



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

D1.1

Architecture and Technical Foundations (Initial)

Document Information

Grant Agreement N°	101136314
Authors and institutions	German Castellanos (ACC, main editor); All partners
Date	28 June 2024
Related WP	WP1 6G Architecture Design
Dissemination level	PU Public, fully open



D1.1 – Architecture and technical foundations (Initial)

Document change history

Version	Date	Author	Description
V0.1	02/02/2024	German Castellanos (ACC)	Document creation and initial TOC
V0.2	19/04/2024	All partners	Initial contributions to the document and first evaluation of the document.
V0.3	05/06/2024	All partners	Contributions from all the partners to complete deliverable for first internal revision.
V0.4	16/06/2024	Maria Pia Fanti (POLIBA), Ramin Fuladi (EBY), Paola Soto (IMEC), Inès El-Korbi (UBOU), Christoph Sommer (TUD), Ayat Zaka Hindi (LIST), German Castellanos (ACC)	Revision and corrections for internal partners.
V0.5	21/06/2024	German Castellanos, Stephen Parker (ACC), Sébastien Faye (LIST), Paola Soto, Miguel Camelo (IMEC)	Editorial revision and merging contributions from all partners.
V1	28/06/2024	German Castellanos (ACC), Sébastien Faye (LIST)	Final Submitted version.

Quality control

	Name	Organisation	Date
Editor:	German Castellanos	ACC	28/03/2024
Peer review 1:	Sébastien Faye	LIST	24/06/2024
Peer review 2	Miguel Camelo	IMEC	24/06/2024
Authorised and submitted by (Project Coordinator):	Sébastien Faye	LIST	28/06/2024

Legal disclaimer

This document is issued within the framework of and for the purpose of the [6G-TWIN](#) project. This project has received funding from the European Union's Horizon Europe Framework Programme, through the Smart Networks and Services Joint Undertaking under the powers delegated by the European Commission and under Grant Agreement No. 101136314. Opinions expressed and arguments employed herein do not necessarily reflect the official views of the European Commission. Neither the European Commission nor the [6G-TWIN](#) partners bear any responsibility for any use that may be made of the information contained herein. This document and its content are the property of the [6G-TWIN](#) Consortium. All rights relevant to this document are determined by the applicable laws. Access to this document does not grant any right or license on the document or its contents. [6G-TWIN](#) partners may use this document in conformity with the [6G-TWIN](#) Consortium Grant Agreement provisions.



Executive Summary

The transition to 6G networks promises a leap forward in communication technologies, driven by the integration of AI-native architectures and Network Digital Twins (NDTs). The **6G-TWIN** project focuses on designing an AI-native reference architecture that incorporates NDTs to optimize, manage, and control future networks in real-time. This architecture aims to address the complex demands of next-generation networks, leveraging the synergies between AI and NDTs to enhance network performance, reliability, and security. To meet this, it is essential to develop a revolutionary 6G architecture providing AI-native management of dense, highly distributed, and potentially cell-free multi-domain networks based on heterogeneous Radio Access Network (RAN) technologies, infrastructures, services, and use cases that focus on sustainability and energy efficiency. The **6G-TWIN** project addresses these challenges by envisioning future 6G architectures that enable a cyber-physical continuum between the physical world and its digital representation.

This document, **D1.1 – “Architecture and Technical Foundations (Initial)”**, aims to provide a comprehensive overview and proposal for the **6G-TWIN** system architecture, covering state-of-the-art 6G technology, simulation tools, functional requirements, and future challenges. This first version, provided at Month 6, will be completed by one update (i.e., D1.4), to be completed in M36. It is organized in a bottom-up manner. It begins in Chapter 2 with a comprehensive state-of-the-art review of 6G architecture, Network Digital Twins, and AI-native architectures. Following this, an in-depth investigation into the simulation and emulation tools necessary to support NDTs is presented in Chapter 3. The next Chapter (Chapter 4) delves into the functional and non-functional requirements, establishing the baseline for Key Value Indicators (KVIs) and Key Performance Indicators (KPIs) that define the project’s use cases described in Chapter 5. The document presents in Chapter 6 a detailed proposal for the **6G-TWIN** system architecture, and concludes it with the open challenges, key findings and future work in Chapter 7.

Technical Foundations of 6G and Network Digital Twins

The foundation of 6G networks rests on the evolution of existing 5G technologies, enhanced by AI and NDT capabilities. The architecture proposed by **6G-TWIN** aims to integrate these advancements to create a robust framework for future networks. An NDT is essential for this vision, composed of two main layers: the physical layer and the digital layer.

The physical layer relies on the RAN and sensing capabilities to capture real-time data from the physical environment. This layer forms the basis for accurate and dynamic modelling by using data collection, data harmonization and model orchestration as an interface with the follow layer. The digital layer comprises applications that model the physical world, enabling real-time analysis and optimization. By creating a digital replica of the physical network, the NDT facilitates proactive management and troubleshooting, enhancing operational efficiency and network resilience.

To effectively model the real world, basic and functional models need to be defined and explored. Basic models represent the fundamental components and interactions within the network, such as radio equipment, while functional models provide detailed simulations of network operations and behaviours, like traffic balancing or network planning. These models are supported by simulation and emulation tools, which are critical for testing and validating the performance and reliability of the NDT and its underlying network infrastructure.

Simulation frameworks are crucial for developing and testing NDTs. This document explores various simulation tools, categorizing them into real-time simulators, high-level architecture simulators, and specific simulators for aerial vehicles, robotics, and vehicular applications. These tools enable detailed and dynamic simulations of network environments, providing a platform for rigorous testing and optimization of NDT functionalities.



D1.1 – Architecture and technical foundations (Initial)

Functional and Non-Functional Requirements

The proposed architecture for 6G-TWIN encompasses both functional and non-functional requirements, laying the groundwork for defining the KPIs and KVIs that are essential for evaluating the project's use cases. The requirements chapter delves into the specific needs of the 6G-TWIN project, identifying both functional and non-functional aspects. Functional requirements focus on the capabilities needed to support zero-touch management, federated management and orchestration (MANO), and real-time data collection and analysis. Non-functional requirements address broader concerns such as security, privacy, scalability, and interoperability.

Zero-touch management is a critical component, enabling automated network operations without human intervention. This requires advanced AI-driven automation technologies to achieve self-optimizing and self-healing network operations. Federated MANO allows for efficient coordination of network resources across different domains, ensuring seamless and dynamic network management. To leverage these requirements, effective data collection methods and technologies are discussed, emphasizing the importance of a robust telemetry framework for real-time data acquisition. This includes the use of sensors and other data-gathering devices to provide accurate and timely information necessary for NDT operations.

Reference Use Cases and KPIs

This document explores various use cases to demonstrate the practical applications and benefits of the 6G-TWIN solutions. It describes the general Key Values (KV) from the UN and other SNS projects and outlines the KVIs and KPIs relevant to the 6G-TWIN project, explaining their importance and measurement criteria. Use cases such as teleoperated driving and energy savings in dense deployments are detailed, highlighting the expected functionalities and performance metrics essential for these scenarios.

Teleoperated driving, for instance, requires low latency, high reliability, and robust data transmission to ensure safety and efficiency. The energy savings use case discusses strategies and technologies to reduce energy consumption in 6G networks, highlighting the functionalities and KPIs related to optimizing network resources and leveraging AI for dynamic energy management.

These use cases provide a practical context for evaluating the effectiveness of the 6G-TWIN architecture, demonstrating its potential to address real-world challenges and deliver significant improvements in network performance and efficiency.

System Architecture Proposal

The culmination of the document presents a detailed 6G-TWIN system architecture proposal. This architecture integrates AI-native functionalities with NDTs, creating a cohesive framework for future 6G networks. Additionally, it emphasizes open and standardized interfaces to ensure interoperability across diverse technologies, facilitating seamless integration of AI and NDT components. Key components of the architecture include the radio access network, core network, and edge computing capabilities, all interconnected through advanced AI-driven orchestration and management systems.

The architecture is designed to be scalable and flexible, accommodating the dynamic and evolving nature of future network environments. By leveraging AI and NDT technologies, the 6G-TWIN project aims to create networks that are not only more efficient and reliable but also capable of autonomously adapting to changing conditions and demands.

The physical network layer incorporates AI-based designs to enhance performance and efficiency, while the digital network layer focuses on data and model management essential for creating and maintaining accurate NDTs. The chapter also discusses the basic and functional models and the harmonized data repository that supports these models within the proposed architecture.



D1.1 – Architecture and technical foundations (Initial)

Conclusion and Future Directions

The 6G-TWIN project represents a significant step towards realizing the vision of AI-native 6G networks. The integration of Network Digital Twins provides a powerful tool for real-time optimization and management, addressing the complexities of next-generation communication systems. The project's focus on open architectures and standardized interfaces ensures that the solutions developed are versatile and widely applicable.

Moving forward, ongoing research and development will be essential to address the remaining challenges and refine the proposed architecture. Future deliverables will explore the implications of orchestrating AI-driven functionalities across multiple network domains, further advancing the state of 6G technologies. Continued collaboration among project partners will be crucial to achieving the long-term goals of the 6G-TWIN initiative and shaping the future of network technologies.



D1.1 – Architecture and technical foundations (Initial)

Abbreviations and acronyms

3GPP	Third Generation Partnership Project	E2AP	E2 Application Protocol
5GC	5G Core	E2E	End to End
5G NR	5G New Radio	E2SM	E2 Service Model
5GS	5G Systems	eMBB	Enhanced mobile broadband
AaaML	Application AI/ML Assistance	ETSI	European Telecommunications
ADS	Automated Driving Systems	EVI	Ego Vehicle Interface
AF	Application function	FMANO	Federated MANO
AI	Artificial Intelligent	FR	Functional Requirement
AlaaS	Application AI/ML Assistance	GDPR	General Data Protection Regulation
AIF	Artificial Intelligent Function	gNB	g Node B
AIML-T	AI/ML Translator	GNN	Graph Neuronal Network
AITM	AI Task Management	GPU	Graphics Processing Unit
AMF	Access and Mobility Function	GRAND	Green Radio Access Network Design
AR	Augmented Reality	GSBA	Global Service-based Architecture
ASM	Automotive Simulation Models	HIL	Hardware In the Loop
AV	Autonomous Vehicles	HLA	High-Level Architecture
BER	Bit Error Rate	HV-VES	High Velocity Virtual Event
BLE	Bluetooth Low energy	ICT	Information and Communication
BM	Beam Management	IEFT	Internet Engineering Task Force
bps	bits per second	IoT	Internet of Things
BS	Base Station	ISAC	Integrated Sensing And
CACC	Cooperative Adaptive Cruise Control	ISO	International Standards Organization
CCL	Compute Continuum Layer	ITU-T	International Telecommunication
CCP	Connect-Compute platform	KPI	Key Performance Indicator
CCPA	California Consumer Privacy Act	KVI	Key Values
CDR	Call Detail Record	KVI	Key Value Indicator
CDT	City Digital Twin	LIDAR	Light Detection and Ranging
CI/CD	Continuous Integration and	MANO	Management and Orchestration
CN	Core Network	MEC	Mobile Edge Computing
CNS	Complex Network Systems	ML	Machine Learning
COST	Commercial off the shelf	MLB	Mobility Load Balancing
CPU	Central Processor Unit	MLOp	Machine Learning Operation
CSI	Channel State Information	mMTC	massive Machine-Type
CTGAN	Conditional Tabular Generative	MNO	Mobile Network Operator
CU	Central Unit	MVC	Model-View-Controller
DAEMO	aDAptive and sELf-Learning MOBILE	NASA	National Aeronautics and Space
DC	Data Collection	NCC	Network Control Center
DDD	Domain-Driven Design	NDT	Network Digital Twin
DES	Discrete Event Simulator	NEF	Network Exposure Function
DL	Deep Learning	NF	Network Function
DNN	Deep Neural Networks	NF/NS	Network Function and Services
DRL	Deep Reinforcement Learning	NFR	Non-Functional Requirement
DT	Digital Twin	NFV	Network Functions Virtualization
DTC	Digital Twin Consortium	NI	Network Intelligence
DTFV	Digital Twin Function Virtualization	NIF	Network Intelligence Function
DU	Distributed Unit	NIO	Network Intelligence Orchestration



D1.1 – Architecture and technical foundations (Initial)

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



Table of Contents

Document change history	ii
Quality control	ii
Legal disclaimer	ii
Executive Summary	iii
Abbreviations and acronyms	vi
Table of Contents	viii
Table of Figures	x
Table of Tables	xi
1 Introduction	1
1.1 Aims and objectives	1
1.1.1 6G-TWIN objectives	1
1.1.2 Deliverable objectives	2
1.2 Relation to other activities in the project	2
1.3 Document structure	3
1.4 Contribution of partners	5
2 Architecture enablers for 6G and Network Digital Twins	7
2.1 Road from 5G to 6G	7
2.2 Introduction to NDT concepts, use-cases, and reference architectures	11
2.2.1 Background on Digital Twins	11
2.2.2 Towards a Network Digital Twin	12
2.2.3 NDT Reference Architectures	13
2.2.4 NDT data models	16
2.3 AI-Native Architectures and link with NDTs	18
2.3.1 Industry perspective	19
2.3.2 Academic perspective	26
3 Simulation frameworks and Simulators	35
3.1 Network simulator to support NDT	35
3.2 Simulation taxonomy	36
3.2.1 Real time simulation	36
3.2.2 Simulation with High Level Architecture	37
3.2.3 Aerial vehicles simulation	37
3.2.4 Robotic Simulation	38
3.2.5 Vehicular Simulation	39
3.3 Simulation tools	40
3.3.1 Industrial Focused tools	41
3.3.2 Research Focused tools	41
3.4 Tools Planned to use in 6G-TWIN	42
3.4.1 TU Dresden Simulation Framework Scope	42
3.4.2 ACCELLERAN dRAX	44
3.4.3 VIAVI RIC Tester	45
4 Functional and Non-Functional Requirements	47
4.1 Data collection	48
4.2 Zero-touch management	50
4.3 Federated MANO	51
4.4 Simulation framework	52
4.5 Requirements considerations	55
5 Reference Use Cases and KPIs	57
5.1 KVs and KPIs Within European Projects	57
5.1.1 Key Values	57



