	Functional Requirement
GDPR	General Data Protection Regulation
gNB	g Node B
GNN	Graph Neural Network
GPU	Graphics Processing Unit
GRAND	Green Radio Access Network
GSBA	Global Service-based Architecture
HIL	Hardware In the Loop
HLA	High-Level Architecture
HV-VES	High Velocity Virtual Event
ICT	Information and Communication
IEFT	Internet Engineering Task Force
IoT	Internet of Things
ISAC	Integrated Sensing And
ISO	International Standards
ITU-T	International Telecommunication
KPI	Key Performance Indicator
KV	Key Value
KVI	Key Value Indicator
LIDAR	Light Detection and Ranging
MANO	Management and Orchestration
MEC	Mobile-Access Edge Computing
ML	Machine Learning
MLB	Mobility Load Balancing
MLOps	Machine Learning Operations
mMTC	massive Machine-Type
MNO	Mobile Network Operator
MVC	Model-View-Controller
NASA	National Aeronautics and Space
NCC	Network Control Center
NDT	Network Digital Twin
NEF	Network Exposure Function
NF	Network Function
NF/NS	Network Function and Services
NFR	Non-Functional Requirement
NFV	Network Functions Virtualization
NI	Network Intelligence

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NIF	Network Intelligence Function
NIO	Network Intelligence Orchestration
NIP	Network Intelligence Plane
NIS	Network Intelligent Service
NIStratum	Network Intelligence Stratum
NS	Network Service
NSAP	Network and Service Automation
NTN	Non-Terrestrial Network
NWAF	Network Function Automated
NWDAF	Network Data Analytics Function
NWMF	Network Management Function
OMG	Object Management Group
O-RAN	Open RAN
ORIGAMI	Optimized Resource Integration
OSI	Open Systems Interconnection
PCF	Policy Control Function
PER	Packet Error Rate
PoC	Proof of Concept
PPO	Proximal Policy Optimization
PRB	Physical Resource Block
PS	Physical System
PT	Physical Twin
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
rApp	RAN Application
RDT	RAN Digital Twin
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
ROI	Region of Interest
ROS	Robot Operating System
RRA	Radio Resource Allocation
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RU	Radio Unit
SDG	Sustainable Development Goals
SDN	Software-Defined Networking
SDO	Standards Development
SDR	Software Defined Radio
SINR	Signal-to-Interference-plus-Noise
SLA	Service Level Agreement
SMF	Session Management Function
SMO	Service Management and
SMPC	Secure Multi-Party Computation
SNMP	Simple Network Management
SNS JU	Smart Networks and Services Joint
SO	Specific Objective
SRCON	Simulated Reality of
THz	Terahertz
TMV	Test, Measurement, and Validation
TPU	Tensor Processing Unit
UABS	Unmanned Aerial Base Station
UAV	Unmanned Aerial Vehicle
UcI	Use case Identification
UE	User Equipment
UEDA	User Equipment Data Analytics
UN	United Nations
URLLC	ultra-Reliable Low-Latency
V2X	Vehicle-to-Everything
VR	Virtual Reality
WG	Working Group
WiFi	Wireless Fidelity
WP	Working Package
WSN	Wireless Sensor Network
XAI	eXplainable AI
xApp	eXtensible Application
ZSM	Zero-Touch Network and Services
ZTL	Zero Trust Exposure Layer

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1 Introduction

The rapid digitization of industries necessitates advancements in network technologies, particularly as we transition towards 6G systems. The overarching objective of 6G-TWIN is to provide the foundation for the design, implementation, and validation of an AI-native reference architecture for 6G systems that incorporates Network Digital Twins (NDT) as a core mechanism for the end-to-end, real-time optimisation, management, and control of highly dynamic and complex network scenarios.

We first outline the objectives of 6G-TWIN, emphasizing its core mission to develop a sophisticated network framework, before specifically focusing on the key targets of this deliverable, presenting its structure and the contribution of the project's partners.

1.1 Aims and objectives

1.1.16G-TWIN objectives

In response to the accelerating digitization across industries, the 6G-TWIN project emerges with a singular mission: to pioneer an AI-native reference architecture for the forthcoming 6G systems. At its core lies an ambitious vision to seamlessly integrate NDTs into the fabric of future networks, revolutionizing their optimization, management, and control in real-time.

To achieve its ambition, the 6G-TWIN has been built around several specific objectives:

- Specific Objective 1 (SO1) is central to the project's ambition, promising to design an open, federated and AI-native network architecture for the imminent 6G landscape. This architectural blueprint is designed to leverage NDTs, empowering intelligent data analytics and real-time decision-making, thereby laying the groundwork for unprecedented network efficiency and performance.
- Moreover, Specific Objective 2 (SO2) underscores the project's commitment to constructing a federated, graph-based NDT capable of accurately representing the intricate dynamics of highly dynamic and complex network scenarios. By establishing this digital sandbox for network planning, management, and control, 6G-TWIN paves the way for enhanced operational agility and adaptability.
- Simultaneously, Specific Objective 3 (SO3) drives the project's efforts towards implementing a robust modelling and simulation framework. This framework serves as a cornerstone for accurately portraying networked environments and rigorously testing the functionalities of the envisioned 6G architecture.
- Ultimately, as the culmination of its efforts, 6G-TWIN aims to materialize Specific Objective 4 (SO4) by testing, validating, and demonstrating the transferability of its solutions. Through the development of dynamic demonstrators catering to tele driving and energy efficiency use cases, the project aims to showcase the practical impact of its architectural foundation on real-world network scenarios, heralding a new era of connectivity and innovation.

Embedded within the core of the 6G-TWIN project lies a foundational framework driven by specific objectives aimed at revolutionizing the architecture of future 6G systems.

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1.1.2 Deliverable objectives

The objectives of the deliverable are the following:

- Specify the evaluation objectives, including the identification of components, solutions or applications to be evaluated, the definition of the type of results to be delivered, and the specification of the evaluation methodology, including references to relevant international standards.
- Specify the hardware and the software necessary for the tests.
- Define the KPIs of the project for measuring the impact and performances of 6G-TWIN, including social impact criteria where applicable.
- Define the KPIs for evaluating the use cases, with a focus on quantitative performance measures.
- Develop a detailed specification of the test scenarios and test cases.
- Define evaluation criteria such as ultra-low latency, extreme mobility, ultra-high data rates, integration of end-terminals, controlled security, and space applications.
- Ensure alignment with related tasks and work packages and provide a consolidated view of partner contributions.

This deliverable completes the **Milestone 2** of the 6G-TWIN project: *Evaluation methodology, requirements and associated KPIs.*

1.2 Relation to other activities in the project

Deliverable 5.1 (D5.1) is the result of Task 5.1 (T5.1), which aims to specify the methodology, data, and requirements, including KPIs, for evaluating the performances and impact of the 6G NDT and the new AI-based communication paradigms. Task 5.1 is the baseline for all WP5 and is connected to all WP5 tasks.

The inputs of the task will be the definition, and the validation of the use cases implemented in WP4. The outputs of this task will be used by WP3 and WP4, which both are underpinned by the KPIs developed in this task. The relationships between WP5 and the other WPs of 6G-TWIN are depicted in Figure 1.

Task 5.2 will be devoted to the computation of the KPIs and process the test cases defined and specified in T5.1. Task 5.3 will leverage on the results of Task 5.2 to propose new paradigms and solutions for the reengineering of the 6G-TWIN architectural solutions designed in WP1 and WP2.

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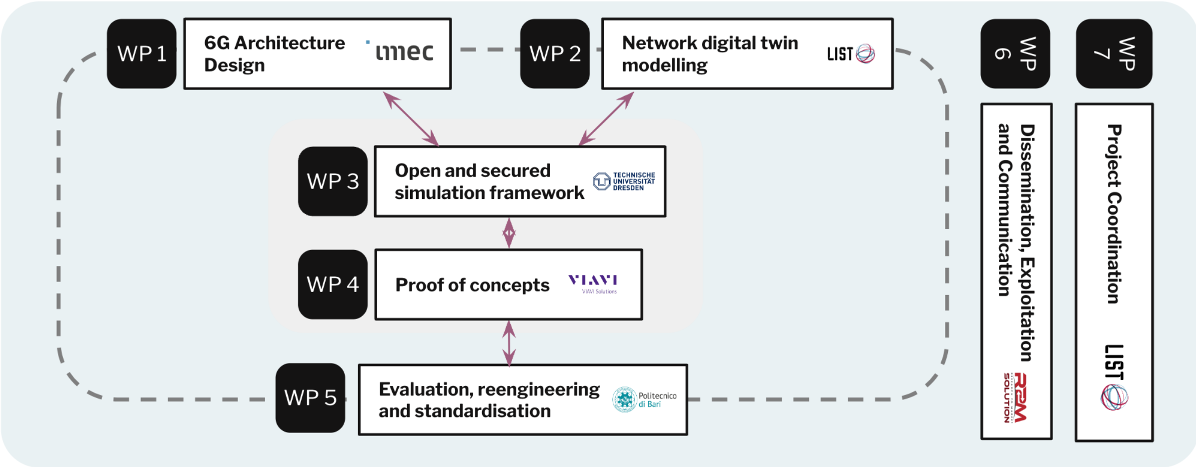

Figure 1 6G-TWIN PERT chart.

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1.3 Report structure

This document specifies the evaluation objectives, the framework, requirements, and the KPIs for evaluating the performances and impacts of the 6G NDTs and the new AI-based communication paradigms. To this aim, the document recalls all the outcomes of the projects yet listed in the 6G-TWIN Grant Agreement and explains the WP tasks, and milestones where they will be described. Moreover, the KPIs that will be computed for evaluating the use cases are defined with the related the test scenarios and test cases.

Section 2 introduces architectural concepts specifically designed for 6G NDT and the evaluation state of the art. Moreover, the ITU-T reference recommendation is introduced and forms the basis to assess NDTs.

Section 3 introduces the FESTA V-process as main evaluation methodology and describes all the phases with their links to 6G-TWIN tasks and WPs. The evaluation is focused on the KPIs computation and the NDT capability level assessment. To this aim, three types of KPIs are singled out and described in this section: 1) the project KPIs, typically qualitative, that are reported in the Grant Agreement and can be evaluated globally at specific project milestones and deliverables; 2) the KPIs computed by the use cases, that are quantitative and need detailed description by listing formulas, data, software and hardware components; 3) the KPIs and the procedure for the complementary sociological evaluation that are proposed to assess stakeholder perceptions regarding the usefulness and impact of the NDT approach. Finally, the Research Questions to be answered in the project are determined and linked to their specific KPI family.

Section 4 describes the evaluation methodology for use case 1: **Teleoperated or remote driving** refers to autonomous vehicles controlled or driven remotely by a human or a cloud-based autonomous software agent**.** The following concepts are described: 1) the objectives of the implemented use case; 2) the definitions of the KPIs to be computed by specifying the measured quantitative evaluation indices with the related formulas; 3) the test scenarios and the test cases; 4) the hardware and software components necessary to obtain the described KPIs.

Analogously, **Section 5** describes the evaluation procedure for the use case 2: **Energy savings in dense deployments** to reduce the network's energy consumption in dense deployments, where multiple base stations (BSs) with different coverage and performance capabilities are used in the same area. The following concepts are described also for this use case: 1) the objectives of the implemented use case; 2) the definitions of the KPIs to be computed by specifying the measured quantitative evaluation indices with the related formulas; 3) the test scenarios and the test cases; 4) the hardware and software components necessary to obtain the described KPIs.

Finally, **Section 6** summarizes the findings and contributions of the report. This section reflects on the objectives outlined in the introduction, evaluates the success in achieving them, and discusses the implications for future work or further research needed to advance the 6G-TWIN project.

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1.4 Contribution of partners

The following table present the contributions from all the partners into the deliverable.

Table 1 Partners contributions to the D5.1 deliverable.

Partner	Sections	Contributions
POLIBA	**1, 2, 3, 6**	Introduction, State-of-the-art, NDT Evaluation Methodology, Conclusions
LIST	**4**	Specification of Use Case 1
IMEC	**5**	Specification of Use Case 2
ACC	4 and 5	Description of the Accelleran dRAX and its relationship with the use cases.
R2M	3.2	R2M proposed the complementary socio-evaluation approach and will lead its implementation in the coming months of the project.
VIAVI	4.4.2,5.4.2	Description of VIAVI TeraVM software
TUD	4.4.2	Simulation tools for use case 1

***Bold** numbers represent section technical leaders*

1.5 Deviations from the GA

Not applicable.

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2 NDT Evaluation objectives

2.1 The NDT architecture

To support the specification of the research questions and the evaluation methodology, Figure 2 recalls the reference architecture defined by ITU-T Y.3090 [1], which has been used as a baseline for the architectural work performed in this project, as described in Deliverable 1.1 [2]. This architecture is composed of three layers:

- **Physical network:** The lower layer contains all elements related to the physical network, including real and virtual elements.
- **Digital Twin layer:** This middle layer is what defines the NDT functions and handles the data and models related to the upper and lower layers. It contains the unified data repository, unified data models and NDT entity management.
- **Application layer:** The application layer creates NDT instances in the NDT layer based on the application's requirements. It also sends control updates to the physical network through the NDT.

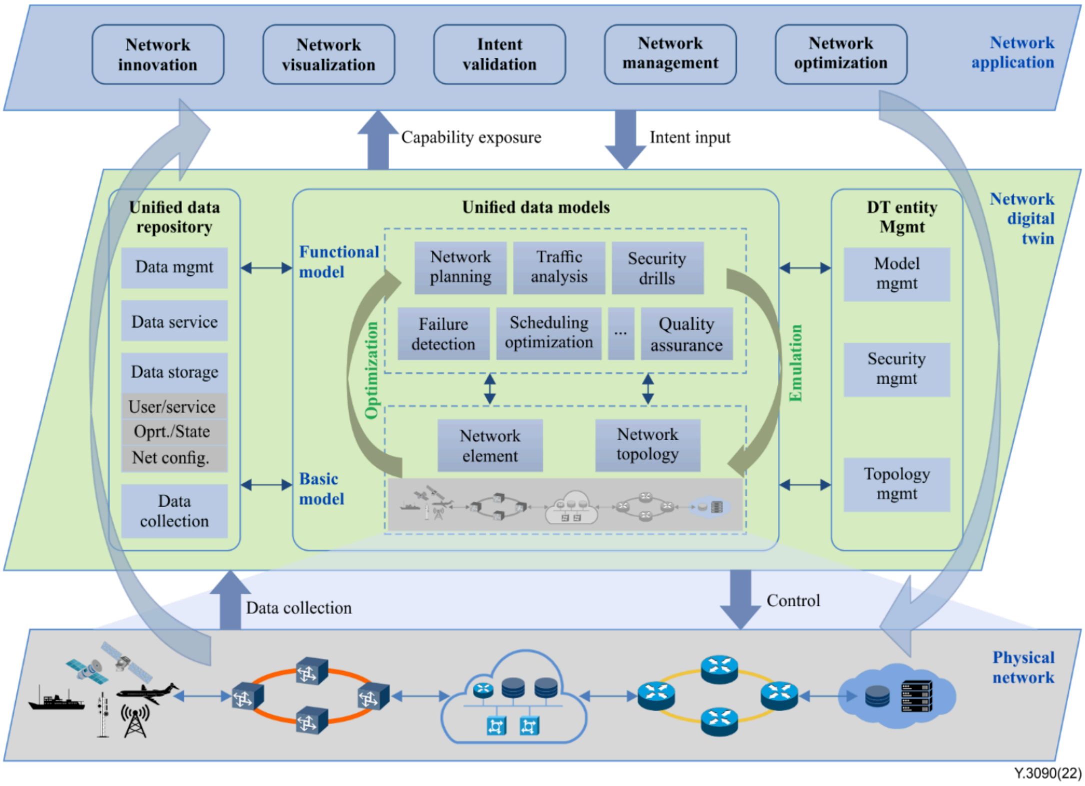

Figure 2 ITU-T high-level architecture.