D1.1 – Architecture and technical foundations (Initial)

5.1.2	KPI family and KPIs	59
5.1.3	Relation between KVI and KPIs	63
5.1.4	KPIs in 6G-TWIN.....	64
5.2	Teleoperated Driving	66
5.2.1	Expected functionalities	67
5.2.2	KPIs	67
5.3	Energy savings in dense deployments	68
5.3.1	Expected functionalities	70
5.3.2	KPIs	71
6	6G-TWIN System Architecture	73
6.1	Layer 1: Physical Network – AI-based Architecture	75
6.2	Layer 2: Digital Network – Data and Models	77
6.2.1	Basic models	78
6.2.2	Functional models.....	79
6.2.3	Harmonised data and model repository.....	80
6.3	Layer 2: Digital network – Federated simulation framework	80
7	Final Remarks	83
7.1	Open challenges.....	83
7.1.1	Security	83
7.1.2	Openness integration.....	85
7.1.3	AI Integration and Orchestration.....	86
7.1.4	Distributed ML and Federated Management.....	86
7.2	Conclusions	87
7.3	Future work.....	88
	REFERENCES	91
	Annex 1: 6G-TWIN Specific Objectives and KPI mapping	99



Table of Figures

Figure 1. 6G-TWIN PERT chart.....	3
Figure 2. 6G Use Case Families based on Hexa-X-II [14]	9
Figure 3. High-level 6G Architecture based on the 5G PPP [16].	10
Figure 4. ITU-T high-level architecture [31].	14
Figure 5. An overview of AI in 5G-Advanced in 3GPP Rel 18 [58]	21
Figure 6. OMNeT++ INET [148]	43
Figure 7. SUMO Simulator [149].	43
Figure 8. Accelleran dRAX Platform.....	45
Figure 9. Viavi Solutions. a) Viavi Ric Tester architecture. b) Viavi RIC Tester GUI.	46
Figure 10. Logical view of the interaction of the simulation framework with other components	53
Figure 11. Example of distributed simulation setup.....	53
Figure 12. UN 17 Sustainable Development Goals to map KVs [166].....	57
Figure 13. KPIs grouped in KPI families.....	62
Figure 14. Illustration of the Teleoperated Driving Use Case.	66
Figure 15. Illustration of the Energy Savings Use Case.....	69
Figure 16. Technical components that leverage an NDT.....	73
Figure 17. High-level architecture of 6G-TWIN	75
Figure 18. High-level architecture of 6G-TWIN, with a focus on the AI-native components	76
Figure 19. Relation of Basic Model and Functional models	78



Table of Tables

Table 1. Partners contributions to the D1.1 deliverable.	5
Table 2. Scientific state-of-the-art of AI-Native architectures.....	26
Table 3. Research projects that integrate AI/ML into the network architecture.	28
Table 4. Features of an AI-Native Architecture	30
Table 5. Real time simulators	36
Table 6. Simulators with high level architecture	37
Table 7. Aerial vehicles simulators	37
Table 8. Robotic simulators	38
Table 9. Vehicular simulators	39
Table 10. Functional requirements regarding data collection	49
Table 11. Non-Functional requirements regarding Data Collection	49
Table 12. Functional requirements regarding ZSM	50
Table 13. Non-Functional requirements regarding ZSM	51
Table 14. Functional requirements regarding F-MANO	51
Table 15. Non-Functional requirements regarding F-MANO	52
Table 16. Functional Requirements regarding components that are used by the simulation framework	53
Table 17. Functional requirements regarding components that use the simulation framework.....	54
Table 18. Functional requirements of the internal layers of the simulation framework	54
Table 19. Non-Functional Requirements of the simulation framework itself	54
Table 14. SNS JU Stream B/ D projects use case examples aligned with verticals	58
Table 15. Examples of use case's KV/KVI definitions for SNS JU Stream B and D projects	60
Table 17. Examples of KPI values for several 6G SNS Stream B/D project use	63
Table 18. Relation between KVIs and KPIs for some SNS projects.	64
Table 19. Prospective KPI family and names for 6G-TWIN	65
Table 20. Reference KPIs for Use Case 1.	68
Table 21. Reference KPIs for Use Case 2	71



D1.1 – Architecture and technical foundations (Initial)

1 INTRODUCTION

The rapid digitization of industries necessitates advancements in network technologies, particularly as we transition towards 6G systems. The **6G-TWIN** project addresses this need by proposing an AI-native reference architecture that incorporates Network Digital Twins (NDTs).

In this chapter, we will outline the aims and objectives of the **6G-TWIN** project, emphasizing its core mission to develop a sophisticated network framework. We detail the specific objectives that guide the project mapped into the objectives of the Deliverable 1.1 (D1.1), which presents the preliminary architectural components and requirements for the **6G-TWIN** system, highlighting the interrelation of this deliverable with other project activities, ensuring a cohesive approach to developing the next generation of network technologies. The relation of the task challenges with other parts of the project is explored in Section 1.3. Finally, the main description of the deliverable is presented, and the contributions of all partners are offered.

1.1 Aims and objectives

1.1.1 6G-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 realize this vision, **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.



1.1.2 Deliverable objectives

The present document is D1.1, “6G-TWIN Architecture and technical foundations (initial)”, presenting the preliminary architectural components, requirements and KVs/KPIs mapped into the project use cases to finally proposing a 6G-TWIN System Architecture. It will be updated to a final version at Month 36.

In specific, the objectives of this document are to gather the requirements for the 6G-TWIN solution and design its architecture. This involves performing an in-depth analysis of the current 5G network architecture and exploring new technologies such as AI and NDT that are likely to shape the 6G landscape. It also aims to identify specific requirements for the 6G-TWIN by engaging with a wide range of stakeholders, including industry experts, academic researchers, and application developers, and extending these discussions to various use cases. Additionally, this deliverable includes a design of the architecture of 6G-TWIN as an open end-to-end system that can integrate different NDT systems to train and validate AI-based network functions and services for intelligent decision-making and optimization in real-time. The architectural design will focus on identifying key components necessary for native AI and NDT support, specifying open and standardized interfaces to ensure interoperability across different technologies, and producing detailed requirements specifications and the overall network architectural design.

1.2 Relation to other activities in the project

The D1.1 deliverable is the result of the Task 1.1 (T1.1), which aims to gather the needs for the 6G-TWIN solution and design its architecture. Specifically, the task will perform an in-depth analysis of the current 5G network architecture and assess emerging technologies such as Artificial Intelligence (AI) and NDT that will shape the 6G landscape. It will identify the specific requirements for the 6G-TWIN by merging a wide range of stakeholders, including industry experts, academic researchers, and end-users/application developers, with extensions to various use cases. Additionally, the task will design the architecture of the 6G-TWIN as an open E2E system that can integrate different NDTs and use them to train and validate AI-based Network Functions and Services (NF/NS) for intelligent decision-making in real-time.

During the architectural design phase, this task will focus on identifying the key components of the system architecture required to enable native support for AI-based NF/NS and NDT, as well as specifying open and standardized interfaces that allow different networking components and NDT systems to interoperate, even if they are built on different underlying technologies. This includes producing requirement specifications in terms of both expected functionalities and objective technical indicators, to focus on the network architectural design.

This deliverable forms the foundation for the next tasks in this work package (WP1) and guides the activities in WP2 and WP3. It ensures that the 6G-TWIN requirements and network architecture design meet the needs of next-generation networking systems, focusing on native AI support and the integration of NDTs. WP1 is key to enable the work on NDT and simulation, as represented in Figure 1 below. By defining the architecture and requirements, this deliverable directly influences WP2, which will specify the capabilities and technological needs of 6G NDTs. WP2 will use this framework to integrate a data layer for real-time data management and propose models for virtual network representation, essential for developing predictive and reactive network management solutions. Additionally, this deliverable guides WP3, which aims to create a reliable DT of the 6G system. The architecture and requirements defined here will help WP3 develop a discrete-event simulation model for testing and optimising the 6G system under various conditions. The outputs from WP2 and WP3, including simulation models and user dashboards, will work together to accurately represent and efficiently manage the 6G network, ensuring all work packages are aligned with the project's objectives.

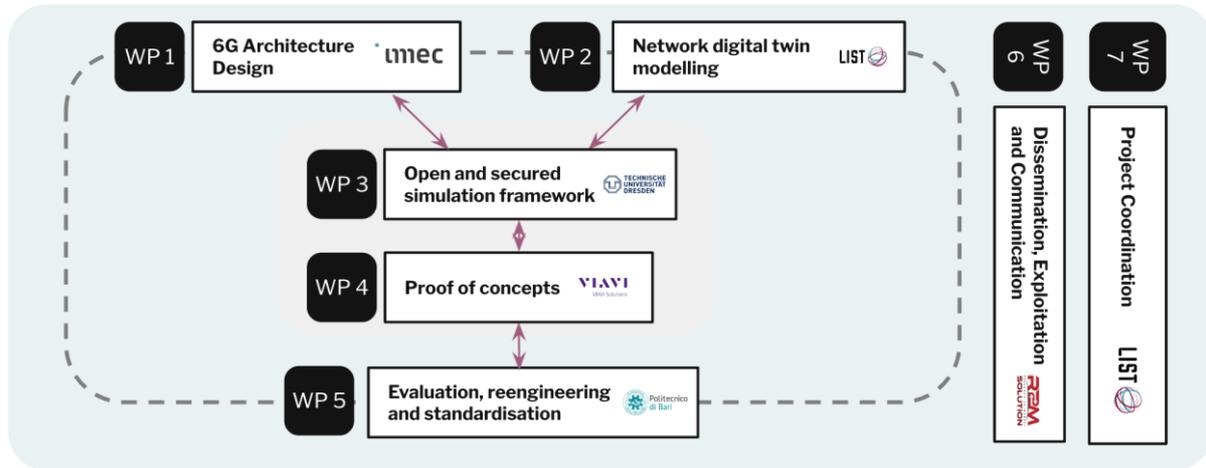


Figure 1. 6G-TWIN PERT chart.

1.3 Document structure

The present report covers a series of aspects related with the network architecture for 6G Digital Twin (DT) environments and how the 6G-TWIN project addresses them. In [Section 1](#), the introduction sets the stage for the report by outlining the overarching goals of the 6G-TWIN project, which is dedicated to creating an AI-native reference architecture for 6G systems. The project's core objective is to integrate NDTs to optimize, manage, and control future networks in real-time. The introduction details four specific objectives: crafting an open federated AI-native network architecture, constructing a graph-based NDT, implementing a robust modelling and simulation framework, and testing and validating solutions through practical use cases such as tele-driving and energy efficiency. These objectives are designed to revolutionize network efficiency and performance, paving the way for next-generation connectivity and innovation. Additionally, the section discusses how the report is connected to other activities within the 6G-TWIN project, emphasizing the collaborative nature of the project. The contributions of various partners are acknowledged, highlighting how their expertise enriches the report's content, ensuring comprehensive coverage of the subject matter.

In [Section 2](#), the architecture for 6G and NDT is presented. It comprises the roadmap from 5G to 6G, detailing the evolution and expected advancements in wireless communication technology. The first architecture definitions and enablers are presented and mapped into the vision for 6G is to create a seamless reality where the digital and physical worlds merge, providing new ways of interaction and work. The requirements for developing NDTs are discussed, including accurate data collection, advanced modelling techniques, and integration with AI/ML algorithms, to define the basic and functional models of the NDT. The section also explores AI-native architectures and their role in enhancing network functionalities, presenting perspectives from both industry and academia on embedding AI within network operations to facilitate real-time analytics and decision-making.

[Section 3](#) provides a comprehensive overview of the simulation frameworks and simulators essential for evaluating and analysing network performance, protocols, and applications within lab environments. This section begins by emphasizing the importance of software-based discrete-event network simulators, widely used across academia, research institutions, and industry, to facilitate network protocol development and performance evaluation. It addresses the challenges these simulators face, such as ease of use, scalability, realism, and accuracy in complex Radio Access Network (RAN) environments. The section delves into the development of network emulators to support NDTs, detailing the creation of digital replicas of physical RAN environments and the generation of synthetic datasets for AI/ML model training. It further explores various simulation frameworks, performing a literature review on existing works, and examining the taxonomy of simulators, including real-time simulators, HLA-based simulators, UAV simulators, robotic simulators, and vehicular simulators. The section



concludes by discussing both industrial and research-focused simulation tools, highlighting their roles in advancing network technologies, and introducing the specific tools planned for use in the **6G-TWIN** project.

Section 4 delves into the functional and non-functional requirements necessary for the **6G-TWIN** architecture. It focuses on the required features and capabilities, such as advanced data collection mechanisms, zero-touch management, federated Management and Orchestration (MANO), and a comprehensive simulation framework. Effective data collection methods and technologies are discussed, emphasizing the importance of a robust telemetry framework for real-time data acquisition. The principles and technologies behind zero-touch management are outlined, highlighting how AI-driven automation allows for self-optimizing and self-healing network operations. Federated MANO is described as essential for managing complex and distributed network environments, detailing its architecture and processes for efficient coordination of network resources. The section concludes with a detailed description of the simulation framework, a cornerstone of the project, enabling comprehensive testing and validation of the proposed architecture.