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This architecture is enabled by the following four elements: data, mapping, model, and interface.

- ***Data*** serves as the foundation, providing a unified repository for accurate and up-to-date information, which is tackled in detail in WP2 of this project.
- Real-time interactive ***mapping*** is what distinguishes NDT from traditional network simulations, relying on the real-time data exchange between physical and virtual systems.
- ***Models*** within the virtual network reflect the key basic and functional features of the twinned physical entities, which are further detailed in this document.
- Standardized ***interfaces*** ensure compatibility and scalability, with southbound interfaces linking physical and virtual networks and northbound interfaces facilitating information exchange between virtual networks and network applications.

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2.2 Evaluation state of the art

The first objective of the evaluation is to judge whether one specific NDT system can meet the application and use case requirements. To achieve this aim, NDT's capability levels should be clearly defined based on ITU-T Y.3090 [1] where they are classified into five levels, as described in the next Section.

It is useful for analysing, diagnosing, emulating, and controlling the physical network based on data, model, and interface to achieve a real-time interactive mapping between a physical network and a digital twin network.

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs).

The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions, as well as issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

Network evaluation is important in assessing a communication network performance, reliability, and efficiency. Important metrics, including throughput, latency, packet loss, and jitter must be evaluated to ensure the network satisfies the required performance criteria. It can be performed in many ways, including real-life experiments and measurements, using large-scale or smaller, laboratory scale equipment like emulators. In many low TRL projects, but also for scalability reasons, network evaluation may rely on simulation tools such as OMNeT++ [3], NS2/3 [4] and advanced testing environments to analyse various aspects of network traffic, configuration, and overall architecture. This allows for the optimisation of resource allocation, through the identification of bottlenecks, and ensuring high-quality user experiences in complex environments like 5G, IoT, and large-scale data centres.

Dealing with NDT evaluation may provide significant jump in the development of the evaluation process as it provides a real-time, virtual replica of a physical network that helps simulate network conditions, predict performance under different configurations, and test various scenarios without impacting the real network [5]. The general concept of NDT evaluation is to ensure that the digital model accurately reflects the actual network and delivers precise insights for optimization and future network planning.

To evaluate NDT performance, we need to identify three main requirements:

- ***Fidelity*** shows how accurate the metrics from performance models are with the physical network.
- ***Efficiency*** has two parts: performance models can be faster than the real-time physical network. The other is that models should be easy to deploy and consume rational resources.
- ***Flexibility*** means that the NDT should be flexible to provide service on-demand according to various network applications by selecting a variety of cross domain resources on demand, flexibly collecting and storing data, combining different data models and interacting with other DTs.

When topology, configurations, or mechanisms change, the model must also accurately generate performance metrics [5]. Therefore, performance evaluation between DT models and the corresponding physical objects is needed. Many efforts are made to study model update strategies or communication mechanism to keep synchronization. For example, Talkhestani et al. [6] adopted an Anchor-Point method to realize variance detection between DT models and the corresponding physical objects. Wei et al. proposed a consistency retention method for CNC machine tool DT models under the consideration of performance attenuation for wear and other damages [7]. Yu et al. proposed a real-time model updating strategy based on an improved Gaussian particle filter and Dirichlet process mixture model to realize complex system health monitoring [8].

When it comes to the NDT, several metrics are used to assess the performance of NDTs. Sai et al. [9] divided these metrics into two categories: model metrics and Network metrics. Model metrics include number of twins, age of information, system cost, and accuracy. Network metrics include latency/delay cost, packet loss ratio or routing failure rate, and link utilization. Analysis can be based on calculation, simulation models or an AI algorithm [10]. Simulation Models predict network behaviour based on various parameters, such as topology, traffic, and buffer sizes. Simulators such as OMNeT++ and NS-2/3 are often used in digital twin evaluations to assess path delay, throughput, and flow latency metrics [10]. AI-based methods could be used in NDT evaluation to predict system behaviours and optimize performance. For instance, neural networks, such as deep learning models, can estimate network delays and throughput accurately [10].

DT is also introduced as a key enabling technology for deploying mobile communication services for the sixth generation (6G). In fact, 6G networks will be the presence of hundreds of billions of connected end devices that will generate a huge amount of data traffic. In AI-native 6G networks, access to real-world data is crucial. However, obtaining a suitably rich dataset that reflects a diverse set of network operating conditions is not always possible. Synthetic data is annotated information that a simulation running in NDT generates and can be used to complement real-world data [11]. Evaluating this kind of network is essential for modelling the behaviour of such massive systems while considering the complex interactions among devices, users, and infrastructure. 6G network uses DT and the information provided by the NDT to anticipate and test various network conditions in advance, evaluate various network deployment scenarios and algorithms, and analyse various performance improvement methods [12].

The European Smart Networks and Services Joint Undertaking (SNS JU) [13] supports numerous 6G projects, all of which adhere to various evaluation methods. For example, CENTRIC outlines the methodology used to evaluate AI-enabled air interface technologies for future 6G networks, focusing on defining Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) to assess both performance and societal impacts [14]

Another project is TARGET-X [15], which focuses on implementing and evaluating beyond 5G use cases across various industrial verticals. To assess the value of these use cases, TARGET-X employs a Methodological Assessment Framework that uses KPIs and KVIs to quantify their technical, economic, and societal impacts.

The 6G-SHINE [16] project, which is also part of the SNS JU initiative, focuses on developing advanced short-range communication solutions for extreme environments. 6G-SHINE applies

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a comprehensive Proof of Concept (PoC) Evaluation Methodology, which evaluates key technology components (TCs) through carefully selected KPIs to assess its innovations. These include low-latency emulation, jamming resilience, and centralized radio resource management. Another project, named FIDAL [17] aims to conduct beyond 5G field trials to explore and validate innovative use cases across multiple verticals. The project follows a structured methodology involving KPIs and KVIs to measure the success of these trials, ensuring both technical performance and societal impact are assessed.

The previous mentioned related projects inspired the subsequent definition and identification of appropriate KPIs for the project and the 6G-TWIN use cases.

2.3 ITU-T Y.3091 Recommendation

With the evolution of 6G networks, NDT introduces a digital layer that allows for more detailed and efficient evaluation. This enables better analysis and decision-making and reducing costs associated with traditional methods.

The ITU published the ITU-T Y.3091 Recommendation [18], which specifies the capability levels and evaluation methods for Digital Twin Networks (NDT) and provides a framework for assessing their maturity and functionality. The recommendation defines five NDT capability levels:

- **L1 Representation level:** NDT can realize one-way mapping from the physical network to the virtual twin.
- **L2 Interaction level:** Based on the representation level (L1), the control channel from the virtual twin to the physical network is added.
- **L3 Prediction level:** Based on the interaction level (L2), the virtual twin can analyze data characteristics and trends based on the collected physical network data and can use strategies and algorithms to infer indicators.
- **L4 Optimization level:** Based on the prediction level (L3), the virtual twin cannot analyze and predict the performance and future trends of the physical network but can also use AI algorithms, expert knowledge, big data analysis and other intelligent technologies.
- **L5 Autonomy level:** As the ideal goal of NDT, the virtual twin and the physical network live in symbiosis with each other.

After the definition of the five levels, the objectives of the evaluation are singling out the set of evaluation areas and the related performance indices by following the SMART principles:

- Specific: Targeting a particular area for improvement.
- Measurable: Quantifying, or at least suggesting, an indicator of progress.
- Assignable: Defining responsibility clearly.
- Realistic: Outlining attainable results with available resources.
- Time-related: Including a timeline for expected results.

To assess the level achieved by the NDT, the ITU-T Y.3091 Recommendation [18] defines the following set of dimensions:

- Data service
- Digital Twin modelling
- Interactive mapping
- Intelligence user experience
- Trustworthiness

Each dimension is evaluated by using a specific set of evaluation indicators with dedicated capability levels. In Table 2, the dimensions and the evaluation indicators are shown with the requirements of each capability level of evaluation indicator to achieve a specific capability level of NDT.

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Table 2 ITU-T Y.3091 Dimensions, evaluation indicators and capability requirements

Dimension	Evaluation indicators	NDT L1	NDT L2	NDT L3	NDT L4	NDT L5
Data service	Data richness	≥L1	≥L2	≥L3	≥L4	=L4
	Update frequency	≥L1	≥L2	≥L3	≥L4	=L5
	Compatibility	≥L1	≥L2	≥L2	≥L3	=L4
	Data quality	≥L1	≥L2	≥L2	≥L3	=L3
	Data service interface	≥L1	≥L1	≥L2	≥L3	=L3
	Efficiency	≥L1	≥L1	≥L2	≥L3	=L3
Digital twin modelling	Basic model integrity	≥L1	≥L2	≥L3	≥L3	=L4
	Functional model integrity	≥L1	≥L2	≥L3	≥L4	=L5
	Standardization	≥L1	≥L2	≥L3	≥L4	=L4
	Interfaces	≥L1	≥L2	≥L3	≥L4	=L4
	Update frequency	≥L1	≥L2	≥L3	≥L4	=L5
	Flexibility	≥L1	≥L2	≥L3	≥L3	=L4
	Efficiency	≥L1	≥L2	≥L3	≥L4	=L4
Interactive mapping	Mapping mode	≥L1	≥L1	≥L2	≥L2	=L3
	Real to virtual mapping	≥L1	≥L2	≥L3	≥L4	=L4
	Virtual to real mapping	≥L1	≥L2	≥L3	≥L4	=L5
	Interface richness	≥L1	≥L2	≥L3	≥L4	=L5
	Interaction quality	≥L1	≥L2	≥L3	≥L4	=L5
Intelligence	Orchestration	≥L1	≥L1	≥L2	≥L3	=L3
	Analysis	≥L1	≥L2	≥L3	≥L3	=L3
	Decision-making	≥L1	≥L1	≥L2	≥L2	=L3
	Instruction execution	≥L1	≥L2	≥L2	≥L3	=L3
	AI/ML model training and inference	≥L1	≥L1	≥L1	≥L2	=L3
	Model quality	≥L1	≥L2	≥L2	≥L3	=L4
	AI/ML model explainability	≥L1	≥L2	≥L3	≥L3	=L4
User experience	Visualization scope	≥L1	≥L2	≥L3	≥L4	=L5

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Dimension	Evaluation indicators	NDT L1	NDT L2	NDT L3	NDT L4	NDT L5
	Data visualization mode	≥L1	≥L2	≥L3	≥L3	=L3
	Entity visualization mode	≥L1	≥L2	≥L3	≥L3	=L4
	Interaction	≥L1	≥L2	≥L3	≥L3	=L4
Trustworthiness	Security	≥L1	≥L2	≥L3	≥L3	=L4
	Privacy	≥L1	≥L2	≥L3	≥L3	=L4
	Reliability	≥L1	≥L2	≥L3	≥L3	=L4
	Resilience	≥L1	≥L2	≥L3	≥L3	=L4

The synthetic capability level of the NDT is recursively calculated by the formulas defined in [18] by associating an evaluation indicator to each KPI defined and computed in the use cases.

In the context of 6G-TWIN, our objective is to reach, as much as possible and for the various dimensions indicated above, the L4 optimization level overall. This reference will serve as a baseline for the upcoming work within WP5.

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3 Evaluation methodology

This section describes the procedure that the 6G-TWIN project will follow to perform the evaluation.

The methodology begins with the Research Questions to be answered in the project to meet the defined objectives. This will be accompanied by the development of innovative and appropriate experimental procedures to collect the data required to answer these questions and the development of a structured evaluation plan to ensure reliable and valid results are achieved from the use case testing.

To achieve these goals, the methodology follows the idea and approach of the **FESTA V-process methodology**, described in the FESTA Handbook [19], initially developed for planning, preparing, executing, analysing, and reporting Field Operational Trials. Even if this project does not have any formal trial and aims at achieving a relatively low TRL level (i.e., 4-5), we believe that the two use-cases/demonstrators targeted by the project will drive a large part of the evaluation work – which results in a similar approach. The three main pillars of this methodology will be followed in this project with the required modifications to address the goals of 6G-TWIN as follows:

i. Prepare
ii. Usage
iii. Evaluation and Impact.

Figure 3 shows the "FESTA V" approach that is used in the 6G-TWIN project and the steps that need to be carried out. The steps of the evaluation procedure are presented in the form of the "V" diagram.