In **Section 5**, reference use cases and KPIs are discussed to assess the success and impact of the **6G-TWIN** project. KVis and KPIs relevant to the project are outlined, explaining their importance and how they will be measured. The section explores the primary use cases, such as teleoperated driving and energy savings in dense deployments. For teleoperated driving, expected functionalities and KPIs are detailed, emphasizing the requirements for low latency, high reliability, and robust data transmission to improve safety and efficiency. The energy efficiency use case discusses strategies and technologies to reduce energy consumption in 6G networks, highlighting the functionalities and KPIs related to optimizing network resources and leveraging AI for dynamic energy management.

Section 6 presents the **6G-TWIN** system architecture, detailing the components and functionalities across different layers. The physical network layer incorporates AI-based designs to enhance performance and efficiency. The digital network layer focuses on data and model management, essential for creating and maintaining accurate NDTs. It explains the basic and functional models and the harmonized data repository that supports these models. The section also discusses open challenges, such as security, openness integration, AI integration and orchestration, and distributed ML, emphasizing the need for ongoing research and development to address these challenges.

Finally in **Section 7**, the report concludes with final remarks, summarizing the key findings and contributions of the **6G-TWIN** project. The section starts discussing open challenges, such as security, openness integration, AI integration and orchestration, and distributed ML, emphasizing the need for ongoing research and development to address these challenges. It reflects on the progress made towards achieving the project's objectives and outlines the next steps for further research and development. The conclusions emphasize the transformative potential of the **6G-TWIN** architecture in shaping the future of network technologies. The section also outlines future directions for the project, identifying areas requiring further exploration and development, and stresses the importance of continued collaboration among project partners to achieve the long-term goals of the initiative.



1.4 Contribution of partners

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

Table 1. Partners contributions to the D1.1 deliverable.

Partner	Sections	Contributions
LIST	1, 2.2, 5.3, 6, 7.	LIST has contributed to Section 2 by integrating the foundational concepts of DTs, and focusing on NDTs, their diverse use cases, and reference architectures. LIST examined the evolution of NDT technology from different perspectives, namely, standardisation bodies, academia, and industry, comparing this new concept to simulation frameworks. LIST also contributed to the use-case definition and transversally to the integration of the NDT concept in the document.
IMEC	2 , 5.3, 6 .	Leveraging its expertise in AI-native architectures, IMEC contributed a literature review on their integration with NDTs for Section 2. As leaders in the proposed Energy Savings use case, IMEC described this use case in Section 5.3. Finally, it helped design the 6G-TWIN architecture and identified several open challenges for future project phases.
POLIBA	2.3.	POLIBA contributed to the writing of Table 6 to present an overview of academic contributions to AI-Native network architectures, serving as a foundational reference to pinpoint future research gaps.
UBOU	5.1, 6.2, 6.3.	UBOU mainly contributed to section 5.1 related to KVI and KPI within European projects. UBOU also contributes to section 6 in describing the functional models of 6G-TWIN Layer 2 System Architecture.
TUD	2.3, 3 , 5.2	TUD focused on the simulation framework, for which the state of the art (section 2.3) and the planned contributions in the 6G TWIN project (section 5.5) have been described. Additionally, TUD contributed to the teleoperated driving use case (section 5.2).
UBI	3.1, 3.3, 3.4, 4	Ubiwhere contributed to the section of functional and non-functional requirements, focusing on the identification of supporting functionalities, zero-touch management and federated MANO subsections. Furthermore, Ubiwhere as the lead of the section unified the information of section 4.
ACC	1-6 (1 , 5 , 7)	Accelleran as the document leader, has reviewed and edited the whole document. The main contributions are focused architectural description of the NDT from the industry point of view and their implementation under O-RAN specifications including data translation and management (Telemetry Framework) for the RIC entity. Also, it contributes with the KVI-KPI description and the Energy Savings Use Case.
EBY	7.1	EBY contributed to Section 7.1.1 regarding security and privacy requirements for 6G architecture integrating DTs. The contribution included the state of the art and the roadmap to ensure security and privacy. Furthermore, EBY served as the reviewer for Section 2: Architecture for 6G and NDT.
PX	2.1	PX contributed transversally to Section 2.1 by providing regular feedback on the content and the perspective from a mobile network operator.
VIAMI	2.3, 3.3, 3.4.	Viavi contributions to the document in section 2.3, particularly in the realm of network emulation to support NDT. Their provision and development of a DT of a 5G Core Network, coupled with the TeraVM Core Emulator, have been instrumental in simplifying the testing and development process for tele-assisted driving and optimizing the performance of 5G User Equipment (UE). Additionally, Viavi described its RIC Test offering comprehensive training and testing capabilities for wireless networks, covering various standards and protocols such as O-RAN, LTE, and 5G. By emulating real-world RAN topologies and scenarios, it enables training AI/ML models for critical use cases like Traffic Steering, Energy Savings, and Admission Control.

Bold numbers represent section technical leaders



2 ARCHITECTURE ENABLERS FOR 6G AND NETWORK DIGITAL TWINS

This section describes the theoretical foundation for the subsequent sections, focusing on the transition from 5G to 6G networks and the associated technological advancements. We begin by describing the need for a new architectural framework for 6G by identifying the primary drivers behind the shift to 6G. Next, we explore NDTs, detailing their definitions and components. We also examine the techniques employed in constructing NDTs, such as AI/ML algorithms and simulators. Finally, we review recent proposals on AI-Native architectures and their envisioned role in the development and enhancement of NDTs.

2.1 Road from 5G to 6G

The roadmap from 5G to 6G is a journey that is already well underway, with the sixth generation of cellular networks expected to become available early in the 2030s [1], [2]. Beyond improving the performance of its predecessor in terms of throughput, latency, coverage and spectrum efficiency, 6G is expected to impact and contribute to the societal, business and policy goals. Here are some key points on the roadmap from 5G to 6G:

- **6G Vision:** The vision for 6G is built on the desire to create a seamless reality where the digital and physical worlds as we know them today have merged [1]. This merged reality of the future will provide new ways of meeting and interacting with other people, new possibilities to work from anywhere, and new ways to experience faraway places and cultures [1], [3]. 6G also introduces new capabilities, including coverage, sensing-related features, AI-related functions, sustainability, interoperability, and positioning. Many of these capabilities lack clearly defined metrics. Therefore, new methodologies, such as KVIs, and widely accepted frameworks need to be developed.
- **AI-Native integration:** Unlike 5G, which treats AI and ML as add-ons, 6G will integrate AI into core functionalities from the outset of design and development [4]. For instance, the AI-Native air interface [5], replaces all primary building blocks with AI models, improving performance and reducing the complexity of wireless transmissions. Additionally, meeting the stringent requirements of newer services necessitates complex network management solutions. This complexity can be effectively managed through enhanced network automation, largely facilitated by AI and ML adoption.
- **Cyber-Physical Continuum:** 6G will make it possible to move freely in the cyber-physical continuum, between the connected physical world of senses, actions, and experiences, and its digital representation [1]. The cyber-physical continuum of 6G includes the metaverse as it is typically understood – a digital environment where avatars interact in a VR/AR world – and goes further, providing a much closer link to reality [1],[6].
- **Technology Development:** To enhance the capacity and coverage of 6G networks, new technologies will be developed. Cell densification will be increased to improve coverage, including solutions to boost spectral efficiency. Achieving new efficiencies over 5G, may be challenging. Innovations such as massive MIMO [7] and usage of higher-frequency bands, like sub-THz [8], aim to offer higher peak rates. Additionally, reconfigurable intelligent surfaces [9] promise to enhance coverage reliability in various environments on a larger scale. The use of non-terrestrial networks [10], is also a promising development for expanding 6G capabilities.



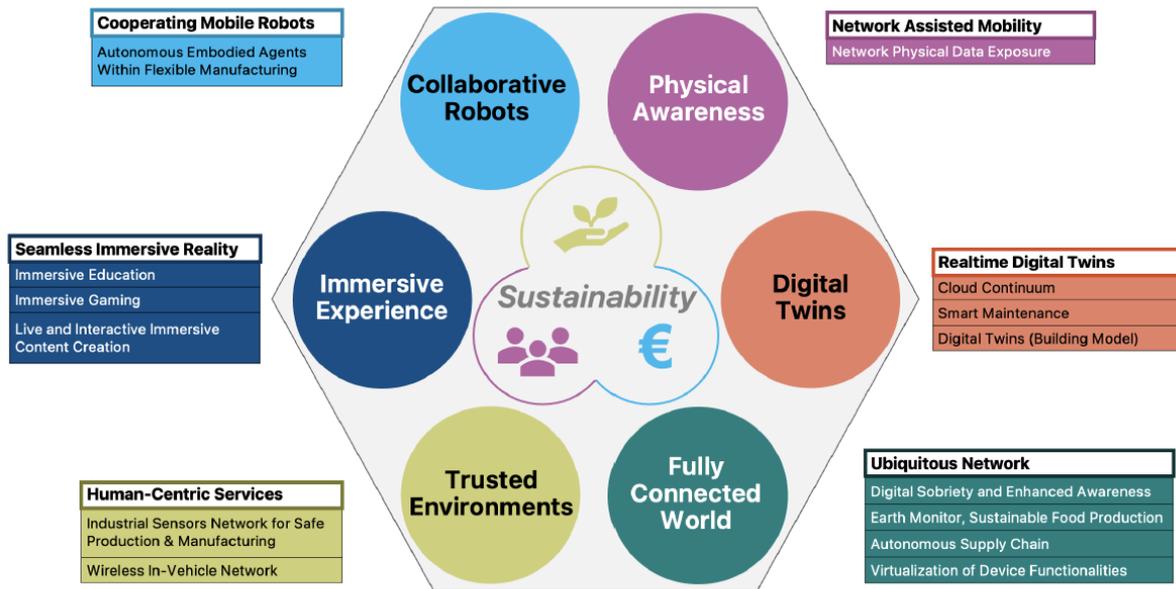
- **6G Use Cases:** The 6G usage scenarios extend the eMBB, mMTC, and URLLC vision of 5G into six new categories [9], [11]: Immersive Communication, Hyper Reliable and Low-Latency Communication, Massive Communication, Integrated AI and Communication, Integrated Sensing and Communication, and Ubiquitous Connectivity. Examples of important 6G use cases include e-health for all, precision health care, smart agriculture, earth monitor, DTs, cobots and robot navigation [1]. These scenarios demand significant enhancements in KPIs, surpassing the capabilities of 5G.
- **5G Advanced:** Just as the roadmap to 5G involved a stepping stone from 4G to standalone 5G in the form of LTE and RAN-enabled 5G, so there will need to be an intermediary step on the journey between standalone 5G and 6G. Also known as '5G Advanced', this evolution of the 5G standard is planned for rollout in 2025 and will improve on current 5G capabilities [2].
- **Next G Alliance Roadmap:** The NGA roadmap working group just issued its Roadmap to 6G report in February 2022. The report identifies 6 “audacious goals”: Trust, Security, and Resilience; Digital World Experiences; Cost Efficient Solutions; Distributed Cloud and Communications Systems; AI-Native Wireless Networks; and Sustainability [1], [12].

The transition from 5G to 6G represents a significant evolution in wireless communication technology, promising to enhance and expand the capabilities introduced by 5G. Despite these advancements, 5G has its limitations. It struggles with coverage gaps, particularly in rural or densely obstructed areas, and has high energy requirements for dense networks. Additionally, handling an increasing number of connected devices with high efficiency remains challenging.

The development of 6G is driven by emerging needs that surpass the capabilities of 5G. Future applications like immersive Augmented Reality (AR) and Virtual Reality (VR) will require even higher data rates, while applications like real-time holographic communication and advanced robotics will demand near-instantaneous response times. 6G aims to provide seamless global coverage, including remote and underserved regions, and integrate AI and machine learning for smarter network management and optimization.

Key innovations in 6G include the utilization of terahertz (THz) frequencies to achieve ultra-high data rates and bandwidth. Advanced AI and machine learning will drive network management for dynamic resource allocation and optimization. Quantum communication will enhance security and data transmission capabilities, while edge computing will bring computational power closer to the data source to reduce latency. Reconfigurable Intelligent Surfaces (RIS) will improve signal strength and coverage by controlling electromagnetic waves, and Integrated Sensing and Communication (ISAC) will combine communication and sensing functions for applications like smart cities and autonomous systems.

Global efforts and standardization are crucial for the development of 6G. Major tech companies, academic institutions, and government bodies are investing heavily in research. Organizations like the ITU and 3GPP are working towards global standards, while early testing and pilot projects are being conducted to understand real-world challenges and refine technologies. For example, the "Hexa-X: A flagship for B5G/6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds" is the pilot 6G initiative of the European Commission aiming to define the role of 6G in societal evolution [13], [14]. The project outlines six main research challenges, providing a foundation to forecast relevant use cases for 6G while considering societal and economic trends. Here, we present an initial, non-exhaustive set of use cases as a baseline to guide future 6G research directions, reflecting current European research activities driven by the 5G PPP and 6G-IA initiatives. These use cases range from evolutionary enhancements of 5G capabilities to disruptive innovations that could transform society as depicted in Figure 2.



Hexa-X-II Use Cases with **Highlighted** Representative Use Cases

Figure 2. 6G Use Case Families based on Hexa-X-II [14] .

The transition to 6G necessitates a new architectural framework to address the limitations and gaps in the current 5G system as defined by the 3GPP. This requirement arises from emerging technological trends and the evolving needs of use cases that mandate the incorporation of several critical components within the 6G architecture [15].

A significant aspect of the new 6G architecture is the integration of AI. With advancements in computational resources, edge- and cloud-computing, and the increasing availability of network and application data, AI can now be applied to almost every aspect of mobile networks. This integration enables automated network operation and user application/service support. To harness the full benefits of AI, 6G systems must be pervasive in AI and computation, necessitating a data-driven architecture. The vision for 6G includes leveraging AI to optimize the air interface, such as physical layer configuration, mobility, resource management, and Quality of Service (QoS) assurance. Moreover, 6G aims to transform the network into a powerful distributed AI platform, making AI as a Service (AlaaS) a pivotal enabler. Additionally, programmability is another cornerstone of the new 6G architecture. While programmability has long been a feature of network devices, the past decade has seen significant enhancements, particularly with the advent of Software-Defined Networking (SDN) and the ongoing trends towards softwarization, edgification, and cloudification. Furthermore, the 6G architecture emphasizes a cloud-native, softwarized, and service-based approach. The 6G architecture must be flexible to accommodate new types of end-user devices and access network topologies, necessitating dynamic functionality upgrades and function distribution to match changing deployment needs.

Another critical reason for a new architecture is the realization of the Continuum Orchestration concept, which represents the evolution of regular management and orchestration techniques towards a continuum that jointly combines different orchestration domains: Core Network (CN), transport network, edge, extreme-edge, and other networks external to the Mobile Network Operator (MNO), such as fixed access networks or private networks.

According to the Networkworld Europe, the 6G vision emphasizes the integration of advanced Information and Communication Technology (ICT) systems to support a broad range of future applications beyond 5G's capabilities. These include telepresence with robots and holography, high-resolution AV and VR for gaming and professional use, automated machines and vehicles, collaborative robotic systems, comprehensive environment sensing, and body monitoring for healthcare. The vision seeks to overcome traditional separations in computing



and communication infrastructures, advocating for a seamless integration of various domains and services. 6G systems will dynamically aggregate service execution platforms with more intelligence and computing power, enabling real-time reconfiguration and deployment of new services. This transformation aims to support a vast number of devices generating and processing large amounts of data, enhancing efficiency and effectiveness through IoT and cyber-physical system integration. To support this, the 6G system architecture will feature highly dynamic, reprogrammable networks that integrate various connectivity modes and technologies, supporting both local and remote objects across different environments. The architecture will manage end-to-end service execution in dynamically composed environments with components from different authorities, addressing both technological performance and societal aspects. AI and machine learning (AI/ML) will optimize deployment, adaptation, and decision-making processes, generating insights from data and enhancing system modularizations. However, AI/ML implementation must consider trade-offs, as it requires significant data transfers, computational resources, and energy consumption. The goal is to develop a cohesive system that balances these demands while ensuring security and minimizing risks. The future network technology will support both the general Internet economy and specific needs of cyber-physical infrastructures, integrating diverse connectivity technologies for a seamless user experience.[16]

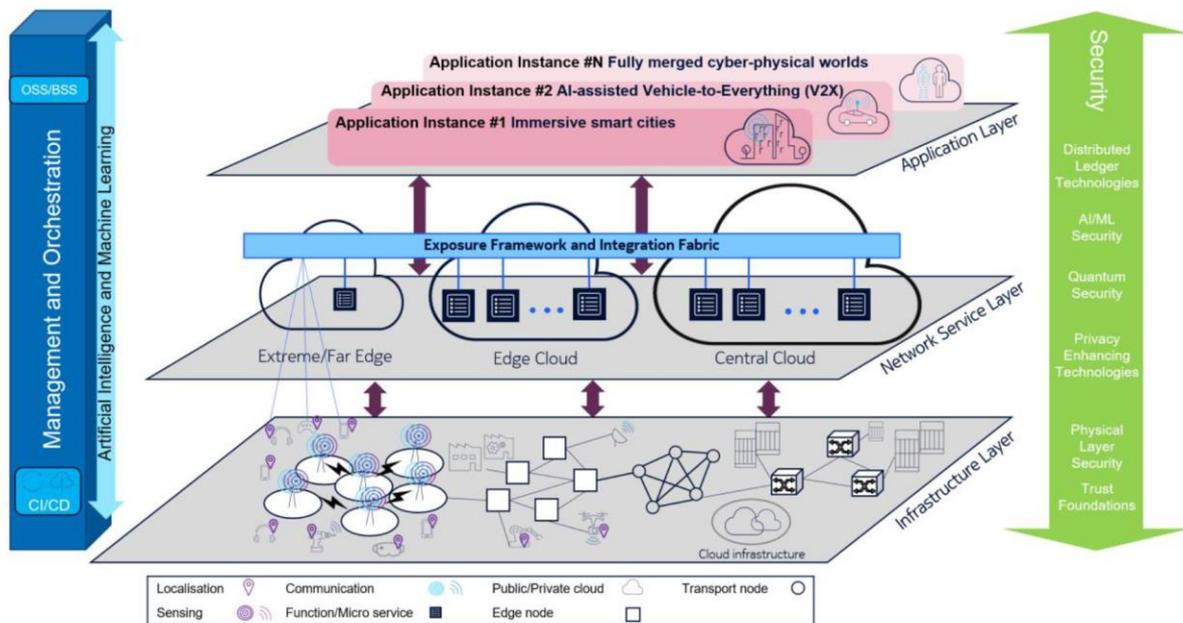


Figure 3. High-level 6G Architecture based on the 5G PPP [17].

The 6G End-to-End (E2E) architecture proposed by the 5GPPP is organized into three primary layers: Infrastructure, Network Service, and Application [17]. The infrastructure layer contains Network RAN, Network CN, and Transport networks, providing the physical resources to host network services and application elements. This layer accommodates new enablers such as localization and sensing, with RAN improvements facilitating extremely low latency, high reliability, high data rate, high capacity, affordable coverage, high energy efficiency, and accurate localization. The network service layer, envisioned to be cloud and micro-service-based, extends from central cloud to the extreme edge cloud. By implementing all network functions, operations, and applications as microservices, the architecture moves towards a softwarized, intelligent, and efficient framework. The introduction of the extreme cloud within this layer supports a high heterogeneity of devices, including personal devices and a wide variety of Internet of Things (IoT) devices, necessitating cloud-native technologies to create cloudlets at the network edge.



Network management and orchestration in 6G are advancing towards full automation with AI/ML, enhancing reliability, flexibility, and resilience through seamless continuum orchestration across device-edge-cloud infrastructures. Security and privacy are crucial, employing a decentralized framework with blockchain to protect data across all layers. Privacy-enhancing technologies and AI/ML security are vital for safeguarding functions, while distributed ledger technologies provide "distributed trust" without central authority, essential for interdomain management.

This architecture follows the principles guiding the development of the 6G architecture include the exposure of capabilities, full automation through AI/ML, flexibility to different topologies, scalability, resilience and availability, service-based interfaces, separation of network function concerns, and overall network simplification. These principles ensure that the architecture remains adaptable, efficient, and robust, addressing the needs of future mobile network deployments. Following this vision, we propose an enhanced AI-Native **6G-TWIN** in Section 6 where the Physical and Digital network are fully explained and mapped into this layered 6G High-level architecture.

2.2 Introduction to NDT concepts, use-cases, and reference architectures

This section aims to review the foundational concepts of DTs, explore the specific domain of network digital twins, and review their diverse use cases and reference architectures. We examine the evolution of DT technology from different perspectives, namely, standardisation organizations, academia, and industry, comparing this new concept to simulation frameworks.

2.2.1 Background on Digital Twins

The Digital Twin concept originated from an industrial context, notably at the National Aeronautics and Space Administration (NASA) [18] where they were developed to understand and predict the behaviour of spacecrafts during mission. Those early twins were not necessarily fully digital, a physical copy of the spacecraft was also realised on earth and all actions from astronauts were reported to the physical copy. It was then transferred to the production industry, inspired by works product lifecycle management [19].

More recently, DT had many definitions, and the concept is being applied to many domains. As a general definition: DT is a virtual representation of a physical entity, designed to collect and transmit real-time data to and from its Physical Twin (PT) counterpart, facilitating a two-way interaction [20]. It offers some services such as simulation, analysis, prediction, etc. [21]

In practice, achieving a full bidirectional data flow between the physical system and its virtual representation is highly challenging. Thus, we talk about digital shadow [22] which are synchronized manually, lacking data and partially implements this bi-directional flow.

DTs are largely relying on communication networks to support bi-directional communication flows. At the same time, due to the increased complexity networks and their increasing utilisation, networks themselves must leverage DT technology to pursue improved and optimized solutions, rather than solely relying on the physical network [23].

Generic DT architectures

The Digital Twin Consortium (DTC) [24], supported by the Object Management Group (OMG) proposes a reference DT architecture and notably its key capabilities. Grieves [21] first proposed a conceptual architecture for DTs with three elements: The DT, the PT, and the connections between them.



This initial concept lacked the idea of external services or a data store. It originated from NASA's experiments where a virtual system mirrored the physical one in real-time.

Later architectures [25], [26] expanded on this core concept by introducing additional elements while maintaining the core idea of replicating the physical system. Five-element architectures, for instance, included: Physical entity, Virtual entity, Database, Set of services, and Connections between them. There are varying definitions of the DT itself. Some proposals define it as all the elements combined [25], while others, including the DTC, consider it solely the digital replica. Additionally, some architectures separate the DT from the data base and connections but include optimization services [26].

The International Standards Organization (ISO) architecture for DTs in Manufacturing [27] aligns with recent proposals, including a DT Framework that excludes the physical system. A study by [28] provides a comprehensive overview of software architectures for DTs. It covers both well-established architectures and those designed for specific systems. The paper also introduces a two-dimensional classification based on abstraction and detail levels, along with a valuable catalogue of 14 quality attributes relevant to DTs. The authors of [29] propose using Domain-Driven Design (DDD) [30] for designing DTs architectures instead of predefined reference models. Analysing the advantages and disadvantages of designing a new architecture using DDD versus implementing an existing one presents an interesting research opportunity.

2.2.2 Towards a Network Digital Twin

Network Digital Twins serve as virtual replicas of physical network infrastructures, providing real-time insights and predictive capabilities. Concerning 6G networks, a consensus has emerged among various references regarding the fundamental features and functionalities, largely aligned with the recommendations set forth by the ITU-T Y.3090 [31]. ITU-T Y.3090 outlines key aspects essential for NDTs, summarized by data, mapping, modelling, and interface.

Given the high complexity and requisite processing power, constructing a single NDT that encompasses all network aspects and scenarios is impractical. Therefore, the development of an NDT is inherently use-case-driven, with its data and models chosen precisely to the scenario it serves.

NDT use-cases

References such as [32], [33], [34] identify the main NDT use cases, that could be categorized into four main groups.

- **Planning:** NDTs can be used to plan the network ahead of deployment and optimize the locations of Base Stations (BSs) according to the area population and surroundings. This use case facilitates network expansion by integrating new equipment such as, new BSs, RIS, or Non-Terrestrial Network (NTN) access points. Data exchange between the NDT and the physical network is minimal during planning, relying instead on pre-existing network and equipment information and data from complementary DTs such as the City Digital Twin (CDT), as demonstrated in [35].
- **Monitoring:** This use case includes network anomalies detection and recovery, and risk prediction. The work in [36] reviews the state-of-the-art big-data approaches to detect and mitigate cellular network anomalies effectively. The NDT relies on data generated from the network measurements and parameters such as Call Detail Record (CDR), location information, User Equipment (UE) movement behaviour, reference signal received power, radio link failure report, and other [36]. Since monitoring is a critical use case, then there is a need for real-time data exchange between the NDT and the physical



network. However, the collected data can be stored temporarily and used to train the NDT models for an enhanced anomalies detection in the future.

- **Optimization:** NDTs will be widely used for optimization purposes since it is the primary goal for network operators and service providers. Here also we can differentiate between two types of optimizations:
 - *Short-term optimization:* This type of optimization is performed in real-time to respond to the needs of a temporary situation, e.g. optimal resource allocation, handover management [37], and enabling autonomous driving (or teleoperated driving).
 - *Long-term optimization:* This type involves training AI/ML models on historical data for applications such as traffic prediction and energy saving. An example of implemented data-driven wireless network optimization is the Simulated Reality of Communication Networks (SRCON) framework [38], which incorporates key features such as beam-space construction, radio map formation, traffic prediction, UE association, and mathematical optimization to enhance wireless network performance.
- **Visualization:** Network visualization is essential in understanding and optimizing network behaviour, which is done using simulation and emulation framework, and testing “what-if” scenarios. Simulation and emulation provide a real-time representation of the network behaviour, aiding in the identification of potential bottlenecks, and areas of improvement. This is tightly related to conducting “what-if” analysis to explore various hypothetical scenarios and their potential to impact the network performance. The work in [39] proposes a what-if analysis module to the DTN, which utilizes Conditional Tabular Generative Adversarial Network (CTGAN) for synthetic data generation to simulate different network scenarios.

2.2.3 NDT Reference Architectures

In this section, we review the state-of-the-art NDT architectures from the perspective of different technology-influencing entities, namely: Standard Development Organizations (SDOs), academia, and industry. We highlight the key contributions from each sector and their distinctive approaches and differences.

Standard Development Organizations (SDOs)

The International Telecommunication Union (ITU-T) Y.3090 recommendations [31] have set the baseline for NDT architecture. The proposed architecture, highlighted in Figure 4, is composed of three layers: Application Layer, Digital Twin Layer, and Physical Network Layer.

- **Physical network:** The lower layer contains all elements related to the physical network, including real (e.g., gNodeB, UE) and virtual (e.g., spectrum resources, user-plane function, elements in the core network) 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 DT 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.



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 will be 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 is 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 (further details in WP2).