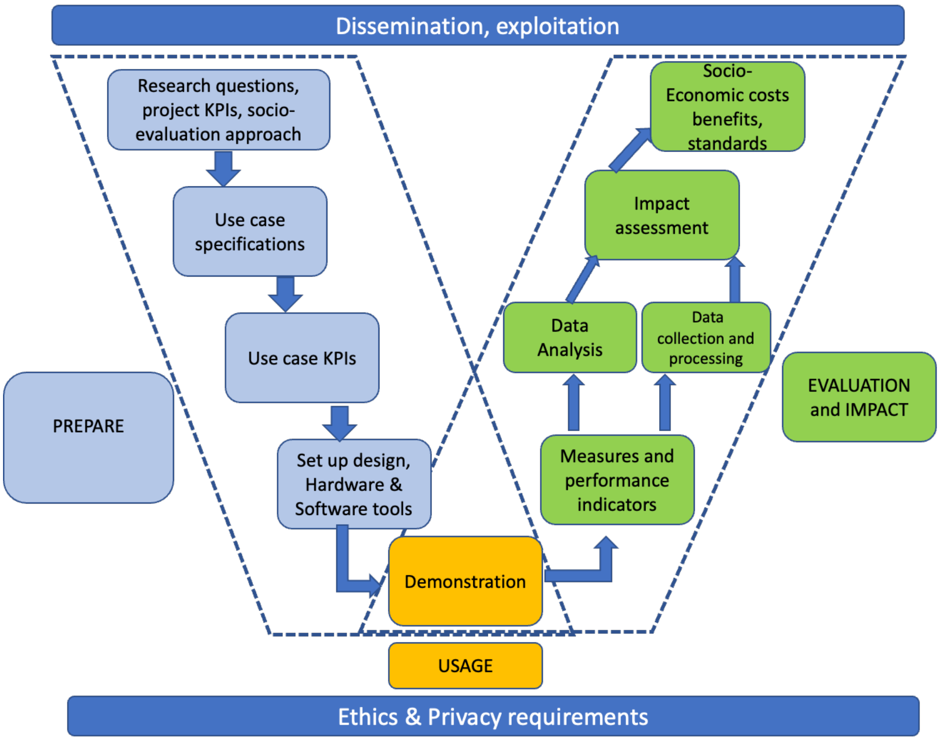

Figure 3 "FESTA V" approach for 6G-TWIN

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During the **PREPARE** phase, the functions to be tested are identified, considering the KPIs to be determined and the data, software, and hardware components to be used during the tests.

The **PREPARE** phase is the primary objective of T5.1 and is described in this deliverable in Sections 4 and 5 devoted to the use cases specifications. In detail, the following four steps have been performed during task T5.1:

- **Step 1:** The first step is devoted to specifying the research questions, with their objectives and evaluation areas. To this aim, the project qualitative KPIs have been defined by recalling the GA specifications.
- **Step 2**: In the second step the use cases and the relative objectives have been described.
- **Step 3:** In the third step, the use cases KPIs have been specified in relation to the use case objectives. The formulas to compute the KPIs and the required data have been described.
- **Step 4:** In the last step of the prepare phase the test scenarios and the test cases for the introduced KPI have been described by specifying the necessary hardware and software components.

During the **USAGE** phase, the data for the KPIs will be collected. This phase starts with Task 5.2 and will happen in parallel to the work done in the other WPs, generated the data.

In the **EVALUATION AND IMPACT** phase, the KPIs are computed and linked to their evaluation indicators to assess the capability level of each dimension and of the NDT. Finally, the impact assessment will be performed, and the socio-economic aspects will be analysed. These phases will be performed in Task 5.2 and will also include tasks from WP3 and WP4.

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3.1 Project research questions and KPIs overview

To achieve the project objectives, for each WP of 6G-TWIN, several project level KPIs have been preliminarily defined in the Grant Agreement in relation to the project objectives and research questions.

The KPIs described in the Grant Agreement are mostly qualitative and will be evaluated globally at a specific project milestone. In Table 3, the related milestones and deliverables are indicated for each qualitative KPI. Conversely, the KPIs determined by the use cases are quantitative and will be specified in successive sections.

As mentioned in Section 3, most of the KPIs will be linked to their evaluation indicators during the EVALUATION AND IMPACT phase to assess the capability level of the NDT.

Table 3 Project level KPIs

WP	KPI	Related Milestones & Deliverables
WP1	**KPI1.1**: Provide a federated and AI-native network reference architecture that integrates multiple NDTs for real-time data analytics and decision-making across at least three network domains.	D1.1 - 6G-TWIN architecture and technical foundations (initial) M6 MS 1 - 6G architecture and NDT initial requirements – M6 D1.4 - 6G-TWIN architecture and technical foundations (final) – M36
	KPI1.2: Achieve the improvements proposed to the KPIs associated with the use-cases compared to a 5G Service Based Architecture and baseline techniques from state-of-the-art research.	D5.2 - Evaluation deployment report – M32 MS 5 - Proof of Concepts implemented and evaluated – M32
	KPI1.3: Provide at least three AI-based NF/NS for data analytics or/and decision-making to optimise network performance per use case.	D2.3 - Functional models (initial) – M16 MS 4 - Release of the federated simulation framework and models – M27 D2.5 - Functional models (final) – M36
	KPI1.4: Guarantee security both during data collection and against malicious attacks, while ensuring a performance penalty of at most 10% in terms of metrics such as network latency and computation speed.	MS 4 - Release of the federated simulation framework and models – M27 D1.4 - 6G-TWIN architecture and technical foundations (final) – M36
	KPI1.5: Have regular links with at least two open network community working	

WP	KPI	Related Milestones & Deliverables
	groups (WGs) (e.g., O-RAN, ETSI-ENI) to support the definition of an OCCA for 6G.	D6.5 - Plan for dissemination and exploitation including communication activities – M36
	KPI1.6: Organise joint activities with at least three projects already funded under SNS JU Stream C or D (2022), including joint papers, workshops and events.	D5.4 - Standardisation – M36
WP2	**KPI2.1**: Provide an NDT that supports the representation and operation of a real network.	D1.1 - 6G-TWIN architecture and technical foundations (initial) – M6 MS1 - 6G architecture and NDT initial requirements – M6 D1.4 - 6G-TWIN architecture and technical foundations (final) – M36
	KPI2.2: Ensure the completeness of the basic model representing the identified use case: covering all the necessary assets and topology.	D2.2 - Basic models (initial) – M16 MS4 - Release of the federated simulation framework and models – M27 MS5 - Proof of Concepts implemented and evaluated – M32 D2.4 - Basic models (final) – M36
	KPI2.3: Ensure the completeness of the functional models, covering at least all the necessary functions	D2.3 - Functional models (initial) – M16 MS4 - Release of the federated simulation framework and models – M27 MS5 - Proof of Concepts implemented and evaluated – M32 D2.5 - Functional models (final) – M36
	KPI2.4: Be involved in the standard description of network elements for DT and the FiWare Smart data schema	D2.3 - Functional models (initial) – M16 D2.2 - Basic models (initial) – M16 MS4 - Release of the federated simulation framework and models – M27 D2.4 - Basic models (final) – M36 D2.5 - Functional models (final) – M36
	KPI2.5: Support the following three operations: Network planning & what-if analysis, Network management and control, Network traffic analysis.	D2.3 - Functional models (initial) – M16 MS4 - Release of the federated simulation framework and models – M27 D2.5 - Functional models (final) – M36

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WP	KPI	Related Milestones & Deliverables
WP3	**KPI3.1**: Design a platform-independent solution that allows the integration of new frameworks by implementing an abstract interface.	D3.1 - Federated simulation framework – M27 MS4 - Release of the federated simulation framework and models – M27
	KPI3.2: Achieve a federation overhead of no more than 15% for moderately complex simulations and less for complex ones.	
	KPI3.3: Ensure that the federation interface is available for at least two programming languages from the domains of both compiled and of interpreted languages.	
	KPI3.4: Provide a reference implementation of the federation interface as Open Source software.	
WP4	**KPI4.1**: Build two different demonstrators (energy-saving and teledriving) to trigger the solution developed within the project	D4.1 - Setup of the 6G-TWIN Demonstrators – M25 D4.2 - Testbed findings and data analytics – M32 MS4 - Release of the federated simulation framework and models – M27 MS5 - Proof of Concepts implemented and evaluated – M32 D5.2 - Evaluation deployment report – M32
	KPI4.2: Define two different deployment scenarios with extreme connectivity constraints impacting the teledriving demonstrator and ensure testbed setup is correct and provides full connectivity.	
	KPI4.3: Define three different deployment scenarios for the energy-saving demonstrator, ensure full interworking between the RIC tool and the DUT, validate scenarios triggering the 6G-TWIN ML and change messaging from x-/r-Apps.	
	KPI4.4: Provide a visual representation of the four most relevant KPIs for each use case and measure their impact on the 6G-TWIN's assets and how they can be optimised.	
WP5	**KPI5.1**: Develop at least two position papers containing business-driven feedback and recommendations for the 6G initiative and EU bodies.	MS5 - Proof of Concepts D5.2 - Reengineering solutions – M36 D5.4 - Standardisation – M36

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WP	KPI	Related Milestones & Deliverables
	KPI5.2: Consolidate and deliver an overview of the relevant WGs that can be addressed and influenced by 6G-TWIN	
	KPI5.3: Involve at least 10 industry leaders, government and regulatory bodies (including at national scale) in shaping standardisation efforts based on 6G-TWIN outcomes	
	KPI5.4: Influence two standardisation bodies as a result of industry recommendations on standardisation in T5.4.	
WP6	**KPI6.1**: Obtain feedback from industry experts involved in DEC activities (min. three round tables)	D6.5 - Plan for dissemination and exploitation including communication activities – M36
	KPI6.2: Provide a clear and consensual business case for each exploitable result (i.e. commonly developed and accepted by its co-owners).	

The KPIs listed in Table 3 are related to the corresponding research questions specified in the GA:

I. *The research is expected to design and develop an open, federated and AI-native network architecture for future 6G systems that integrates NDT to enable intelligent data analytics and decision-making in real-time.*
   KPI1.x (for x=1,…,6) are used to describe the advance of the state of the art concerning the open architecture and networking technologies.

II. *The research is expected to design a federated, graph-based NDT that accurately represents highly dynamic and complex network scenarios and serves as a sandbox for optimising network planning, management and control applications.*
   KPI2.x (for x=1,…,5) describe the federated, graph-based NDT and its main components represented by basic and functional models.

III. *Can the modelling and simulation framework implement an accurate, reliable, open and secured to represent a networked environment and test the functionalities of the proposed 6G architecture?*
   KPI3.x (for x=1,…,4) are used for evaluate how the simulation framework implement an accurate, reliable, open and secure networked environment to test the functionality of the 6G architecture.

IV. *Is the validation, testing and transferability of the solutions developed in 6G-TWIN guaranteed?*

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KPI4.x (for x=1,…,4) are defined to test, validate and facilitate the transferability of the solutions developed in the 6G-TWIN by two demonstrators supporting highly dynamic use cases, with two key focus areas: teledriving and energy efficiency:

V. *Does 6G-TWIN operation system support standardisation to ensure the interoperability, platform openness and operation harmonisation of future 6G-TWIN?*

KPI5.x (for x=1,…,4) are KPIs related to the standardization of the 6G-TWIN operation system to ensure the interoperability, platform openness and operation harmonization of future solutions.

VI. *Do 6G-TWIN solutions and visions provide industry with insights on innovative business models?*

KPI6.x (for x=1,2) provide innovative business models based on 6G-TWIN solutions and visions.

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3.2 Complementary socio-evaluation approach

In addition to the technical KPIs defined for evaluating the 6G-TWIN project that are introduced in the deliverable, a complementary socio-evaluation approach is proposed to assess stakeholder perceptions regarding the usefulness and impact of the Digital Twin (DT) approach introduced in the project. This qualitative assessment will provide insights into how end-users and key stakeholders involved in the two use cases (see Sections 3 and 4) perceive the benefits, usability, and potential barriers to adoption of Network Digital Twins (NDTs).

3.2.1 Objectives

The socio-evaluation aims to:

- Capture stakeholder feedback on the perceived usefulness, reliability, and added value of NDTs in the context of 6G.
- Identify potential adoption barriers and enablers from a user perspective.
- Complement the project's technical KPIs with qualitative insights from real-world implementation.
- Ensure that this evaluation remains complementary to ongoing surveys from related SNS JU projects, such as 6G4Society, avoiding redundancy while leveraging synergies.

3.2.2 Methodology

A semi-structured questionnaire will be developed and distributed to stakeholders involved in the use-case demonstrations. The survey will target:

- Technical experts (e.g., network operators, system integrators) to assess the practical feasibility and integration of NDTs.
- End-users (e.g., teleoperators, energy sector stakeholders) to gauge usability and perceived benefits.
- Regulatory and industry representatives to understand broader adoption concerns and potentially to feed standardisation activities to be conducted in T5.4.

The questionnaire will be circulated at a strategic point in the project timeline, ensuring that stakeholders have sufficient exposure to 6G-TWIN's NDT solutions before providing feedback. A draft of the questionnaire is presented in Annex 1.

3.2.3 Alignment with 6G4Society

6G-TWIN already contributes to the annual "Survey to SNS Projects" conducted by the 6G4Society CSA [20] which examines Key Value Indicators (KVIs) and social acceptance of 6G technologies.

To ensure complementarity, the questions in our socio-evaluation will:

- Focus specifically on the Digital Twin paradigm and its perceived value in the two use cases.

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- Avoid duplicating aspects already covered in 6G4Society's broader survey on 6G acceptance.
- Provide additional granularity on stakeholder experiences within the 6G-TWIN context.

3.2.4 Expected outcomes

The expected outcomes from the administered questionnaire are:

- A qualitative dataset that enriches the technical evaluation with real-world stakeholder perspectives.
- Insights to refine NDT implementations based on end-user feedback.
- Potential contributions to broader SNS JU discussions on the role of Digital Twins in 6G standardization and adoption.

This socio-evaluation will complement the performance-based assessment in WP5, ensuring a holistic evaluation of 6G-TWIN's impact.

The two next sections focus on the two project's use-cases, which will be further specified and implemented in WP4.

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4 Specification of Use case 1

4.1 Objectives of the use case

Teleoperated or **remote driving** refers to the concept where a vehicle is controlled or driven remotely by either a human operator or a cloud-based autonomous software agent. This innovative approach bridges the gap between autonomous driving and manual driving, leveraging advanced network and communication technologies [21].

The primary goal of teleoperated driving is to assist autonomous vehicles in navigating challenging situations they cannot handle independently. Additionally, this concept is gaining traction across various industries due to its potential to enable new services, such as teleoperated goods delivery, teleoperated taxis, and remote valet parking services.

Unlike fully autonomous driving, which requires numerous sensors and sophisticated algorithms like object identification, teleoperated driving with human operators can be realized with fewer resources. For instance, a vehicle's onboard camera can stream live video to a remote human operator, enabling them to assess potential hazards without the need for complex computing. Based on this video feed, the remote operator can send commands to the vehicle to ensure safe navigation.

However, the performance and safety of teleoperated driving are highly dependent on network conditions. Factors such as latency, end-to-end available bandwidth, packet loss, network availability, and reliability play a critical role. These conditions can vary significantly depending on the location, physical environment, and network load, impacting the overall efficacy of teleoperation.

To address these challenges, the 3rd Generation Partnership Project (3GPP) has specified stringent **requirements** for teleoperated driving use cases [22]. These include:

- Supporting a user-experienced data rate of up to **1 Mbps for downlink (DL)** and **20 Mbps for uplink (UL)** between the V2X application server and the user equipment (UE) at absolute speeds of up to 250 km/h.
- Ensuring **ultra-high uplink and downlink reliability of 99.999%** or higher for UE supporting safety-related V2X applications.
- Achieving **end-to-end latency of 5 ms** between the V2X application server and the UE for safety-related applications at speeds of up to 250 km/h.

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This use case focuses on two main objectives:

- Predictive power adaptation: This objective aims to optimize the downlink transmission power for teleoperating a robot dog over a private 5G network while maintaining SINR above a predefined threshold to meet QoS requirements. Using predictive coverage estimation from real-time and historical data, the system aims to dynamically adjust power to ensure stable, low-latency communication.
- Path planning and optimization: The goal is to transition from a controlled lab to a larger simulated area with real-world data, incorporating multiple remotely operated vehicles. Additional complexity will be introduced by integrating LEO satellites and UAVs to enhance connectivity, either as network infrastructure or active users. Using the 6G-TWIN architecture, the goal is to optimize path planning and communication links dynamically, ensuring resilient and efficient connectivity in large-scale deployments while providing insights into terrestrial 6G, satellite, and UAV-assisted networks.

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4.2 Definition of the used KPIs

This use case will contribute to the following project-level KPIs:

Table 4 Use Case 1 Contributions to Project KPIs

KPI	Contribution
KPI1.1	Couple at least two different simulators to demonstrate the feasibility and benefits of integrating multiple NDTs. Involve three different network domains: vehicular domain, aerial domain (UAVs, LEO satellites), and edge domain (edge infrastructure).
KPI1.2	Optimise the energy of the edge nodes by managing the sleep/wake up mechanism to achieve ~30% energy improvement.
KPI1.3	Define at least three AI-based functional models specific to this use case.
KPI2.1	Use a real private 5G network to achieve the first objective of this use case. Use real data provided by a mobile network operator to calibrate the large-scale simulation environment (second objective).
KPI2.2	Define basic models specific to this use case.
KPI2.3	Define functional models specific to this use case.
KPI2.5	Define and run what-if scenarios in the simulation framework
KPI3.1	Implement an abstract interface to couple multiple domain-specific simulation tools
KPI3.2	Obtain a federation overhead <15% for moderately complex scenarios.
KPI3.3	Federation interface available for compiled and interpreted language.
KPI3.4	Federation interface is open source.
KPI4.1	Full end-to-end connectivity for control and user traffic.
KPI4.2	Define two different deployment scenarios defined for this use case.
KPI4.4	Visualize four metrics among the ones defined in the next section.

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The use case will measure the following quantitative KPIs:

Table 5 Use Case 1 Quantitative KPIs

KPI Family	KPI	Definition
Response time	Packet delay (s)	$D_{total} = D_{prop} + D_{trans} + D_{proc} + D_{queue}$ D_{total}: total packet delay $D_{prop} = \frac{d}{s}$: propagation delay $D_{trans} = \frac{L}{R}$: transmission delay D_{proc}: processing delay D_{queue}: queuing delay
	Jitter (s)	$J_i = \lvert D_i - D_{i-1} \rvert$ J_i : jitter for the i^{th} packet D_i : delay experienced by the i^{th} packet D_{i-1} : delay experienced by the previous $(i - 1^{th})$ packet
Capacity	Datarate (bps)	$R = \frac{nr. of\ bits\ transmitted}{time\ taken}$
Reliability	Packet loss rate	$PLR = \frac{lost\ packets}{total\ sent\ packets}$
Compute	Edge node utilization	$U_{tot} = w_1 * U_{CPU} + w_2 * U_{Memory} + w_3 * U_{Storage} + w_4 U_{Network}$ w_1, w_2, w_3, w_4: weight factors based on resource importance U_{CPU} : CPU utilization U_{Memory} : memory utilization $U_{Storage}$: storage utilization $U_{Network}$: network utilization
Channel	Spectral efficiency (bps/Hz)	$SE = \frac{C}{B}$ C : channel capacity or achieved datarate B : channel bandwidth

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4.3 Specification of test scenarios and test cases

4.3.1 Scenario 1: Predictive power adaptation

This scenario focuses on teleoperating a single robot dog over a private 5G network consisting of one gNB in a **small-scale lab environment**. The primary objective is to optimize the downlink (DL) transmission power while ensuring that the average Signal-to-Interference-plus-Noise Ratio (SINR) remains above a predefined threshold to meet Quality of Service (QoS) requirements.

For this scenario, the network is assumed to have sufficient time-frequency resources to simplify the problem and to focus primarily on transmission power adaptation in the downlink. The system must ensure that latency and reliability constraints are met, potentially aligning with Ultra-Reliable Low-Latency Communication (URLLC) standards. These constraints are inherently tied to the SINR threshold, meaning that power adjustments must be made dynamically to maintain optimal performance.

To achieve this, the scenario adopts a **predictive approach** for coverage estimation. Before the robot dog begins moving, the system has access to a coverage map generated from real-time and historical network measurements collected from the lab network infrastructure. Based on past observations, the system aims to predict how coverage will evolve at specific locations as the robot dog moves. This predictive capability allows for pre-emptive power adjustments, helping to mitigate connectivity issues before they arise.

In a first step, the coverage prediction will be performed without the support of the simulation framework, relying solely on past data and real-time measurements. However, future iterations of the experiment may explore integrating the **6G-TWIN simulation framework** to refine and validate predictions, potentially improving the system's adaptability and accuracy.

By implementing a predictive transmission power adaptation strategy, this scenario leverages the 6G-TWIN architecture to ensure that the robot dog maintains stable and high-quality connectivity throughout its operation. This approach minimizes latency fluctuations and signal degradation, ultimately enhancing the effectiveness of teleoperation within the lab environment.

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4.3.2 Scenario 2: Path planning and optimization

This scenario extends the scope of the previous experiment by shifting from a controlled lab environment to a larger simulated geographical area for which real-world data is available. A potential location for this deployment will be selected, where existing infrastructure from an MNO could provide valuable network insights.

The focus here is on multiple remotely operated vehicles, each of which must plan and execute its movement paths while maintaining reliable connectivity. Unlike the previous scenario, where a single robot dog was teleoperated, this setup introduces additional complexity due to the presence of multiple teleoperated entities. The challenge lies in optimizing their communication links dynamically, ensuring continuous and high-quality connectivity throughout their journey.

A key aspect of this scenario is the inclusion of LEO satellites and UAVs as part of the system, which provide an additional layer of connectivity, complementing the terrestrial network and enabling seamless communication in areas with limited network coverage. In this scenario, UAVs could be considered as infrastructure elements or active users in the network:

- If UAVs are treated as infrastructure, they could function as relay nodes or network extenders, helping to enhance coverage and reduce communication delays for the vehicles below.
- If UAVs are considered users, they would behave similarly to the cars, requiring their own optimized communication paths and network resources. This approach introduces additional complexity but presents a more dynamic and innovative use case.

Given these considerations, the initial implementation will likely prioritize the most feasible approach, while acknowledging in project deliverables that the alternative configuration remains a potential future extension.

By leveraging the 6G-TWIN architecture to optimize path planning in a multi-vehicle, multi-layered network environment, this scenario aims to enhance connectivity resilience and efficiency in simulated large-scale deployments. The experiment provides insights into the interaction between terrestrial 6G, LEO satellites, and UAV-assisted networks, offering valuable lessons for real-world implementations.

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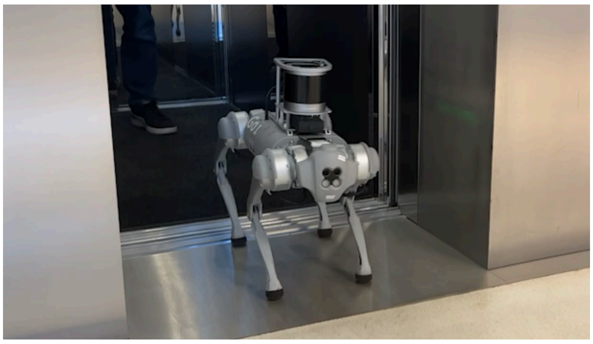
4.4 Specification of hardware, software and data for the tests

4.4.1 Hardware

Robodog “Go1 Edu Explorer 2”

The Go1 Edu Explorer Version from Unitree [23] is an enhanced iteration of Unitree Robotics' Go1 Edu quadruped robot, tailored for educational and research applications. Building upon the standard Edu model, the Explorer version incorporates additional features such as a 3D LiDAR sensor and an NVIDIA Jetson NX module. These enhancements enable advanced functionalities including dynamic obstacle avoidance, navigation planning, and sophisticated machine learning applications like gesture recognition and Visual Simultaneous Localization and Mapping (VSLAM). Designed to foster innovation and experimentation, the Go1 Edu Explorer offers a versatile platform for developers and researchers to explore cutting-edge robotics technologies. This platform will emulate a teleoperated vehicle in Scenario 1.



Private 5G Network Setup

A private 5G network testbed is equipped with a comprehensive range of hardware and software components for advanced experimentation and research. The reference set-up in the project will be provided by LIST in Luxembourg. It includes two USRP B210 and two USRP N310 software-defined radios (SDRs), an OAIBox for seamless OpenAirInterface (OAI) integration, and a Firecell setup based on the 7.2 functional split, providing a disaggregated and flexible RAN architecture. It operates within the licensed C-band spectrum (3800–3900 MHz) for real-world 5G experimentation. Additionally, the facility i ncludes a 5G signal generator, a spectrum analyzer, and various commercial off-the-shelf (COTS) SDRs such as BladeRF, further enhancing the testing capabilities. This setup will be used to operate Scenario 1.

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4.4.2Software

Simulation Tools

Among software, simulation tools are the most important tools for Scenario 2, besides the functional models for optimizing this scenario. Several types of simulation software (simulators) are needed to run the scenario.

- A RAN simulator is needed to simulate the communication between the different participants, especially between the vehicles and the gNBs. Examples for RAN simulation software are OMNeT++, ns-3, and VIAVI TeraVM AI RAN Scenario Generator. Such simulators can often be extended by libraries. For instance, in use case 1, OMNeT++ can be extended by Simu5G.

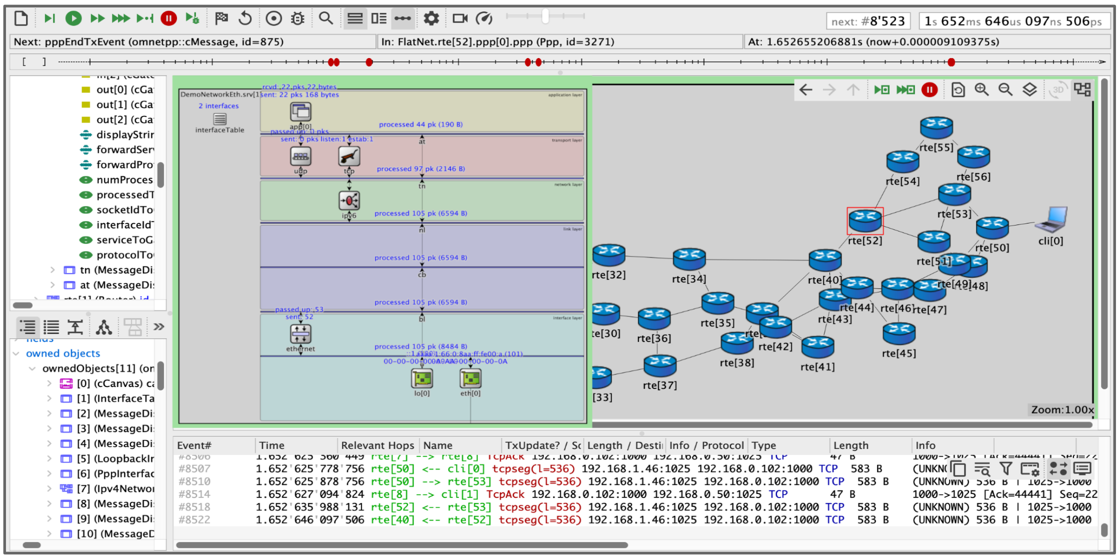

Figure 4 OMNeT++ INET Framework

- A mobility simulator is needed to get realistic paths of the vehicles in the scenario. Eclipse SUMO [24] is the most well-known mobility simulator, which allows to import maps from OpenStreetMap to simulate vehicles driving on roads that also exist in the real world. Additionally, different vehicle types and driver models (car following models) can be selected to simulate different types of road users. SUMO provides an interface that can be used to couple it to other simulators, it is called TraCI (traffic control interface).

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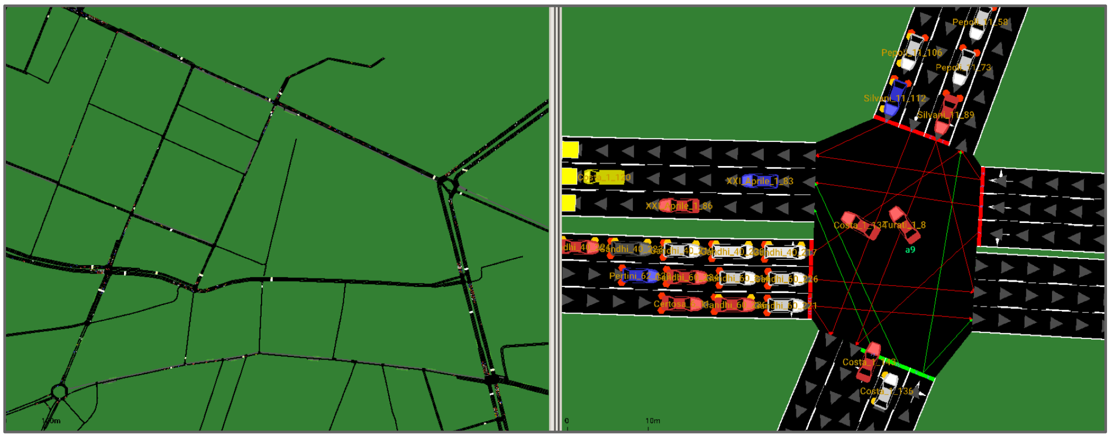

Figure 5 SUMO

- A UAV simulator, e.g. AirMobiSim, supports the simulation of an arbitrary number of UAVs. Furthermore, it provides the mechanism of implementing mobility and energy models for different types of UAVs. The existing implementation of AirMobiSim supports two different types of mobility models, one is *linearmobility* where UAVs move in straight line pattern and the other one is *splinemobility* where the UAVs move in a spline shape given the waypoints, including curved and spiral shapes. AirMobiSim provides an open gRPC interface which allows it to be coupled with various network simulators.