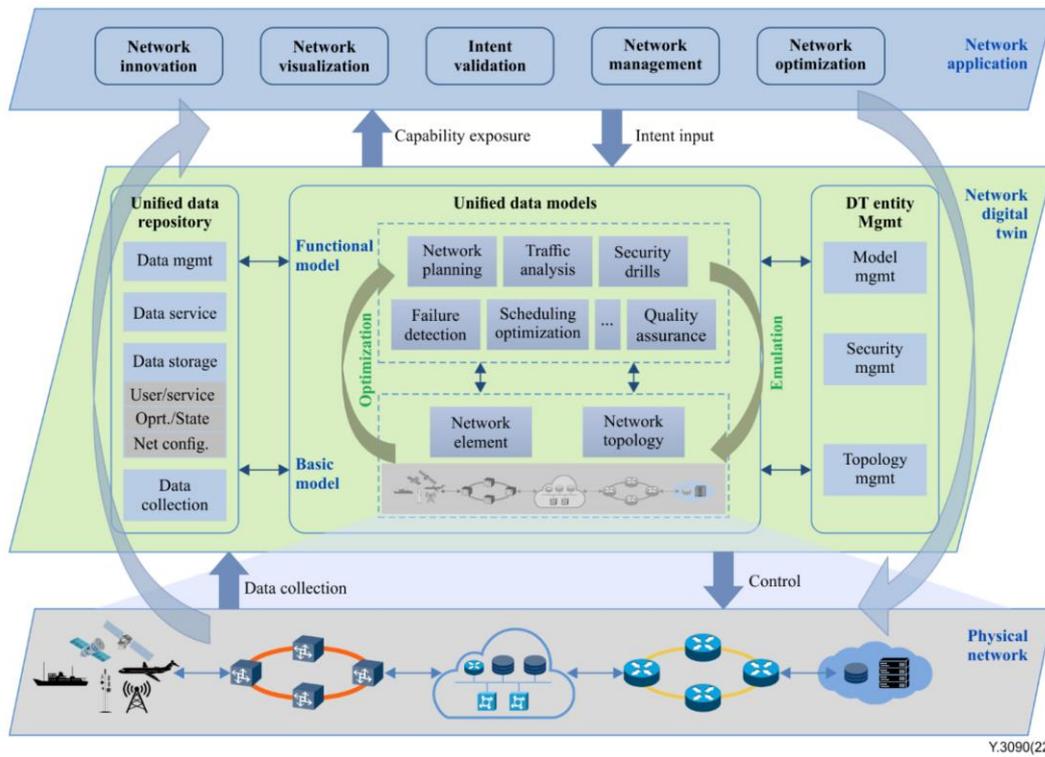


Figure 4. ITU-T high-level architecture [31].

Regarding other SDOs, the Third Generation Partnership Project (3GPP) proposes intended work for release 19 in 3GPP TR 28.915 [40]. This preliminary document explains the relation between NDTs and network automation functions, and how to integrate NDT models into these functions. It also reviews some of the important use cases for NDTs. Moreover, the European Telecommunications Standards Institute (ETSI) [32], and Internet Engineering Task Force (IETF) [41], both provide a similar view of the NDT architecture as the ITU-T recommendations.

Academic perspective

The scientific community started investigating AI/ML techniques for communication networks long before conceptualizing NDTs. In 2015, the article in [42], provided a detailed survey of how AI-based techniques apply to emerging heterogeneous networks. The authors describe how AI can be used to surmount several challenges related to management, optimization, and



maintenance of mobile networks, stemming from the fast-developing mobile communication industry. The use of the term DT for networks has first appeared in 2019 in the article "Deep Learning for Hybrid 5G Services in Mobile Edge Computing Systems" [43], which used Deep Neural Networks (DNN) to optimize energy efficiency for critical and delay-tolerance services in a Mobile Edge Computing (MEC) system.

In the meantime, academic research provides different perspectives of NDT architectures than SDOs. For instance, authors in [44] present a novel hierarchical DT network for satellite communication networks to facilitate the deployment and evolution of those. In this architecture, edge-DTs are deployed on ground stations near its physical entities. The Physical System (PS) is composed of on-orbit satellites, wireless links, and terminals. Each edge-DT builds a model for the physical entity based on the collected information, and performs real-time operations such as fault diagnosis, beam scheduling, radio resource allocation, and data processing. Edge-DTs communicate with central-DTs, deployed in a centralized Network Control Center (NCC). The central DTs are responsible of global network controlling by creating multiple isolated personalized central-DTs to meet diverse network management, and control requirements, including verification, global optimization, traffic engineering, and slicing management. In the system, one physical entity is only mapped to a unique edge-DT, whereas multiple central-DTs share edge-DT information. This method could significantly reduce the system overhead since the edge-DTs avoid redundant resource consumption from duplicating multiple DTs of the same physical entity for different central-DTs.

Some works focused on RAN NDTs. For instance, [45] proposes a framework that is aligned with both O-RAN Alliance and IETF specifications [41]. The proposed architecture includes three main modules: data repository, services mapping models (basic and functional models), and the DT management. The proposed architecture considers that different applications can make use of the RAN NDT. Each application is provided with a RAN NDT instance customized according to the specific requirements of the App. This customization can embrace the activation of selected service mapping models, the specification of the data to gather in the data repository, the definition of the required KPIs, the specification of analysis and visualization capabilities for the application, the specification of emulations if required, etc.

The comprehensive survey in [46] provides an overview of NDT requirements, use-cases, and challenges. The survey adopts IETF and ITU-T recommendations and considers four main characteristics for an DT, including data, mapping, model, and interface. It also describes the architectural framework of the NDT as a three-layer, three-domain, and double closed-loop architecture [31].

Industrial perspective

The concept of NDTs is gaining traction across the telecommunications industry, driven by the need to optimize and manage increasingly complex network infrastructures. NDTs provide significant advantages in terms of operational efficiency, predictive maintenance, and strategic planning.

One of the leading works from industry is the white paper presented by Spirent [47]. The paper defines NDT as emulated software and hardware replica of a 5G physical network, allowing for continuous prototyping, testing, assurance, and self-optimization. The proposed architecture by Spirent breaks down 5G network into several main components and emulates each one of them separately. The main presented components are the following:

- **5G Radio Channel Emulation:** Models new 5G RF channels, densities, and technologies.
- **gNodeB & eNodeB Emulation:** Emulates 5G and 4G base stations for various functionalities.
- **Fronthaul Emulation:** Models next-generation Ethernet fronthaul devices and traffic.



- **Core Network and Cloud Edge Emulation:** Emulates core network functions and their distribution to the edge.
- **Network Slices:** Emulates multiple network slices with different configurations and performance requirements.
- **Device and Traffic Emulation:** Simulates millions of devices to validate network performance.
- **GNSS Simulator:** Simulates satellite constellation signals with environmental control.
- **Real-World Emulation:** Replicates real-world signals and traffic for testing.
- **Impairment Emulation:** Models network impairments to test network behaviour and performance.
- **Security Threat Emulation:** Simulates complex multi-vector attacks to identify vulnerabilities.

The above architecture provides a high level of modularity and flexibility in testing and modelling the network using NDT.

Another white paper presented by ZTE [48], introduces yet a novel NDT architecture, by adding a service layer which aggregates capabilities into microservices, offering scalability, flexibility, and simplified maintenance. The service layer combines different NDT functions into nine microservices. These microservices act as containers for individual capabilities, all openly accessible and independent of different technical architectures, programming languages, and data storage methods.

1. **Data Collection:** Collects data from both physical and digital twin networks.
2. **Model Generation:** Refines and generates models from raw data using a blended approach.
3. **Simulation:** Utilizes a simulation engine for real-time decision-making.
4. **Strategy Optimization:** Optimizes network strategies based on simulations.
5. **Visualization:** Provides visual representations of data and simulations.
6. **Algorithm Deployment:** Facilitates the deployment of algorithms within the network.
7. **Data Augmentation:** Enhances data quality for better analysis.
8. **Fault Diagnosis and Prediction:** Identifies and predicts network faults.
9. **Physical Network Capability Provisioning:** Simulates network elements and their interactions.

Microservices 1 to 4 provide foundational capabilities, microservices 5 to 8 offer advanced functionalities, and microservice 9 represents the potential capabilities of future open prototype networks.

2.2.4 NDT data models

As shown in Figure 4, one of the key architectural components of NDTs is the unified data model, which is part of the middle layer (DT layer). It acts as the foundation for data-driven modelling, providing versatile model instances for various network applications. This enhances the agility and programmability of network services. NDT data models are classified in two main categories: basic and functional models. On one hand, a basic model [31] refers to the



network element model and network topology model of the NDT entity based on the basic configuration, environment information, operational state, link topology and other information of the network element, to complete the real-time accurate description of the physical network. In addition, basic models can help verify and emulate control changes and optimization solutions to ensure the effectiveness and reliability of the change control before it is sent to the entity network.

On the other hand, functional models serve as a pivotal enabler for NDTs. They are employed to model, optimize, and predict the behaviour of the network elements by leveraging previous insights and knowledge gathered from basic models. Given the complexity and scale of current networks, functional models mostly use data-driven approaches. They can be categorized by network type (single or multiple domains), function type (state monitoring, traffic analysis, security drill, fault diagnosis, quality assurance), and generality (general or special-purpose models). Moreover, the functional models can be combined across multiple dimensions for specific applications, e.g., a traffic balance optimization model for a core switch in a campus network.

Basic Models

The basic model involves modelling physical network elements and their interconnections, consisting of two main components: the network element model and the topology model [49]. The network element model represents various types of physical network devices such as switches, servers, gateways, and firewalls. However, given the variety in network manufacturers, a model normalization might be required, where only one model per device type is needed.

The topology model describes the physical network topology and the status of network flow and performance. It includes physical and logical connections, such as underlay, overlay, and VPN, to meet visualization needs. Additionally, network flow data and performance data from the physical network are superimposed on various topologies, creating a flow and stateful network topology model.

Basic models are typically built using network simulation and mathematical abstraction. A more detailed overview of network simulators is given in Section 3. Network modeling based on mathematical abstraction involves numerically calculating physical network data. Despite offering low resource consumption, such methods are affected by the large scale of modern networks.

Functional Models

The functional model involves creating various data models for network analysis, simulation, diagnosis, prediction, and assurance, using data from physical networks for specific application scenarios. These models leverage a unified data repository and can be constructed and expanded across multiple dimensions:

- **By Network Type:** Models can serve single or multiple network domains.
- **By Function Type:** Models can include state monitoring, traffic analysis, security drills, fault diagnosis, quality assurance, and more.
- **By Generality:** Models can be general or special purpose.

These dimensions can be combined to create specific application models. Moreover, functional models can be built using AI algorithms for tasks such as flow prediction, network performance prediction, and coverage optimization. Additionally, knowledge graphs can be used to develop functional models for network fault diagnosis and repair, continuously accumulating experience and knowledge to accurately model network maintenance scenarios.

Several works have investigated the modelling of network elements and dynamics through the construction of basic and functional models. For instance, Haddadi et al [50] survey the



approaches on network topology modelling and generation of the Internet topology at both the router and administrative levels. They also compared the mathematical models assigned to various topologies and the generation tools based on them.

Moreover, Zhou et al [51] focuses on modelling node energy consumption in Wireless Sensor Networks (WSN). It presents detailed energy models for the core components of WSN nodes, including processors, RF modules, and sensors, considering their different operational states and transitions. By utilizing an event-trigger mechanism, the paper aims to establish accurate node energy models to improve the precision of simulations, aiding in protocol development, system design, and performance evaluation. The study addresses the critical issue of energy consumption in WSNs, providing a framework for analysing energy usage, evaluating communication protocols, and optimizing node deployment and WSN applications.

More focused on the management of basic and functional models, Chen et al [49] presents a detailed classification of NDT models and a comparative analysis of model building, and the connection between the basic and the functional models through model orchestration is realized. More recently, Ferriol-Galmés et al [52] proposes a Graph Neural Network (GNN)-based network model able to understand the complex relationship between queuing policy (scheduling algorithm and queue sizes), network topology, routing configuration, and input traffic matrix, providing an accurate estimate of the end-to-end path delay. Such GNN model can support Service Level Agreement (SLA)-driven optimizations and what-if analysis.

Looking a broader perspective, Wen et al [53] provide a comprehensive critical overview on how entities and their interactions in Complex Networked Systems (CNS) are modelled across disciplines as they approach their ultimate goal of creating a DT that perfectly matches the reality.

Lastly, three surveys have been published in important journals in the last three years, which proves the relevance of NDT in current research. Firstly, Wu et al [54] presents a comprehensive survey of NDTs to explore the potential of DT and depict the typical application scenarios such as manufacturing, aviation, healthcare, 6G networks, intelligent transportation systems and urban intelligence in smart cities. Mihai et al [55] survey the key enabling technologies, challenges, prospects, design goals, research and commercial developments, applications, use cases, and future research dimensions of DTs, offering deep insights and case studies across various industries, including industry, infrastructure, and healthcare. Finally, Hui et al [33] identify three requirements (fidelity, efficiency, and flexibility) for performance evaluation of the basic and functional models, and present a comparison of selected data-driven methods to build them and investigate their potential trends in data, models, and applications.

2.3 AI-Native Architectures and link with NDTs

AI/ML is emerging as a critical enabler for the future of the telecommunications industry, particularly adept at addressing complex and large-scale network issues where traditional heuristic or exact modelling approaches fall short. Leveraging their ability to learn from vast amounts of data, AI/ML models are exceptionally capable of delivering rapid and accurate predictions, forecasts, and decisions. This capability is particularly transformative in areas like network optimization and strategic planning, where AI/ML can streamline processes, reduce operational costs, and enhance service delivery, positioning it as a cornerstone technology in the evolution of next-generation telecom networks. Consequently, the success and long-term viability of next generation systems will depend crucially on the effective integration of AI/ML solutions within the network architecture.