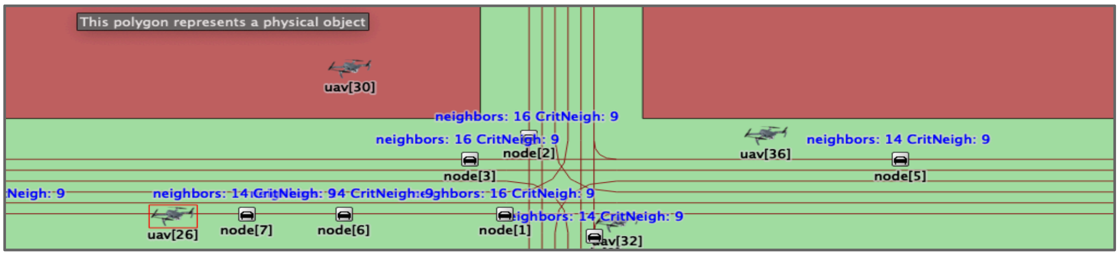

Figure 6 AirMobiSim

- A satellite simulator, e.g., space_Veins, models the satellites' mobility and communication with ground nodes. Since the ground nodes are moving, too, the simulator must support mobility models in two different domains, i.e., the space segment and the ground segment. The corresponding mobility models differ very much in terms of scale, speed, distance, and dimensionality. The space_Veins framework implements an approach that exploits the use of a Satellite Observer Position (SOP) to calculate the satellites' position relative to a well-defined point on Earth. This approach has the advantage that the position of all network nodes can be expressed as Cartesian coordinates, which are mostly used by networking models, in the same coordinate system while, at the same time, it does not require to project the satellites' position onto a map. As a result, it minimizes projection errors and provides high precision for relevant geometric measures for channel modelling, like relative azimuth angle, elevation angle and distance.

These different simulators must be coupled with the simulation framework that is developed in 6G-TWIN WP3. The purpose of that simulation framework is to couple different simulators at

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runtime to allow the interaction of these simulators, as the mobility should influence the communication and the communication the mobility.

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Acceleran dRAX - Intelligent RIC for O-RAN Innovation

Accelleran will propose the dRAX and its Telemetry Gateway for both Use Cases.

Accelleran dRAX is a cloud-native, fully virtualised RAN Intelligent Controller (RIC) designed to enhance O-RAN networks through AI-driven intelligence, automation, and programmability. It provides a flexible and scalable platform for managing and optimising RAN, integrating seamlessly with third-party xApps and rApps to enable advanced use cases. dRAX aligns with O-RAN principles by offering a disaggregated and vendor-agnostic approach to RAN control, improving flexibility, cost efficiency, and innovation potential in modern mobile networks.

The dRAX operates as a Near-Real-Time RIC, interfacing with O-RAN-compliant radios and network elements to provide real-time network control and optimisation. Its modular and open architecture supports a broad ecosystem, enabling the deployment of custom xApps and rApps tailored to specific network needs. The system is designed with AI/ML integration at its core, allowing intelligent RAN automation, including energy savings, traffic steering, and performance diagnostics. The system is further enhanced by a developer-friendly SDK and xApp Catalog, streamlining the development and deployment of custom applications for RAN optimisation.

The platform supports multiple O-RAN interfaces, ensuring seamless interoperability across the network. The E2 interface facilitates real-time control of the RAN components, while the A1 interface enables policy-based guidance from the Non-RT RIC. The O1 interface provides essential network management capabilities through the SMO. As a cloud-native solution, dRAX can be deployed in containerised environments, supporting flexible orchestration across private, public, or hybrid cloud setups.

One of the critical components supporting Accelleran dRAX in advanced telemetry and control is the Telemetry Gateway (TGW). This module plays a fundamental role in integrating multiple data sources (3GPP and non 3GPP compliant) and ensuring seamless telemetry flow within O-RAN environments. The TGW facilitates protocol adaptation by converting data formats between various O-RAN interfaces and external systems, ensuring compatibility with both legacy and modern network elements. Beyond protocol adaptation, the TGW aggregates and processes network telemetry in real time, feeding critical insights into xApps and rApps. Its deep integration with dRAX ensures that collected input from the Kafka bus is efficiently managed, allowing real-time message distribution across the network. The TGW is responsible for translating and regenerating telemetry data from Radio Units (RUs) and Distributed Units (DUs), making it a vital component in telemetry-driven RAN intelligence.

The TGW also provides northbound data egress for external AI/ML frameworks and supports southbound integration with O-RAN components. This functionality allows for seamless data exchange between different network elements and external analytics engines. Additionally, the TGW plays a crucial role in energy efficiency, feeding real-time performance and power consumption data into AI-driven network automation processes. This capability enhances power-saving xApps, ensuring that network operations remain both efficient and sustainable.

Accelleran dRAX is instrumental in enabling energy efficiency in RAN through AI-driven power management and adaptive cell operations. Its traffic steering and load balancing capabilities dynamically optimise network resources, ensuring optimal user experience and performance. The advanced telemetry and monitoring functionalities provide real-time insights via Kafka-based data distribution, enhancing network reliability and operational efficiency.

Within 6G-TWIN, dRAX serves as the backbone for the Telemetry and Control Framework, ensuring seamless data collection, processing, and distribution within the O-RAN ecosystem. Its AI-driven network optimisation enables predictive analytics for dynamic network reconfiguration and self-healing capabilities.

Figure 7 shows the internal components of the dRAX and RIC implementation and how they are integrated towards the platform. In the left side, the x/rApps environment contents a series of defined applications and the SDK to create them. The lower part describes the Near RT RIC with the interface's brokers. Above this is the SMO and Non-RT RIC section that integrates orchestration and configuration parameters within the integration of the dashboard control and its API. These two entities are interconnected by the internal dRAX databus that connect all the interfaces in a single bus for easy access and extension to third party integration. The TGW resides inside the data bus as a medium to harmonize data in the bus.

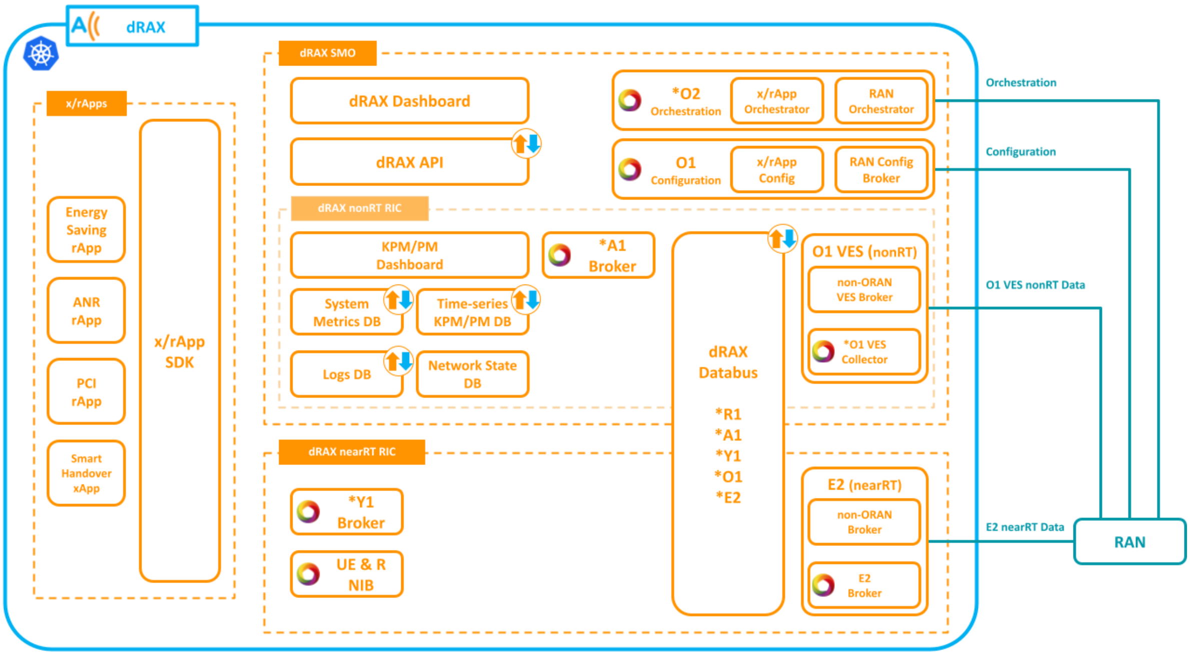

Figure 7 dRax Architecture

Finally, Figure 8 shows and example of the dashboard integrated with in the dRAX to show and present metrics of the system, included application specific metrics.

An example of the implementation and functionality of the dRAX and its telemetry can be found in the following video from the BeGREEN SNS project; (https://www.youtube.com/watch?v=Iauc_-ffb8E&ab_channel=SNSBeGREEN).

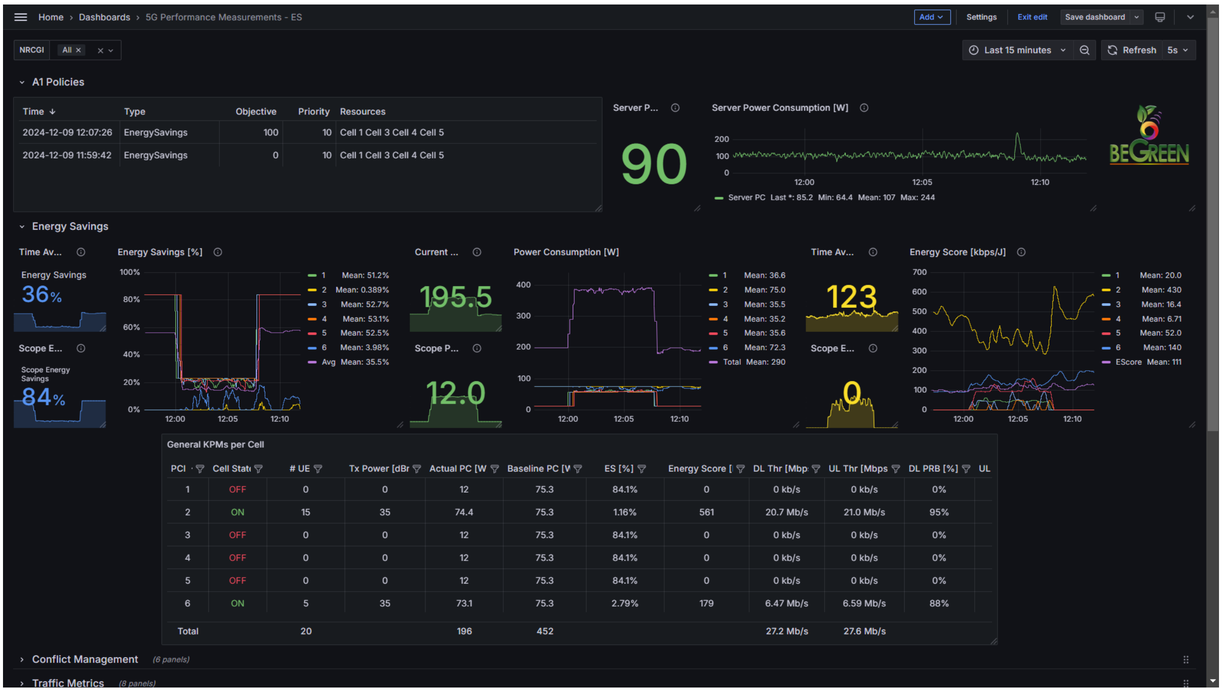

Figure 8 dRaxDashboard

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TeraVM Core Emulator

Core Emulator emulates 5G, EPC, and 3G core networks, including IP Multimedia Subsystem (IMS). It offers connectivity to multiple gNBs via N1/N2/N3 interfaces (5G) and connectivity to Internet/Application servers via N6 interfaces. It supports connections to thousands of base stations and millions of UEs. Core Emulator is a multi-threaded system for real-world traffic emulation and utilizes DPDK for fast packet processing, which provides the emulator with high-performance user-plane capability.

Core Emulator provides the ability to run different types of core network emulations, e.g. emulate a complete 5G Core in support of gNB Wraparound testing. Common 5G SA Core Emulator scenario tests N1, N2, N3 and N6 interfaces of a 5G RAN. Figure 9 shows test topology:

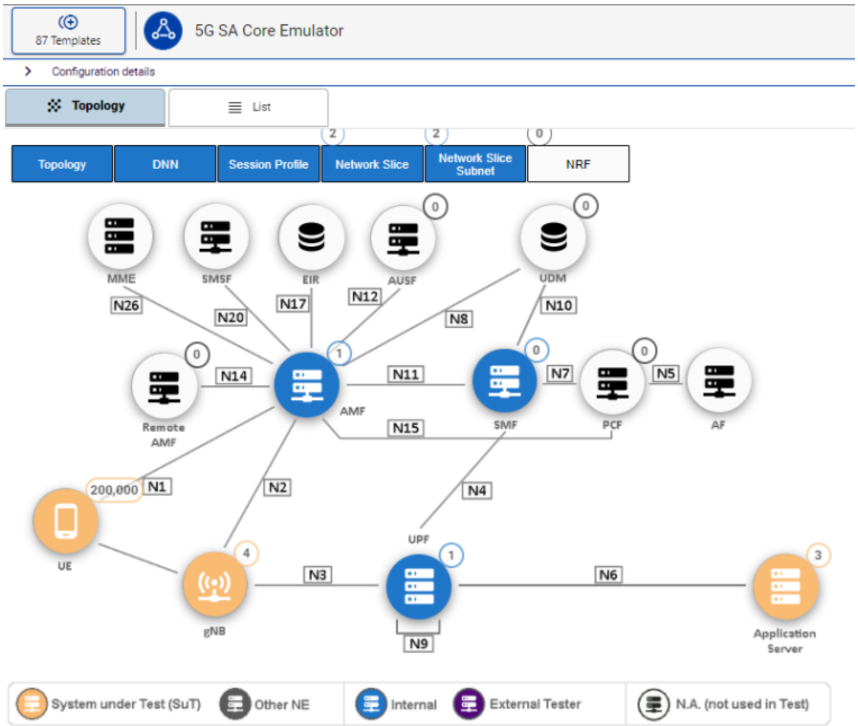

Figure 9 5G SA Core Emulator

The general configuration enables the user view and configure the following:

- Topology: This is typically focused on the number of each element e.g. number of AMFs, UPFs, etc.
- DNN (groups): Data Network Name.
- Session Profile: this includes network slice service type and differentiator to be used by the session profile as well as other information such as QoS information and Uplink/Downlink speeds.
- Network Slice: slices configuration
- Network Slice Subnet: parameters and values associated with the network slicing subnet(s).
- NRF: NRF parameters.

The elements in blue represent the emulated CORE, and each element on the map provides access to the corresponding parameters and values: AMF, SMF, and UPF.