AI-Native telecommunication architectures are fundamentally designed and optimized to leverage AI and ML technologies, creating a new paradigm in network management and operation. Unlike traditional networks, where AI is often an add-on, AI-Native architectures integrate AI capabilities deeply into the core functions of the network. This integration allows



for more intelligent, adaptive, and efficient operations. Key characteristics of AI-Native architectures include the embedding of AI and ML algorithms directly into the network infrastructure, the ability to process and analyse data in real-time through edge computing, and the development of self-optimizing networks that can autonomously adjust parameters based on current conditions and predicted trends. These networks aim for high levels of automation, enabling self-configuration, self-healing, and self-management, thus reducing the need for manual intervention. Designed to be highly scalable, AI-Native networks can easily accommodate increasing volumes of data and the growing complexity of network services.

This section examines the cutting-edge developments in AI-Native architectures and their integration with NDTs. It considers perspectives from both academia and industry. From the industry angle, we examine the advancements by major SDOs in embedding AI/ML within network architectures to enhance core functionalities. Academically, we explore contributions from researchers and academic projects, scrutinizing how theoretical advancements are being translated into practical applications that could shape future network operations. This review aims to bridge the gap between academic innovation and industrial application, highlighting collaborative efforts that drive the evolution of network technologies.

In practical applications, AI-Native architectures play a pivotal role in enabling autonomous drive vehicles and creating energy-efficient networks. For autonomous drive vehicles, the integration of AI within telecommunications infrastructure is crucial for ensuring real-time communication and data processing capabilities. AI algorithms enhance the ability to manage vast amounts of sensor data from vehicles, enabling real-time decision-making that is essential for the safety and efficiency of autonomous driving. This includes optimizing traffic flow, reducing latency in Vvehicle-to-Everything (V2X) communications, and ensuring robust connectivity.

Energy-efficient networks benefit significantly from AI-Native architectures by optimizing resource allocation and minimizing energy consumption. AI-driven predictive analytics can forecast network demand and dynamically adjust network resources to align with actual usage, thereby reducing wastage and improving overall energy efficiency. Moreover, AI algorithms can identify and mitigate inefficiencies within the network, leading to more sustainable and cost-effective operations. By enhancing both performance and sustainability, AI-Native telecommunication architectures support the immediate operational needs of modern networks and contribute to long-term environmental goals.

2.3.1 Industry perspective

The integration of AI/ML in telecommunications is transforming network operations, particularly through AI-Native architectures and NDTs. Here we explore the advancements driven by 3GPP standards and the O-RAN Alliance in embedding AI capabilities within network infrastructures, adopting enhanced performance and operational efficiency. It also highlights the practical applications of NDTs in optimizing network functions, marking the vital role of AI/ML in the evolution of next-generation telecom networks by bridging academic research with industrial innovations.

The ITU role in AI-based networks

The ITU plays a pivotal role in advancing AI-native networks through various initiatives aimed at integrating AI/ML in next-generation communication systems, particularly 5G and beyond. These efforts focus on optimizing network performance, enhancing efficiency, and ensuring robust and scalable connectivity.

AI for Good [56] is a flagship initiative designed to leverage AI to tackle some of the world's most pressing challenges. Launched to advance the United Nations' (UN) Sustainable Development Goals (SDGs), the program seeks to harness AI technologies to address issues like poverty, hunger, health, education, and environmental sustainability in the context of



communication networks. By fostering collaborations across sectors, AI for Good aims to create practical AI solutions that can be implemented on a global scale.

One notable initiative under the AI for Good umbrella is the AI/ML in 5G Challenge [57]. This challenge focuses on applying AI and ML to optimize 5G networks, enhancing their efficiency, reliability, and scalability. Participants from over 100 countries work on developing AI models to solve real-world network challenges, such as resource management and anomaly detection. This initiative highlights the practical applications of AI in enhancing next-generation communication systems.

Additionally, ITU collaborates with industry stakeholders, academia, and research institutions to create standards and frameworks that guide the ethical and effective implementation of AI in telecommunications. By fostering a collaborative environment, ITU aims to ensure that AI technologies are used to create more intelligent, adaptive, and resilient networks. Through these initiatives, ITU is driving the integration of AI into network infrastructure, paving the way for more efficient, reliable, and scalable communication systems that can meet the demands of future digital economies and societies.

3GPP Standards and AI-Native Networks

3GPP has been pivotal in advancing AI-Native network architectures through a series of technical reports and specifications in its Release 18 [58], [59], [60], which marks the beginning of the 5G-Advanced era. This release focuses on integrating AI/ML capabilities to enhance network performance, reduce complexity, and improve operational efficiency. These advancements are crucial for supporting the increasing demands on mobile networks, driven by the proliferation of IoT devices, high-bandwidth applications, and the need for URLLC.

3GPP's approach involves embedding AI/ML models directly into the network infrastructure to enable real-time analytics and decision-making. The aim is to create self-optimizing networks that can autonomously adjust their parameters based on current conditions and predicted trends. This deep integration of AI/ML technologies helps in addressing complex scenarios that traditional methods struggle with, such as dynamic spectrum sharing, interference management, and predictive maintenance.

X. Lin in [61], [62] provide an overview of the various activities and efforts within 3GPP Rel18 concerning AI integration into 5G-Advanced networks. It details the study and work items dedicated to AI, emphasizing the importance of standardization for the widespread adoption of AI in telecommunications. The design aspects and rationales behind standardization, is presented in coherence of the 3GPP's AI activities as a cohesive framework aimed at enhancing network performance and efficiency through AI. Figure 5 illustrates the architectural framework and key components of AI integration within 3GPP 5G-Advanced. It outlines the interaction between AI functions and network elements, highlighting the roles of AI models, data collection mechanisms, and inference processes. The figure depicts how AI is embedded into various network layers, facilitating real-time data processing, predictive analytics, and automated decision-making. This integration aims to optimize network operations, enhance service delivery, and support advanced applications by leveraging AI's capabilities in a standardized manner.

The main important documents related with the architecture, framework, definitions and terminology are specified in TS 23.501 [59], TS 23.502 [60], TS 23.503 [63] and TS 23.288 [58] for the usage in the AI/ML native architecture in 3GPP. The TS 23.501 discusses the architecture of the 5G Core Network and its support for AI/ML operations. The architecture includes non-roaming and roaming configurations, integrating 3GPP and non-3GPP access. Specific AI/ML support is detailed, highlighting functionalities such as AI/ML operation splitting, model/data distribution, and federated learning. The Application Function (AF) can request the network to provide QoS for AI/ML operations, utilizing the Network Exposure Function (NEF) for monitoring and assistance. Member UE selection for AI/ML tasks, like federated learning, is supported by interacting with 5G Core NFs, such as Policy Control Function (PCF), Network Data Analytics Function (NWDAF), Access and Mobility Management Function (AMF), and

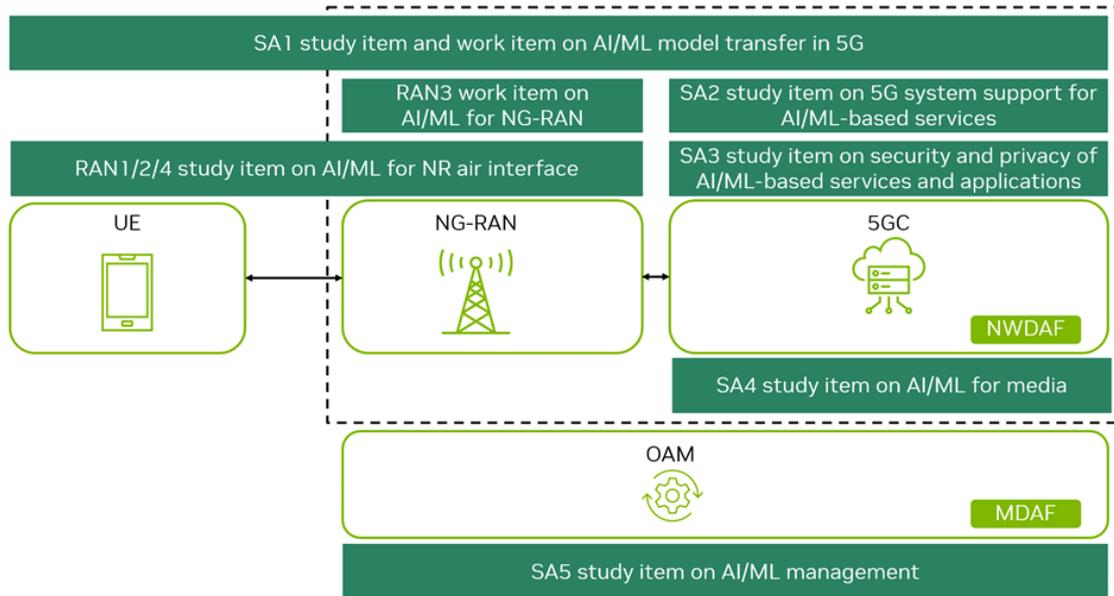


Figure 5. An overview of AI in 5G-Advanced in 3GPP Rel 18 [58]

Session Management Function (SMF). These capabilities ensure efficient AI/ML operations within the 5G ecosystem, facilitated by detailed procedures and compliance with 3GPP standards.

According to 3GPP TR 23.700-80 [64], [65], integrating AI/ML into the 5G system presents significant architectural challenges, particularly in monitoring network resource utilization, enhancing 5G Core (5GC) capabilities for information exposure, provisioning external parameters, optimizing traffic transport mechanisms, and enhancing QoS and policy controls. The need to track data throughput and session inactivity is crucial for efficient resource management, requiring new mechanisms within the network. Enhancing 5GC capabilities to expose relevant information to UE and third parties is essential for enabling intelligent decision-making and optimization processes, which necessitates developing new interfaces and protocols to manage the increased data demands of AI/ML applications. The document introduces the AI/ML Translator (AIML-T), which translates AI/ML-related assistance requests from UEs into analytics requests for the 5GC and converts the analytics information produced by the 5GC into assistance information for UEs. Additionally, the document discusses the Application AI/ML Assistance Network Function (AaML NF), which coordinates 5GC services to support AI/ML operations, and the NWDAF, which provides analytics to assist AI/ML applications by predicting network conditions and performance metrics. Additionally, provisioning external parameters such as environmental data into the 5G network architecture ensures AI/ML models have comprehensive data inputs. Optimizing traffic transport to handle the high volumes and specific patterns of AI/ML data demands rethinking traditional traffic management strategies to provide the necessary bandwidth and low latency for real-time operations. Finally, developing new QoS parameters and policy controls tailored to AI/ML traffic is vital for maintaining performance requirements, involving the creation of advanced monitoring tools and dynamic policy adjustment mechanisms based on real-time data and AI insights. Addressing these challenges requires significant modifications to the existing network architecture and the development of innovative interfaces, protocols, and management tools.

The 3GPP TR 28.908[66] report addresses AI/ML management capabilities in mobile networks, detailing management throughout the operational phases including training, validation, testing, deployment, and inference. It outlines the process of developing and fine-tuning models using historical and current data, evaluating model performance with test data to ensure accuracy and generalization, verifying model functionality in a controlled environment before deployment, and implementing the model in the network for live operations. It also covers the continuous use of the deployed model for real-time predictions



and decisions. The document emphasizes performance evaluation through continuous monitoring to ensure the model functions as expected, control through adjustments and updates based on operational feedback and network environment changes, and supervision to detect and correct issues promptly. It highlights the importance of security and reliability to ensure models are robust against threats and function reliably under various conditions. AI/ML integration into network functions includes latency reduction by optimizing network performance, resource optimization for efficient use of network resources like bandwidth and energy, and predictive maintenance to anticipate and prevent network failures. Challenges such as transparency in AI/ML decision-making, ethical considerations to prevent bias, and model adaptability to changing usage patterns and network conditions are also discussed. The document stresses the importance of interoperability to ensure AI/ML solutions are compatible across different systems and vendors, and international collaboration to develop common standards.

Some key areas that represent 3GPP's efforts to integrate AI/ML into network infrastructure, aiming to improve efficiency, reliability, and overall network performance in telecommunications [61], [67], [68]:

- **Channel State Information (CSI) Enhancements:** Enhancing frequency domain compression and time-domain prediction to better manage channel conditions and optimize network performance.
- **Beam Management (BM):** Developing AI/ML algorithms for spatial and temporal prediction to improve beamforming techniques, crucial for advanced radio networks.
- **Positioning:** Utilizing AI/ML for direct and assisted positioning, enhancing the accuracy and reliability of location-based services.
- **Network Slicing:** Implementing AI/ML to optimize resource allocation in network slices, ensuring that each slice receives the necessary resources based on demand and network conditions.
- **Traffic Management and Optimization:** Using AI/ML for network traffic management and optimization, improving traffic distribution and reducing congestion.
- **Predictive Maintenance:** Applying AI/ML techniques to predict failures and plan preventive maintenance, increasing network reliability and availability.
- **Energy Efficiency:** Optimizing network energy consumption using AI/ML algorithms, contributing to more sustainable and cost-effective operations.
- **Quality of Service and Policy Management:** Developing new QoS parameters and controls specific to AI/ML, ensuring that AI/ML-based applications meet performance requirements.
- **Security Enhancements:** Implementing AI/ML for real-time threat detection and response, identifying anomalous behaviours and potential attacks.
- **Federated Learning:** Supporting federated learning operations where AI/ML models are collaboratively trained using distributed data without the need for centralization.
- **Data Analytics and NWDAF:** Using the NWDAF to provide predictive and performance analytics that assist AI/ML applications.

These efforts ensure that AI/ML can be effectively embedded into the core functionalities of the network, enabling real-time decision-making and optimization.



O-RAN Alliance and AI Integration

The Open RAN (O-RAN) Alliance complements 3GPP's efforts by promoting the integration of AI/ML into open and intelligent radio access networks. O-RAN specifies several frameworks and standards to facilitate this integration. By fostering openness and interoperability, O-RAN aims to democratize AI/ML applications, ensuring they are accessible to a wide range of vendors and network operators.

O-RAN's initiatives are essential for creating a competitive ecosystem where innovation can thrive. This approach helps in overcoming the limitations of proprietary solutions, making AI-driven advancements more scalable and sustainable. The alliance's work spans various aspects of network operations, from real-time traffic management to predictive maintenance and energy efficiency. As described in [69] there is deep description into the integration of AI in the evolution of mobile networks, focusing on 5G-Advanced and the transition towards 6G and its integration with O-RAN perspective. It focuses the collaborative efforts between 3GPP and O-RAN to standardize AI technologies, facilitating their widespread adoption in telecommunications. Here, use cases like network optimization, predictive maintenance, and enhanced service delivery, are evaluated while proposing a roadmap for integrating AI into 6G networks to create more intelligent, adaptive, and efficient communication systems. Additionally, it details how AI addresses the complex requirements of modern mobile networks, providing examples of its impact on network automation, resource management, and user experience enhancement. By leveraging AI, the industry aims to achieve significant improvements in network performance, energy efficiency, and operational costs. Similar initiatives by the O-RAN community are listed below:

- **AI/ML Frameworks:** O-RAN develops modular and flexible frameworks for integrating AI/ML into RAN, enabling various AI-driven use cases.
- **Interoperability Standards:** Establishing clear standards for AI/ML integration to ensure seamless collaboration between different vendors' solutions.
- **AI-Enabled Traffic Steering:** Implementing AI models to optimize network traffic distribution, enhancing overall network performance and user experience.
- **AI/ML Model Lifecycle Management:** Managing the lifecycle of AI/ML models, including training, validation, inference, and deployment, ensuring robust and reliable integration.
- **Energy Efficiency:** Utilizing AI/ML to optimize energy consumption within the network, contributing to more sustainable and cost-effective operations.

The potential of O-RAN to replace hardware-specific RAN components with generic hardware, specialized software, and open signalling interfaces, propose a technology opportunity that facilitates the integration of AI/ML algorithms into RAN management, particularly at the user plane, enhancing 5G's capabilities such as network slicing and virtualization. This can be highlighted in [70] where software control over RAN enables faster analytics, supporting 5G's latency requirements and advanced usage scenarios like enhanced Mobile Broadband (eMBB) and ultra-Reliable Low Latency Communications (uRLLC). Additionally, an AI/ML network management and optimization platform is shown in [71], where the importance of AI in automating and enhancing decision-making processes in real-time is presented. By leveraging AI, O-RAN can dynamically adjust to network conditions, optimize resource allocation, and predict potential failures, thus improving overall network performance and reliability. The integration of AI/ML supports the goal of creating a more intelligent and adaptable network infrastructure. Also, the concept of Explainable AI is shown in [72] where the disaggregation of traditional RAN functionalities, the adoption of open interfaces, and a hierarchical control architecture managed by RAN Intelligent Controllers (RICs) is described. This survey details XAI methods, their deployment in O-RAN, and the automation of XAI pipelines, addressing challenges such as trust, security, and transparency in AI-driven network



management. The document emphasizes the importance of XAI in enhancing human understanding and trust in AI systems within the O-RAN ecosystem, facilitating more efficient and transparent network operations. Similarly, the EXPLORA framework, is designed to provide explainability for Deep Reinforcement Learning (DRL) control solutions in O-RAN [73]. Utilizing attributed graphs, EXPLORA links DRL agent actions with input state spaces, offering detailed AI decision explanations. This framework enhances transparency and trust in AI systems, tested on an O-RAN-compliant near-real-time RIC, showing significant performance improvements through better explainability.

The OpenRAN Gym, is an open-source toolbox designed for developing, testing, and prototyping AI/ML solutions compliant with O-RAN standards [71]. The framework integrates several software components to facilitate data collection, design, and deployment of AI/ML eXtensible Applications (xApps) on a near-Real-Time RIC. OpenRAN Gym enables researchers to test AI/ML models on various platforms, including the Colosseum wireless network emulator and real-world PAWR testbeds, providing a comprehensive environment for end-to-end AI/ML RAN research.

Security issues are also covered in [74] where the vulnerabilities of AI/ML models deployed in O-RAN systems to adversarial attacks are presented. It demonstrates how slight manipulations in input data can significantly degrade the performance of an ML-based interference classifier xApp within the near-Real-Time RIC. This study reveals that even minor adversarial attacks can drastically reduce the accuracy of ML applications, highlighting the critical need for robust security measures in AI-driven O-RAN environments. Also, [75] explores the vulnerabilities introduced by the open and flexible nature of O-RAN, particularly concerning AI/ML integration, by discussing how the disaggregation of RAN components, combined with the programmability and automation provided by RICs and AI-driven xApps and RAN Applications (rApps), can lead to misconfiguration issues. The study examines the potential for AI/ML to both identify and exacerbate these misconfigurations, presenting a case study on conflicting policies among xApps and proposing AI/ML-based solutions to mitigate these problems. The research emphasizes the critical need for robust management frameworks to ensure reliable and efficient O-RAN operations.

Finally, in [76] the Colosseum project identifies several key challenges in the development and deployment DTs over Open RAN systems. One significant challenge is the necessity for high-fidelity emulation of real-world RF environments to ensure accurate testing and validation of AI/ML models. Creating an environment that can reliably replicate real-world conditions is crucial for developing robust AI-driven network management solutions. This includes addressing the variability in signal propagation, interference, and other dynamic factors that affect network performance. Another challenge highlighted is the integration of diverse hardware and software components to create a fully programmable and flexible RAN system. This involves not only the physical integration but also ensuring interoperability and seamless operation across different vendors' equipment. Additionally, the paper emphasizes the complexity of developing automation pipelines for continuous software validation and testing. These pipelines are essential for maintaining the reliability and performance of AI applications in Open RAN, especially given the dynamic nature of network conditions. The ability to automate testing and validation processes helps in quickly identifying and resolving issues, ensuring that AI models remain effective and accurate over time

Integration with Network Digital Twins (NDTs)

NDTs play a significant role in optimizing network operations by creating virtual replicas of physical networks. These replicas allow for simulation, monitoring, and optimization using real-time data and AI-driven insights. Leading companies like Nokia, Ericsson, and Huawei, have been pioneers in this field. NDTs provide a virtual environment where network operators can test new algorithms, configurations, and updates without risking the live network's performance.



Ericsson explores the integration of AI/ML within 5G RAN, highlighting the importance of standardizing AI/ML processes to ensure interoperability across different vendors' equipment [77]. The 3GPP works on specifications to support AI/ML in 5G RAN, focusing on key use cases such as load balancing, mobility optimization, and energy savings. The aim is to create a framework where AI/ML processes are explainable and interoperable, ensuring they can be effectively used to enhance network performance and efficiency. Ericsson aims to work closely with the 3GPP's initiative to define inputs, outputs, feedback, and signalling procedures necessary for AI/ML functions in 5G RAN. This standardization effort is crucial for creating AI-native cellular networks that can leverage AI/ML to optimize various network functions autonomously. By establishing these standards, the industry can ensure that AI/ML solutions are reliable and can work seamlessly across different network components, leading to more efficient and intelligent network operations. Ericsson is deeply involved in the development and deployment of AI-native networks, particularly in the context of 5G and beyond. One notable collaboration involves Deutsche Telekom and Google Cloud, where Ericsson's cloud-native 5G core network functions were implemented on Google Distributed Cloud Edge. This project demonstrated significant improvements in deployment speed, scalability, and operational efficiency, achieving a voice-over-Internet Protocol call setup in just minutes at a Deutsche Telekom lab. This collaboration aims to bring cloud services closer to mobile devices, ensuring higher performance and meeting EU data protection standards [78].

Similarly, Nokia is significantly advancing AI-native 6G networks. One of their key initiatives involves integrating AI/ML into the radio air interface, which allows 6G radios to learn, train and adapt to various network conditions. This AI-native air interface can optimize network performance dynamically, accommodating the specific needs of different applications, devices, or users in real-time. For example, a network could be configured for industrial sensors and then reconfigured for video surveillance, or robotic systems as needed. This adaptability enhances efficiency and reliability across diverse use cases [79], [80]. Nokia's DT technology simulates network environments, enabling operators to predict and resolve issues before they impact the network. This technology is also employed to optimize network performance and improve the accuracy of AI/ML models. The Dynamic Digital Twin project by Nokia Bell Labs aims to create a real-time, continuously updated digital replica of physical networks. This twin simulates network environments, helping operators predict and resolve issues before they impact the network. It leverages AI and machine learning to optimize performance, improve reliability, and enhance the accuracy of predictive models. By providing a detailed, dynamic view of the network, this technology facilitates proactive management and efficient troubleshooting, ultimately enhancing the operational efficiency and resilience of modern networks [81].

Huawei is actively involved in advancing AI-native networks and NDT, particularly in the context of 6G. Huawei's approach to 6G involves deeply integrating AI at the architectural level to create networks that are capable of end-to-end AI learning and inference. This native AI integration aims to provide real-time, trustworthy, and energy-efficient intelligent services, supporting high levels of network autonomy. The concept of a DT in this framework involves creating a real-time interactive mapping of physical network entities and their digital counterparts, allowing for intelligent analysis, simulation, and control of the physical network based on data-driven models [82]. Additionally, Huawei's "Intelligent World 2030" report outlines its vision for future ICT technologies, including the role of AI and DTs in transforming network management and operations. The report highlights how these technologies will enable more precise, predictive maintenance and optimization of network performance, ultimately leading to fully autonomous network operations. This forward-looking approach aligns with Huawei's broader goal of leveraging AI to create a more connected and intelligent world, addressing both current and future network challenges [83].



2.3.2 Academic perspective

In recent years, the convergence of AI/ML and networks has spurred a wave of innovative research and development efforts across academia and various research projects. This dynamic intersection has generated a wealth of insights and advancements in AI-Native network architectures. In this section, we review some of the scholarly endeavours and collaborative initiatives driving forward the understanding and implementation of these AI-Native networks and what is the role of DTs.

Academia

Table 2 presents an overview of academic contributions to AI-Native network architectures, serving as a foundational reference to pinpoint future research gaps. It categorizes contributions by title, provides brief summaries of each proposed AI-Native architecture, and distinguishes whether they are designed as end-to-end architectures or are specific to particular network domains (i.e., Taxonomy column). This organization helps clarify the landscape of current academic efforts and their applicational contexts within the field.

Table 2. Scientific state-of-the-art of AI-Native architectures

Title	Summary	Taxonomy
Orchestration Procedures for the Network Intelligence Stratum in 6G Networks [84].	The paper proposes the specific requirements of Network Intelligence (NI) algorithms and the procedures that shall be supported by a Network Intelligence Orchestration (NIO) sitting in the NI stratum to effectively manage NI algorithms, based on the recent concept of NIO. In addition, the study introduces a reference implementation of the NOI defined using cloud-native open-source tools.	End-to-End
DAEMON: A Network Intelligence Plane for 6G Networks [85].	The paper introduces a novel architecture (proposed within the EU-funded DAEMON project), which includes a Network Intelligence Plane (NIP) that natively integrates NI into the network operation, management, and orchestration procedures. A design of a NIO that handles the most important NI-related mechanisms such as lifecycle management, coordination, and data management is proposed.	End-to-End
End to End AI Architecture for Next Generation Network [86].	The paper proposes an AI Task Management (AITM) module that orchestrates, coordinates, and manages the network's intelligence in a multi-domain fashion. The approach is an end-to-end orchestrator allocated in the Service Management and Orchestration (SMO) module introduced by O-RAN. Moreover, a new functionality, User Equipment Data Analytics (UEDA), is introduced to take advantage of the increasing computing capability of UEs while considering their power consumption limitation. An instance of the near real-time RIC is responsible for managing the RAN domain, while an NWDAF manages the core network.	End-to-End
Toward AI-Enabled NextG Networks with Edge Intelligence-Assisted Microservice Orchestration [87].	The paper looks at different enablers for next-generation networks based on AI. On the one hand, SDN - Network Functions Virtualization (NFV) provides support for the virtualization of network functions, paving the way for the adoption of software architectures. On the other hand, the cloud computing service and management platforms (e.g., OpenStack, Docker, Kubernetes) that break down the monolithic components of service applications are into smaller managed containers in a computing environment, leading to an enhanced class of inter-connected softwarized heterogeneous networks.	Domain-specific (Edge)