The elements in orange represent the System Under Test (SUT), and they give access to the parameters associated with each such element.

- UE: Provides access to the values and parameters for N1 interface to the AMF.
- gNB: Provides access to the values and parameters for the N2 interface to the AMF and the N3 interface to the UFP.
- Application Server: Provides access to Internet services over the N6 interface.

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TeraVM CoreTest

TeraVM Core Test can be configured to be a Core network tester, a wraparound of individual network components, or a network element emulator. It is built upon a Ubuntu 64-bit OS cloud image deployed on a KVM host via uvtool and is a scalable system that produces highest performance for 36 or more cores + KVM with SR-IOV.

TeraVM Core Test emulation has sophisticated RAN Topology capabilities for 5G, 4G, 3G, 2G and Wi-Fi. It can emulate thousands of base stations, and millions of UEs, with state-of-the-art control-plane scenarios. TeraVM Core Test uses DPDK for fast packet processing, which provides the tester with a high-performance user-plane capacity. TeraVM Core Test is a multi-threading system for real-world traffic emulation.

Figure 10 presents a high-level view of the system architecture.

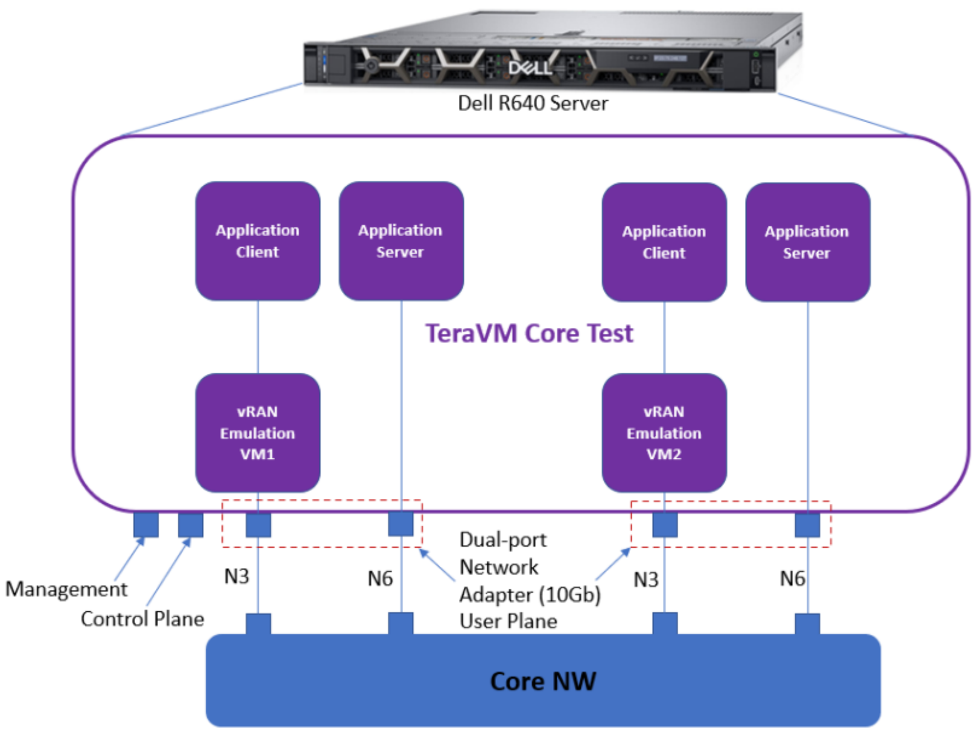

Figure 10 TeraVM CoreTest high level architecture

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Figure 11 shows typical 5G SA Core Wraparound Test topology.

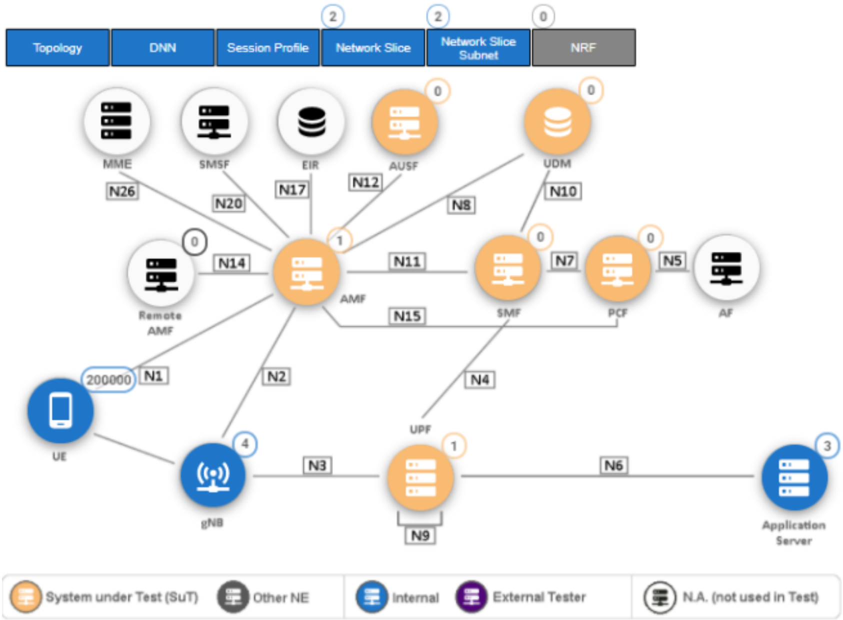

Figure 11 CoreTest 5G Core wraparound test

As this is a test of the 5G Core, the RAN is emulated. The map elements in blue represent the emulated RAN tester, and clicking on each element in the map provides access to the corresponding parameters and values:

- UE: provides access to the values and parameters for N1 interface to the AMF.
- gNB: provides access to the values and parameters for the N2 interface to the AMF and the N3 interface to the UFP
- Topology button and use the panel on the right-hand side, as described in the Configuring a Topology section.
- Application Server: provides access to Internet services over the N6 interface.

The map elements in orange represent the System Under Test (SUT), and clicking them provides access to the parameters associated with each such element. The values of these parameters must be appropriate for the SUT in question to ensure that a successful test can be executed.

Hardware Requirements

Both test and simulation systems have similar HW requirements which depend on the amount of UP traffic that needs to be generated. Following information is only a guideline and should be refined at a later stage when traffic requirements are defined.

- CPU: 36 or 48 Cores, 2.6GHz, Intel Xeon Gold or similar
- RAM: 64GB
- Network: 10G or 25G Intel NIC with DPDK and SRIO support
- Storage: at least 500GB

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5 Specification of Use case 2

5.1 Objectives of the use case

Use case 2 focuses on reducing the network's energy consumption in dense deployments, where multiple base stations (BSs) with different coverage and performance capabilities are deployed in the same area to fulfil the heterogeneous requirements of all users. BSs are the most energy-intensive components of the network and are responsible for approximately 80% of the total network's energy consumption. However, since the load on different base stations changes dynamically with time depending on traffic arrivals and user mobility, there is a high potential to improve the network energy efficiency with smart algorithms that dynamically change the network configuration. The use case considers different sources of energy reduction in an iterative manner by splitting it into the following three scenarios.

- Optimisation in 6G radio access technologies will focus on the two 6G RAN enablers, namely high-frequency bands (mmWave and sub-THz) and reconfigurable intelligent surfaces (RIS). High-frequency bands enable extremely high data rates in localized areas near the base stations due to the availability of a vast amount of unexploited bandwidth but limited propagation characteristics and vulnerability to blockages. Phased antenna arrays should be used for signal beamforming to overcome the transmission range limitations. However, optimal beams vary with time, and predictive beam selection algorithms are needed to steer the signal in the correct direction and avoid power waste. To tackle possible blockages, RIS can be used to reflect the signal in the direction of the target user. Since RIS consists of passive reflective elements, it does not use power for signal reflection. Still, it needs a power source for reconfigurability, i.e., to change the phase shifts in response to commands from the RIS controller.
- Network management and control with heterogeneous radio access technologies focus on the management of the network comprising base stations operating on different frequency bands. Some base stations will use high-frequency bands to enable high data rates and user density in certain areas, while other base stations will rely on traditional frequency bands, such as C-band or low-frequency bands for macro cells. In such deployments, not all base stations always need to be active, especially in periods of low usage, e.g., at nighttime. Hence, the network management algorithms are required to assign users to different base stations (and frequency bands) depending on their traffic requirements and future traffic predictions, as well as to control power saving at base stations via power control and sleep modes.
- Federated cross-domain radio and computing resource optimisation focus on end-to-end energy efficiency. This scenario builds upon the previous two but assumes that a separate administrative entity manages and optimizes the RAN domain. As a result, Multi-access Edge Computing (MEC) applications at the network edge must adapt to changes occurring in the RAN domain. However, since the RAN operates under a different administrative domain, joint orchestration, and resource management are not feasible, requiring the edge to take a more reactive approach. Leveraging the Federated NDT, the edge can anticipate these changes more effectively, ensuring continuity in service quality and maintaining the required QoS for users.

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5.2 Definition of the used KPIs

This use case will contribute to the following project-level KPIs:

Table 6 Use Case 2 Quantitative KPIs

Name	Units	Definition	Formula
Network KPI			
Shannon's capacity	Mbps	The maximum amount of traffic that a network can handle per time unit estimated with Shannon's equation	$C_{Shannon} = \sum_{i=1}^{users} w_i \cdot \sum_{j=1}^{streams} BW \cdot \log_2(1 + SINR_{i,j})$, where w_i is the weight associated with user i, $SINR_{i,j}$ is the signal-to-interference-plus-noise ratio for user i and spatial stream j, BW is the total available bandwidth
Measured capacity	Mbps	The maximum amount of traffic that a network can handle per time unit measured at 100% load	$C_{measured} = \frac{RXed\ data}{experiment\ time}$ provided that network operates at 100% load
Maximum number of satisfied users	N/A	Maximum number of users that the network can handle without violation of the SLAs	N/A
Shannon's total throughput	Mbps	The amount of delivered PHY layer data per time unit estimated with Shannon's equation	$T_{Shannon} = \sum_{i=1}^{users} \sum_{j=1}^{streams} BW_i \cdot \log_2(1 + SINR_{i,j})$, where BW_i is the bandwidth allocated to user i, $SINR_{i,j}$ is the signal-to-interference-plus-noise ratio for user i and spatial stream j
Measured total throughput	Mbps	The amount of delivered PHY layer data per time unit	$T_{measured} = \frac{RXed\ PHY\ data}{experiment\ time}$
Measured total goodput	Mbps	The amount of delivered APP layer data per time unit	$G_{measured} = \frac{RXed\ APP\ data}{experiment\ time}$

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Name	Units	Definition	Formula
Spectral efficiency	bits/s /Hz	The amount of delivered PHY layer data per time unit per Hz	$SE = \frac{RXed\ PHY\ data}{experiment\ time \cdot BW}$
Packet loss ratio	N/A	Ratio of lost packets to the total number of transmitted packets	$PLR = \frac{Number\ of\ lost\ pkts}{Number\ of\ TXed\ pkts}$
Packet delay	ms	Time between packet generation and its successful delivery (measured per user as they have different SLAs)	$D = Delivery\_time - TX\_time$
Power consumption	W	Total power consumed by the network	$P = P_{RAN} + P_{computing}$ (P_{RAN} is calculated according to BS Power model, e.g., from VIAVI tool or literature)
Energy efficiency	bits/s /J	The amount of delivered PHY layer data per time per Joule of consumed energy	$EE = \frac{RXed\ PHY\ data}{experiment\ time \cdot consumed\ enegy}$
Usage of compute resources	N/A	Total amount of used CPU, GPU, RAM and other compute resources required for execution of network functions to guarantee SLAs	N/A
Model KPIs			
Age of Information	ms	Metric of NDT information freshness	$AoI = \sum_{i=1}^{params} w_i \cdot (t_{current} - \tau_i)$, where $t_{current}$ is the current time, τ_i is the time of the last update for parameter i, w_i is the weight associated with parameter i reflecting the need for fresh information.
Accuracy	%	Metric representing how accurately the state of the NDT	MAE/MSE/MAPE, or similar

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Name	Units	Definition	Formula
		reflects the physical network	
Resource demand	N/A	How much resource (CPU, GPU, RAM, etc.) is needed to deploy the NDT	N/A

Other KPIs:

- Coupling of at least 2 NDTs: 1 for RAN optimization, and 1 for computing optimization (*KPI 1.1*)
- Multiple AI-based NF/NS involved (*KPI 1.3*):
- Traffic prediction
- Beamforming optimization
- RAN energy consumption optimization
- Computing optimization
- Visualization of at least 4 numeric KPIs at the dashboard (*KPI 4.4*)
- Implementation of the demonstrator to verify the solution (*KPI 4.1*).

5.3 Specification of test scenarios and test cases

5.3.1 Scenario 1: Optimisation in 6G radio access technologies (high frequency)

Higher frequencies, such as mmWave and sub-THz, offer significantly higher bandwidth at an expense of worse propagation properties due to vulnerability to blockages, higher path loss, and oxygen absorption. However, due to lower wavelength, the size of the antenna becomes smaller, which allows building antenna arrays consisting of large number of closely spaced antenna elements. Such antenna arrays are perfectly suitable for beamforming of the signal towards the direction of the receiver. We restrict the study to analog beamforming only due to multiple reasons.

- Digital beamforming is significantly more complex, as it requires one digital-to-analog converter per antenna element. Since the number of antenna elements for transmission at high frequencies can be very high, the complexity becomes a significant drawback.
- Data transmission at higher frequencies is typically more often power limited than bandwidth limited, making the beamforming more important than spatial multiplexing, which can be achieved only with digital beamforming techniques.

The performance of the network at high frequencies crucially depends on the beam management, i.e., the functionality that establishes and retains a suitable *beam pair,* the transmitter-side beam direction and a corresponding receiver-side beam direction. In the complex environment with multiple obstacles, the directions of these beams can be different from the line-of-sight direction. To find the optimal beam pair, especially in case of initial beam establishment and re-establishment after a link failure, 5G NR relies on *beam sweeping*. Specifically, synchronization signals (SSB) are transmitted in downlink using different beam directions. For receiver-side beam sweeping, each SSB transmitted with a certain transmitter-side beam direction is repeated multiple times. The total number of beam pairs that can be swept is restricted by the maximum number of SSBs, which is equal to 64 for mmWave bands.

Since high-frequency bands are extremely vulnerable to blockages, Reconfigurable Intelligent Surfaces (RIS) are considered as a powerful technology to achieve robust transmissions in dynamic complex environments. We consider RIS is a passive meta-surface that consists of multiple RIS elements, each of which can be configured to add a different phase shift to the signal. This way, RIS can change the direction of the reflected signal and direct it in the direction of the receiver blocked by an obstacle. Since RIS is passive, it cannot measure the channel. Hence, the phase shifts should be controlled based on the measurements at the base station and at user devices. The sweeping of beam pairs together with RIS phase shifts can lead to big overhead in real networks, as more synchronization and reference signals should be transmitted at different directions. The 6G-TWIN approach is to address this challenge with data-driven algorithms trained using the data generated by the digital twin. The accuracy of beam selection directly affects the energy efficiency of the network, since with optimal beams less transmission power can be allocated to fulfil the application requirements.

In ETSI group report [GR_RIS_003] [25], multiple reference test cases for evaluation of RIS-assisted 6G networks are proposed. For 6G-TWIN, the following two test cases are especially relevant.

Outdoor street canyon

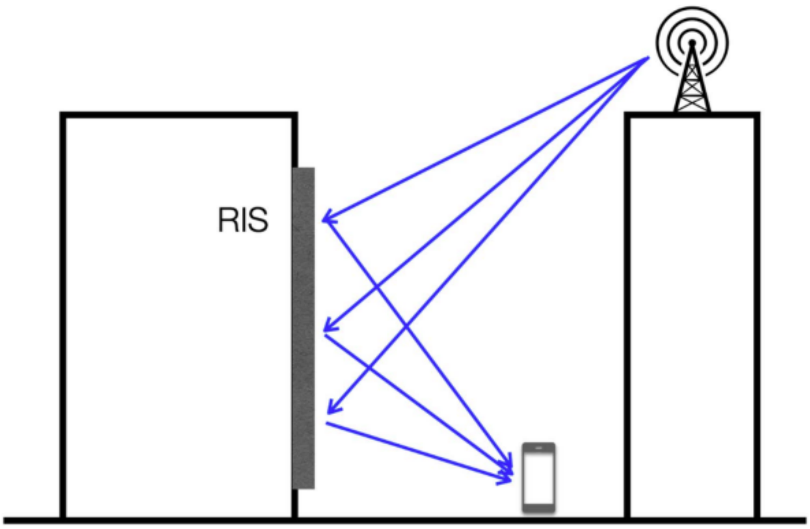

Figure 12 Outdoor Street Canyon Test Case[1]

[1]Source: [GR_RIS_003]

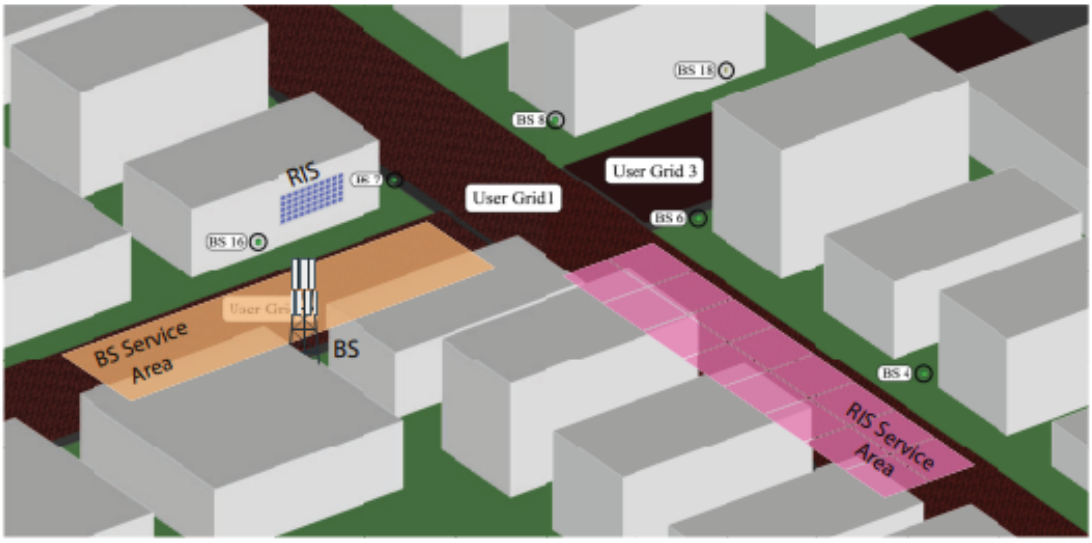

Figure 13 Outdoor Street Canyon Test Case – Intersection[2]

In this test case, an intersection of two streets is considered. This represents an urban space surrounded by buildings on both sides of the streets. The base station is deployed on one of the streets, while some of the target users are in the crossing street behind the corner, where the line-of-sight is blocked by the buildings. To provide coverage to these users, the RIS is deployed on the facade of one of the buildings facing to the direction of the users.

The parameters of the test case can be set based on the O1 scenario of DeepMIMO project [26] (https://www.deepmimo.net/scenarios/o1-scenario/), as well as on link-level and system-level parameters defined in [GR_RIS_003] [25] and [TR_38.843] [27].

Indoor Blockage

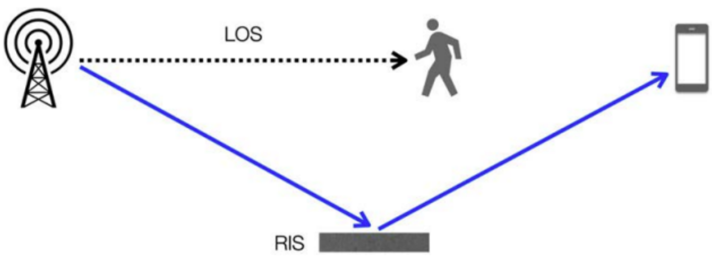

Figure 14 Indoor Blockage Test Case[3]

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[2] Source: "Digital Twin Aided RIS Communication: Robust Beamforming and Interference Management" https://arxiv.org/pdf/2406.04188

[3] Source: [GR_RIS_003]

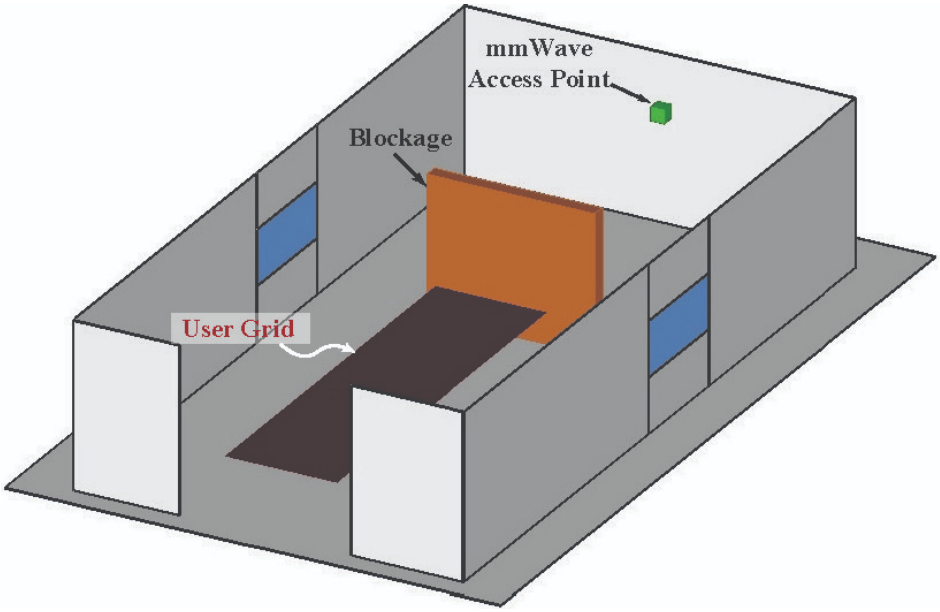

Figure 15 Indoor Blockage Test Case Rectangular Room[4]

In this test case, the rectangular room is considered, where the mmWave base station and the target users are separated with a blockage. To serve these users, the RIS is mounted on the wall, so that the reflected from the RIS signal can reach them. The parameters of the test case can be set based on the I2 scenario of DeepMIMO project [deepMIMO] (https://www.deepmimo.net/scenarios/i2-scenario/), as well as on link-level and system-level parameters defined in [GR_RIS_003].

5.3.2Scenario 2: Network management and control with heterogeneous radio access technologies

Growing densification of networks raises demand for joint deployment of radio access technologies (RATs) utilizing high (e.g., mmWave) frequencies and classic sub-6GHz (e.g., C-band) frequencies. While base stations (BSs) operating on sub-6GHz frequencies provide coverage in wide areas, mmWave BSs use wide range of available bandwidth to satisfy requirements of users in a specific area. For example, when high number of users are located in a limited area, e.g., in a stadium or in a big building, the total demand for bandwidth may exceed the available bandwidth in sub-6GHz. Additionally, new types of applications, such as extended reality and smart industry, impose challenging requirements on delay, throughput, and reliability, which cannot be always satisfied without access to high bandwidth. Such multi-RAT deployments fit into the general concept of heterogeneous cellular deployment with macro-, micro-, pico- and femtocells.

Due to the natural dynamicity of network load and user demands, it is important to efficiently manage all the available resources. Different users should be dynamically assigned to different frequencies depending on the application they use, channel conditions, and availability of

[4] Source: https://www.deepmimo.net/scenarios/i2-scenario/

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resources. When some of the BSs are significantly underloaded, many resources are wasted with a great impact on energy efficiency. In such cases, some of the BSs can save power (e.g., by turning off), while other BSs will distribute additional load. Moreover, more fine-grained control of the BS's power consumption can be achieved via Advance Sleep Modes (ASMs), which require different activation and deactivation durations depending on components that they turn on or off. To cope with the high complexity of the overall system, NDT is seen as a tool for trial of different management decisions to verify how those decisions affect the satisfaction of service level agreements (SLAs) and the network energy efficiency. Such NDT test case considered in 6G-TWIN is schematically depicted in Figure 16.

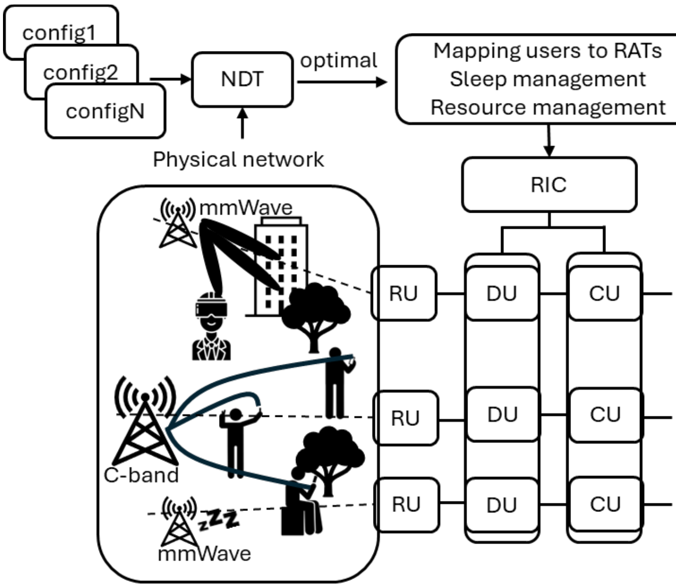

Figure 16 Advance Sleep Modes (ASMs) Test Case

5.3.3 Scenario 3: Federated cross-domain radio and computing resource optimisation

This scenario focuses on optimizing the edge network to achieve end-to-end energy efficiency. Advanced sleep modes are one of the RAN's most effective strategies for reducing energy consumption [28], [29]. However, their effectiveness highly depends on local traffic patterns, such as user mobility. As a result, changes in traffic patterns are also reflected in the aggregated traffic observed at the user plane function, impacting applications running at the edge. From a MEC perspective, activating or deactivating a base station translates into variations in the aggregated traffic that must be processed. Accurately identifying these changes is crucial to maintaining user QoS and QoE. Additionally, power-aware orchestration of MEC applications can be further optimized to enhance energy efficiency without compromising service performance.

To evaluate this scenario, we assume that the RAN and Edge operate under separate administrative domains, requiring a federation mechanism to achieve end-to-end energy efficiency. To proactively adapt to varying traffic patterns, the edge can request different traffic traces from a RAN NDT as part of its internal optimization loop, effectively enabling "what-if" scenario analysis. For example, in one scenario, the edge may request the RAN to simulate bursty traffic, while another scenario could involve on-off traffic patterns.

Additionally, the edge collects data from its own infrastructure to model the impact of different traffic patterns on QoS metrics such as latency. By combining these insights, an Edge NDT can be created, allowing for the evaluation of various management strategies, such as scaling. Such strategies might also include energy efficiency among their optimization objectives [30], [31]. Using these models and traffic traces, the system can simulate different scenarios, testing multiple scaling strategies. Ultimately, after analysing the results, the Edge NDT can recommend the most suitable scaling approach for each traffic pattern, ensuring optimal performance during real-world operation.

Figure 17igure 13 shows the UML diagram of the interactions between the different components in this test scenario.

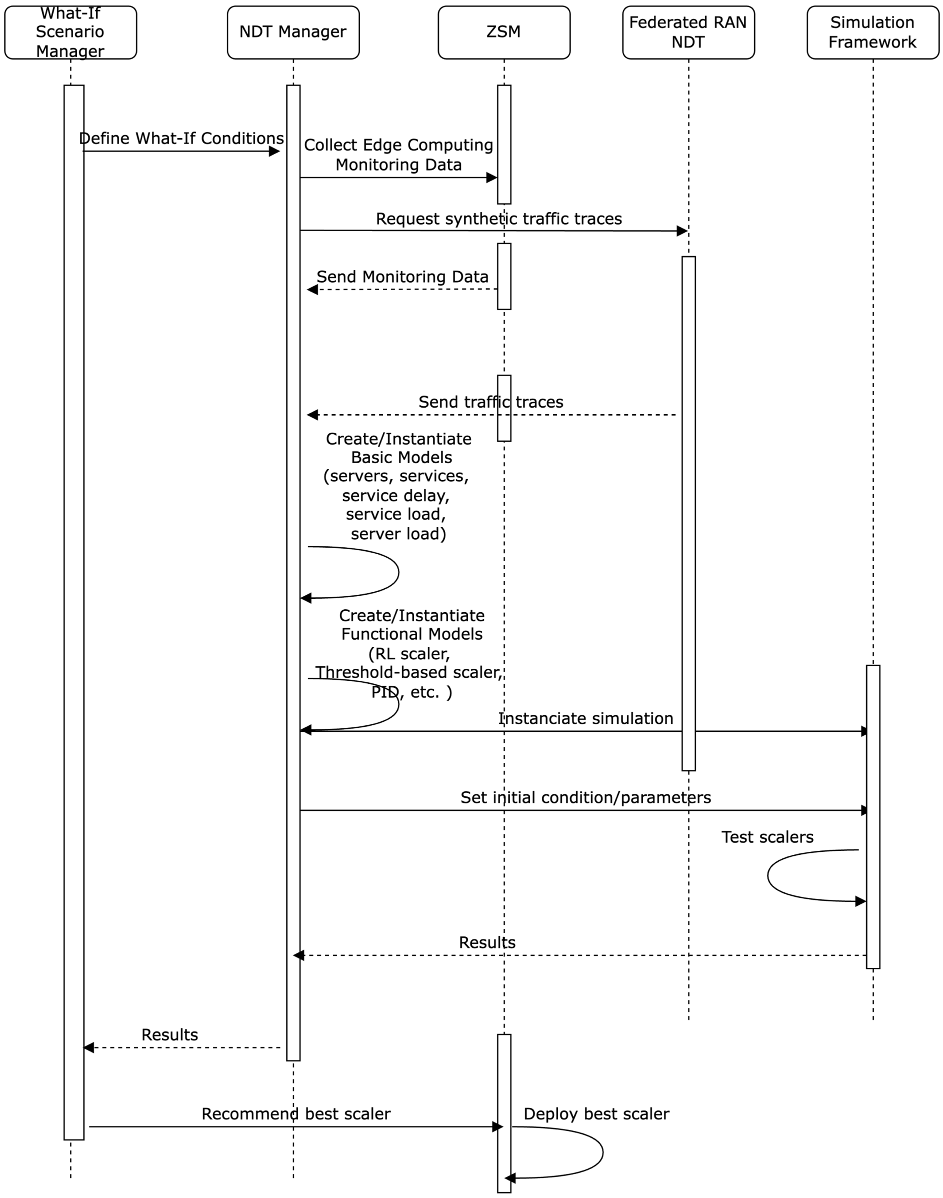

Figure 17. UML diagram of the testing for scenario 3 in use case 2.

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5.4 Specification of hardware, software and data for the tests

5.4.1 Hardware

IMEC mmWave Radio Units

The following hardware components will be used for mmWave radio communication: two USRP X410 (SDRs), two TMYTEK BBox One beamformers, and two up/down converters. The beamformers operate at licensed FR2 band 26.5-29.5 GHz. The software component TMXLAB provided with TMYTEK BBox One enables the beam management capabilities.

IMEC GPULab

For the training and validation of reinforcement learning algorithms, GPULab testbed will be used. GPULab is a distributed system for running jobs in GPU-enabled Docker-containers. GPULab consists out of a set of heterogeneous clusters, each with their own characteristics (GPU model, CPU speed, memory, bus speed, among others), allowing you to select the most appropriate hardware. Each job runs isolated within a Docker container with dedicated CPUs, GPU, and memory for maximum performance.

IMEC Virtual Wall

The Virtual Wall is a high-performance network and cloud testbed hosted and operated by imec IDLab ilab.t, consisting of two interconnected testbeds designed for networking, cloud computing, and distributed systems research. Virtual Wall 1 includes 206 nodes (pcgen1 and pcgen2), while Virtual Wall 2 features 159 nodes (pcgen3, pcgen4, pcgen5, and GPU-enabled nodes) for compute-intensive applications. The infrastructure supports both bare-metal deployment, where an operating system runs directly on the hardware, and virtualized environments through OpenVZ containers or XEN virtualization. XEN virtualization is available in two configurations: shared nodes (non-exclusive), where VMs run on shared physical hosts, and dedicated nodes (exclusive), where VMs have exclusive access to physical hosts, allowing full control over XEN parameters with root access to DOM0. The Virtual Wall testbed provides a versatile and scalable hardware platform for cloud computing, networking, and AI research, enabling controlled experiments and large-scale emulation.

Hardware Requirements

Following information is only a guideline and should be refined at a later stage when RAN model requirements are defined.

- CPU: 2 x Intel Xeon Gold 6140 2.3G, 18C/36T, 10.4GT/s 2UPI, 24.75M Cache, Turbo, HT
- (140W) DDR4-2666.

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- RAM: 16 x 16GB RDIMM, 2666MT/s, Dual Rank.
- Disk: 1 x 960GB SSD SATA Mixed Use 6Gbps 512e 2.5in Hot-plug S4610 Drive.
- No RAID with Embedded SATA.
- Network interface: 1 x Intel i350 Quad Port 1GbE Base-T, rNDC.
- PAMS: 1 x iDRAC 9, Enterprise license.

5.4.2Software

Simulation Tools

Use Case 2 experiments will use the following simulation tools:

- *Matlab* with communication and 5G toolboxes to model the channel and signal propagation. For example, link-level simulation of beam sweeping in RIS-assisted network will use the models of RIS, 5G multi-antenna transmitters and receivers.
- Simulation tools for fast and accurate channel modelling, such as *DeepMIMO* and *Sionna*, can be considered for performance evaluation of the developed algorithms for different geometric parameters of the environment.
- RAN system-level simulation will be done using *Viavi TeraVM AI RSG* described below. Alternative open-source RAN simulators, e.g., *5G-LENA* module of NS-3 simulator and *Simu5G*, will be considered.
- DynaSim is an edge computing simulator developed at imec that builds on top of the Simulation of Discrete Systems of All Scales (Sim-Diasca), a general-purpose, parallel, and distributed discrete-time simulation engine for complex systems written in the Erlang language. DynamicSim allows the definition of actor-based models for the VNFs, physical server, and load balancers. It also provided a native interface to create, train, and test reinforcement learning agents for computing auto-scaling.

TeraVM AI RSG

AI RSG is an AI enabler for Intelligent SON applications and r/xApps development. It is an AI enablement tool focussing on data generation for AI training and test. The integration architecture of AI RSG in usual infrastructures is depicted in Figure 18.

TeraVM AI RSG can simulate up to 10,000 user equipment (UEs) and several thousand cells (between 1,000 and 5,000) per reference server. It can be deployed in Docker containers within cloud environments or on dedicated servers. The scale depends on the specific use case, with the ability to generate data at various granularities, from one minute to daily intervals. The tool’s scalability matrix helps define parameters for different scenarios.

Users can import real-world maps with streets, buildings, and network configurations to create UE profiles that simulate movements, handovers, and resource requests. The more real the network scenarios and user behaviours are the more ‘what if’ scenarios can be generated to train the AI apps. Traffic demand profiles can also be generated, enabling UEs to switch between idle and active states while consuming varying amounts of Physical Resource Blocks (PRBs). Layer 1 radio conditions are modelled and fed into the Layer 2 scheduler, which assigns PRBs based on the Channel Quality Indicator (CQI).

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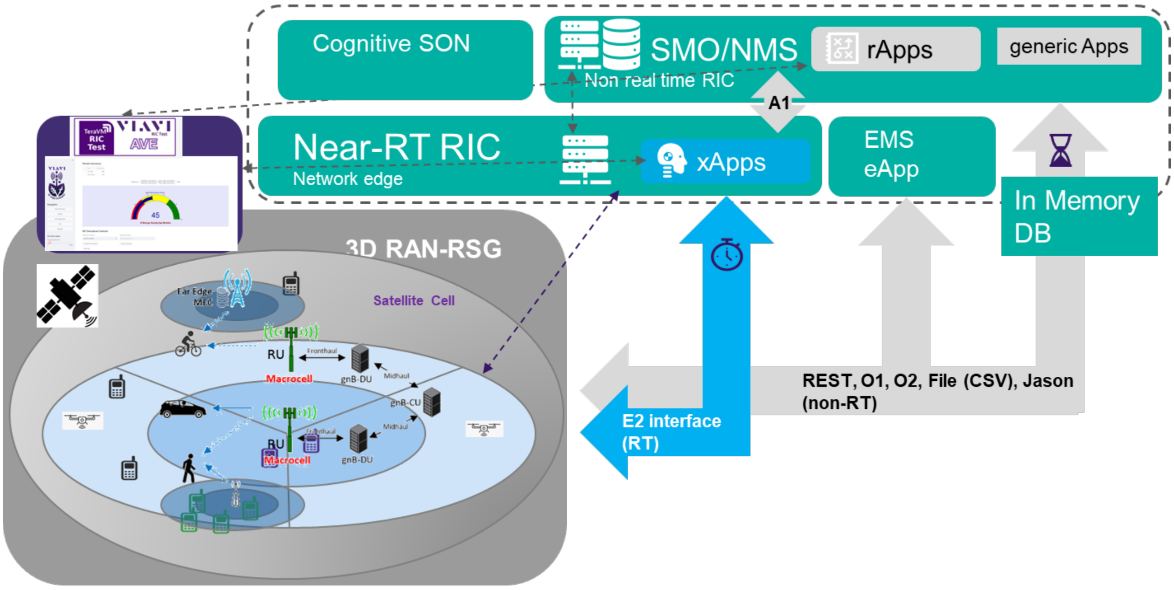

Figure 18 High level AI RSG Integration Architecture

6 Conclusions

This deliverable presents the evaluation methodology, planning and coordination strategies to obtain and validate the main objects of 6G-TWIN project: to provide the foundation for the design, implementation and validation of an AI-native reference architecture for 6G systems that incorporates NDT as a core mechanism for the end-to-end, real-time optimisation, management and control of highly dynamic and complex network scenarios.

To this aim, the document started by describing the NDT architecture concept of data spaces specifically designed for 6G NDT and the evaluation state of the art.

This evaluation methodology, inspired by the FESTA V-process, was described by considering the different phases and their links to the project tasks and WPs, including the computation of the KPIs and the assessment of the NDT capability level as recommended by the ITU-T.

The qualitative project level KPIs reported in the GA were firstly described. For such KPIs, the document points out the milestones and the deliverables where they will be achieved. Moreover, a procedure to assess complementary social and economic stakeholder perceptions regarding the usefulness and impact of the Digital Twin (DT) approach was introduced.

Subsequently, the more complex procedure of the identification and computation of the quantitative KPI related to the two 6G-TWIN use cases: 1) **Teleoperated or remote driving**, and 2) **Energy savings in dense deployments** has been described. The use cases are strongly related to the NDT capability level assessment and to the evaluation indicators recommended by the ITU-T. To this purpose, the document describes in detail their objectives, the definitions of the KPIs to be computed, the test scenarios, the test cases and, finally, the hardware and software components required to perform the computations.

The contributions of this reports will be of basic importance for the success of the project. Indeed, the detailed description of the use cases evaluation will allow the achievements of the 6G-TWIN project. The outputs of this deliverable will be the inputs for the next tasks of WP5, to process the test cases (T5.2), propose the new paradigms and solutions for the reengineering of the network architectures (T5.3) and propose solutions for the architectural standardisation work (T5.4).

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8 Annex 1: Semi-structured stakeholder questionnaire on the usefulness of 6G-TWIN's Digital Twin Approach (Draft)

Objective: this questionnaire aims to gather stakeholder feedback on the usefulness, usability, and perceived impact of the **Network Digital Twin (NDT)** approach introduced in the 6G-TWIN project. It will help assess the **practical benefits, challenges, and adoption barriers** encountered by stakeholders involved in the project's **teledriving** and **energy efficiency** use cases.

Target Respondents:

- **Technical experts** (network operators, system integrators)
- **End-users** (e.g., teleoperators, energy sector stakeholders)
- **Regulatory and industry representatives**

Instructions:

- The questionnaire consists of **open-ended and Likert-scale** questions.
- Responses will remain **anonymous** and will only be used for research purposes.
- Estimated completion time: **10 minutes**.

Section 1: Background Information

1. **What is your role in the 6G-TWIN project?**

   ☐ Technical expert (network operations, system integration)

   ☐ End-user (e.g., teleoperator, energy sector stakeholder)

   ☐ Policy/Regulatory representative

   ☐ Other (please specify): _______________

2. **Which of the two 6G-TWIN use cases are you involved in?**

   ☐ Teledriving (Predictive DT)

   ☐ Energy Efficiency (Reactive DT)

   ☐ Both

   ☐ Not directly involved

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Section 2: Awareness and Understanding

3. **Before participating in 6G-TWIN, were you familiar with the concept of Network Digital Twins (NDTs)?**

   ☐ Yes, I had prior experience with Digital Twins in telecom/ICT.

   ☐ Somewhat, I was aware of the concept but had no direct experience.

   ☐ No, this is my first exposure to NDTs.

4. **How well do you understand the role of NDTs in 6G networks after engaging with 6G-TWIN?**
   (1 = Not at all, 5 = Fully understand and can apply it in my work)

   ☐ 1

   ☐ 2

   ☐ 3

   ☐ 4

   ☐ 5

Section 3: Perceived Usefulness and Benefits

5. **To what extent do you agree with the following statements?** *(1 = Strongly Disagree, 5 = Strongly Agree)*

Statement	1	2	3	4	5
The NDT approach improves **network planning and optimization**.	☐	☐	☐	☐	☐
The NDT approach enhances **real-time decision-making** for network operations.	☐	☐	☐	☐	☐
Using NDTs in 6G **reduces operational complexity** in highly dynamic networks.	☐	☐	☐	☐	☐
NDTs provide **tangible energy efficiency benefits** for network infrastructure.	☐	☐	☐	☐	☐
The NDT methodology introduced in 6G-TWIN is **transferable** to other 6G applications.	☐	☐	☐	☐	☐

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6. **In your opinion, what are the most significant advantages of the NDT approach in 6G networks?**
   (Open-ended response)

---

7. **Are there any specific technical or organizational challenges that you foresee in adopting NDTs in real-world networks?**
   (Open-ended response)

Section 4: Usability and Adoption Challenges

8. **How easy or difficult was it to integrate the NDT solutions into the 6G-TWIN use cases?**
   (1 = Very difficult, 5 = Very easy)

   ☐ 1

   ☐ 2

   ☐ 3

   ☐ 4

   ☐ 5

9. **What were the main barriers (if any) to using the NDT solutions in your specific use case?**
   (Open-ended response)

---

10. **Do you see a need for additional training or tools to facilitate the adoption of NDTs in operational networks?**

    ☐ Yes

    ☐ No

    ☐ Not sure

11. **What would help improve the usability and impact of NDTs in future telecom applications?**
    (Open-ended response)

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Section 5: Overall Experience and Future Outlook

12. **Would you recommend the integration of NDTs in other 6G applications based on your experience in 6G-TWIN?**

    ☐ Yes, definitely

    ☐ Yes, but with some improvements

    ☐ Not sure

    ☐ No, I don't see the added value

13. **Are there any specific improvements you would suggest for the future development of NDT solutions?**
    (Open-ended response)

14. **Do you have any additional comments or feedback on the NDT approach in 6G-TWIN?**
    (Open-ended response)

Next Steps:

Thank you for your time! Your feedback will help refine the evaluation of NDTs in 6G networks. If you would like to receive a summary of the survey results, please leave your email (optional):

____

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