<p>Toward a 6G AI-Native Air Interface [5]</p>	<p>The paper introduces a new AI-based air interface that enables optimized communication schemes for any hardware, radio environment, and application. This new interface leverages learning to make more efficient use of the spectrum by identifying and optimizing new modulation schemes, pilot sequences, and codes. Moreover, it promotes learning-based design and less standardization, which facilitates adoption and implementation.</p>	<p>Domain-specific (Radio)</p>
<p>Distributed AI-native Architecture for 6G Networks[88]</p>	<p>The paper investigates 6G networks through the lens of distributed native intelligence, focusing on the structure that supports autonomous intelligent nodes and their synergistic interactions. They delve into the intricacies of inter-domain communication and the sharing of insights, advocating for a synthesis of distributed learning with network operations. Beyond just proposing an AI-native framework, the research outlines the demands AI functionalities place on existing networks and charts a path towards an infrastructure inherently designed for AI integration.</p>	<p>End-to-End</p>
<p>A network architecture for scalable end-to-end management of reusable AI-based applications [89].</p>	<p>The paper proposes a network framework to facilitate AI-based applications throughout various network areas, aiming to avoid AI silos by enabling the reuse of data and models for scalable implementations. This AI-native framework consists of the Network and Service Automation Platform (NSAP) for optimizing and managing Network Intelligence Functions (NIFs) across domains, and the Connect-Compute platform (CCP) for managing NIF lifecycle operations. They also outline workflows for managing AI applications and validate their architecture with a vehicular application case study.</p>	<p>End-to-End</p>
<p>Toward native artificial intelligence in 6G [90].</p>	<p>This paper analyses the role of native AI as a defining element in 6G, proposing that it will be essential for realizing fully autonomous and intelligent communication networks. It reviews current research on network intelligence, advocates for a 6G framework featuring hierarchical and distributed intelligence, deep integration of connectivity and intelligence, and shared intelligence capabilities. The paper concludes that while native AI is crucial for 6G's evolution, future research must address balancing training costs with performance benefits, evaluating native AI network performance, and dynamically deploying AI models.</p>	<p>End-to-End</p>
<p>Toward an Open, Intelligent, and End-to-End Architectural Framework for Network Slicing [91].</p>	<p>The paper analyses the end-to-end network slicing concepts, methods, solutions and functioning architectures towards 6G, to aim the connection between the human, physical, and digital worlds with high level of intelligence and openness. An architectural solution harmonizes the most recent specifications of the relevant de jure and de facto standards development organizations in their applicable layers with the aim of architecting a pre-standard-compliant and preliminary network for slicing the 6G network is proposed.</p>	<p>End-to-End</p>
<p>Five Disruptive Technologies in 6G to Support Digital Twin Networks. [92]</p>	<p>The paper outlines the basic knowledge of DTs and the possible innovative technologies expected in 6G networks that will help DT systems to reach full potential, and deliver the high-level performance needed for the next generation of communications.</p>	<p>Domain-specific (NDT)</p>
<p>A Digital Twin Network Approach for 6G Wireless Network Autonomy [23]</p>	<p>The paper proposes a DT network approach to solve the challenge related to the future communication network (more communication modes, service types, users and devices) and to realize a high level of autonomy for 6G wireless network. The study proposes an end-to-end logical architecture, functionalities and the enabling technologies for the DT network.</p>	<p>End-to-End</p>



DRL-Driven Digital Twin Function Virtualization for Adaptive Service Response in 6G Networks [93]	The paper shows a novel software-defined DTN architecture with DT function virtualization (DTFV) for adaptive 6G service response. In addition, a proximal policy optimization deep reinforcement learning (PPO-DRL) based DTFV resource orchestration algorithm on realizing massive service response quality optimization is proposed. Experimental results show as the proposed method outperforms heuristic DT resource managements methods.	End-to-End
---	--	------------

Other research projects

Similar to Table 2, Table 3 examines some examples of completed and ongoing research projects that incorporate AI/ML into network architectures. The projects are organized by title, providing concise overviews of each AI-Native architecture proposed and classifying them as either comprehensive end-to-end solutions or tailored to specific network domains. These examples highlight the significant research interest in Europe regarding AI-Native architecture. Each project introduces unique innovations and architectural enhancements aimed at improving network intelligence, performance, and sustainability.

However, NDTs are not fully integrated within these AI-Native architectures. Instead, NDTs are considered as supportive applications for some core functionalities within the architecture. The methodologies for building such NDTs and using them to enhance network planning, management, and control are not addressed within the scope of these projects.

Table 3. Research projects that integrate AI/ML into the network architecture.

Title	Summary	Taxonomy
H2020 – DAEMON [94]	The European project Network intelligence for aDAptive and sELf-Learning MOBILE Networks (DAEMON) proposed a novel AI-Native architecture for 5G and beyond networks [84] This architecture introduces the Network Intelligence Stratum (NI Stratum) [85], a cross-layer architecture that complements and interacts with the existing planes in current and next-generation mobile networks, i.e., the user/data, control, and management planes.	End-to-End
H2020 - HEXA-X [13]	The European project Hexa-X proposed a novel end-to-end system architecture, radio performance, connecting intelligence, network evolution and expansion, and impact creation towards 6G.	End-to-End
6G-SANDBOX [95]	The European project 6G-SANDBOX brings a complete and modular facility for the European experimentation ecosystem, to support technology and research validation processes needed in the pathway towards 6G.	End-to-End
ORIGAMI [96]	The European project Optimized Resource Integration and Global Architecture for Mobile Infrastructure (ORIGAMI) for 6G aims at spearheading the next-generation of mobile network architecture, overcoming factual barrier, based on three critical architectural innovation: Global Service-based Architecture (GSBA), Zero Trust Exposure Layer (ZTL) and Compute Continuum Layer (CCL).	End-to-End
6G-BRICKS [97]	The European project 6G-BRICKS aims to deliver a new 6G experimentation facility, building on the baseline of mature ICT-52 platforms, that bring breakthrough cell-free and RIS technologies. In addition, a novel unified control paradigms based on Explainable AI and Machine Reasoning are studied. All enablers will be delivered in the form of reusable components with open APIs, termed “bricks”. Initial integrations with O-RAN will be performed, aiming for the futureproofing and interoperability of 6G-BRICKS outcomes.	End-to-End
BeGREEN [98]	The European project BeGREEN will take a holistic view to provide evolving radio networks that not only accommodate increasing traffic and service levels but also consider power consumption as a factor. The provided solution will include a AI native intelligent plane that extends the capabilities of the O-RAN aligned architecture to easily provide AI/ML tools to RAN control components such as the Near RT RIC and the Non-RT RIC.	End to End



The main features that 6G-TWIN is planning to provide are summarized in Table 4. The table shows how the state-of-the-art literature is handling such features and challenges. We considered five different aspects during the evaluation, namely, built-in AI functionalities, optimized performance for AI workloads, scalability and flexibility, integration with AI development tools, and integration with NDTs.

The “*Built-in AI Functionalities*” column evaluates the incorporation of AI functionalities within the architecture examined in the reviewed studies, questioning their existence and integration. A truly AI-native design embeds AI elements—like machine learning algorithms, neural networks, NLP, and computer vision—from inception, making them foundational to the architecture’s structure.

Conversely, the “*Optimized Performance for AI Workloads*” column examines how the studied architectures address AI-specific computational demands. AI-native structures are tailored for the efficient execution of AI tasks, potentially leveraging specialized processing units like Graphics Processing Unit (GPUs) or Tensor Processing Unit (TPUs), software enhancements, or a synergy of hardware and software to expedite AI processes and enhance performance.

The column on “*Integration with AI Development Tools*” examines how the reviewed architectures natively support essential AI tasks like model training, inference, optimization, and deployment. It looks at the provision of specialized APIs, services, or interfaces designed to facilitate and enhance AI development workflows.

The “*Decentralized/Federated*” column analyses whether the architecture in question integrates decentralized or federated features. Such AI-native structures are key to bolstering data privacy, reducing latency, and efficiently managing network traffic, fostering intelligent, energy-efficient collaboration within and across network strata.

Additionally, the column “*Security*” is dedicated to analysing the security mechanisms within the AI-native architecture being reviewed. As 6G is anticipated to underpin critical infrastructure, healthcare, and autonomous systems, these architectures must be inherently secure, capable of intelligent defence against complex cyber threats, including zero-day attacks, by utilizing self-learning behavioural analytics for continuous monitoring and prediction of potential attack vectors.

Finally, the “*Integration of NDT*” column discusses how the reviewed architectures incorporate support for NDT. NDTs enable organizations to create dynamic, real-time models of complex networked systems, allowing for better monitoring, analysis, optimization, and decision-making. By integrating NDT capabilities into the architecture, developers can leverage AI and data analytics techniques to extract insights from DT data, predict system behaviour, optimize network performance, and automate decision-making processes. Additionally, NDTs facilitate scenario testing, what-if analysis, and predictive maintenance, enabling proactive management of network assets and resources.

The table highlights a significant gap in the literature regarding the integration of NDTs into network architecture, underscoring the innovation of our proposal. While references [87] and [89] treat DTs as services for specific use cases rather than as essential components of an AI-Native architecture, our approach recognizes their core role. Additionally, security is often noted as a critical concern, especially as networks evolve into essential infrastructure requiring protection from adversarial attacks and malicious activities. This concern is compounded by the vulnerability of AI-based algorithms to security breaches through subtle data manipulations that could compromise network integrity.



Table 4. Features of an AI-Native Architecture

Reference	Features					
	Built-in AI Functionalities	Optimized Performance for AI Workloads	Integration with AI Development Tools	Decentralized/Federated	Security	Integration of NDT
Orchestration Procedures for the Network Intelligence Stratum in 6G Networks [84]. DAEMON: A Network Intelligence Plane for 6G Networks [85]	Yes, via Network Intelligent Functions (NIFs) and Services (NISs).	Yes, via NI Virtual Infrastructure Manager and NI Orchestrator.	Yes, it includes ML pipelines	A distributed data pipeline discussed but not introduced in the architecture. Moreover, a centralized, end-to-end orchestrator is designed, where through interfaces it gathers data from local controllers and orchestrators.	Not discussed in the architecture.	No
End to End AI Architecture for Next Generation Network [86]	Yes, via the NWDAF (core), RIC (RAN) and UEDA (UE)	It is assumed but it is not included in the architecture.	Yes, by introducing the Intf1, allowing the AITM to communicate with an external third-party.	Distributed NWDAF (Rel18) are exploited together with Federated Learning to guarantee data privacy, reduce network resource usage, and maximize the value of the data with collaboration across different data domain. However, the orchestration of intelligence is centralized in the SMO.	Not discussed in the architecture.	No
Toward AI-Enabled NextG Networks with Edge Intelligence-Assisted Microservice Orchestration [87].	No, they are build per use case requirements.	It is assumed but it is not included in the architecture.	No. The architecture uses software enablers such as Kubernetes, Jupyter and TensorFlow to manually deploy the AI models.	The architecture considers a Data Distribution and Collaborative Plane that shares the network data collected on the three-layers network architecture (physical, network, and services).	Security is discussed as an open challenge, mentioning efforts from ETSI on securing AI, but not integrated in the architecture.	DTs are seen as an application that could be supported by the architecture rather than a component of such architecture.
Toward a 6G AI-Native Air Interface [5].	Yes, ML are presented to replace processing blocks from a radio receiver.	It is assumed but it is not included in the architecture.	No. It was discussed but not included in the architecture.	Not discussed in the architecture	Not discussed in the architecture.	No
Features						



Reference	Built-in AI Functionalities	Optimized Performance for AI Workloads	Integration with AI Development Tools	Decentralized/Federated	Security	Integration of NDT
Distributed AI-native Architecture for 6G Networks [88].	Yes, through the AI-native NF or the Standalone AI	Yes. It is discussed in the architecture, but more from a requirement perspective.	Yes. The architecture considers a model training layer and an inference and decision layer. Moreover, the architecture considers a model, data and knowledge warehouse to accumulate the models, data and knowledge during AI service.	The proposed architecture follows the same guidelines as proposed by 3GPP in the NWDAF. The architecture leverages techniques such as federated learning to support distributed model training. The architecture contemplates a coordination function to support hierarchical distributed intelligence, data and knowledge sharing, among others.	Not discussed	No
A network architecture for scalable end-to-end management of reusable AI-based applications [89].	Yes, via the Artificial Intelligent Functions (AIFs)	Yes. Through the Connect-Compute platform. Beyond addressing the computing perspective, the architecture also considers shared pipelines for data and for multiple AI models.	Yes, the proposed model manager (part of the data pipeline) enables the lifecycle management of AI/ML models.	The Network and Service Automation Platform acts as a coordinating node of the different orchestrators such as MEC and NFV ones. It is more a hierarchical architecture that allows collaboration between multiple levels.	Not discussed in the architecture. Assumed through managed platforms such as MEC and NFV.	No. Only discussed as an application to support a mobility use case.
Toward native artificial intelligence in 6G [90].	Yes, through the intelligent function, belonging to the function layer.	Operation Administration and Maintenance problem: Provide E2E orchestration and management for AI workflows, which is seamlessly integrated with network management.	The intelligent function has the capability of performing model training, validation and selection/optimization. However, it is not discussed in detail.	Distributed intelligence is discussed in the architecture, more from the disaggregated RAN perspective of Open-RAN. However, the architecture considers a central node for coordination among the distributed nodes.	It is thought as a module inside the architecture that provides protection to other modules and components of the network. However, it is not fully detailed.	No
Features						



Reference	Built-in AI Functionalities	Optimized Performance for AI Workloads	Integration with AI Development Tools	Decentralized/Federated	Security	Integration of NDT
Toward an Open, Intelligent, and End-to-End Architectural Framework for Network Slicing [91].	Yes, through CN NF AI-driven, and AI-native interfaces and transmission technologies in the Radio Unit (RU). Advanced integration AI/ML algorithms into 6G slicing framework	It is assumed but it is not included in the architecture.	It was discussed but not included in the architecture.	No. It was discussed but not included in the architecture.	Not discussed in the architecture.	No
Five Disruptive Technologies in 6G to Support Digital Twin Networks [92].	No	No	It was discussed but not included in the architecture.	No.	Yes. The architecture considers physical space and virtual space	The paper outlines possible innovative technologies expected in 6G networks that can help DT systems to reach full potential and deliver the high-level performance.
A Digital Twin Network Approach for 6G Wireless Network Autonomy [23].	Yes, at the design stage, 6G considers deep integration with AI.	Not considered	The DT is considered to define the architecture. The network requirements will become AI use cases, which will be satisfied by calling various AI services of the network (including AI training, AI verification, AI reasoning and AI data).	The presented 6G DT network provides a hierarchical cross-domain architecture that combines centralized and distributed architectures.	Yes. The architecture is based on development of an NDT.	The paper describes the new DT network integrated with the native intelligence plane, the data plane and virtual-real interaction.
Features						



Reference	Built-in AI Functionalities	Optimized Performance for AI Workloads	Integration with AI Development Tools	Decentralized/Federated	Security	Integration of NDT
DRL-Driven Digital Twin Function Virtualization for Adaptive Service Response in 6G Networks [93].	Yes, an online and AI-based DT resource orchestration policy to optimize the quality of services has been used for the SDN.	No, the paper constructs a Markov decision process model to formulate the service response problem in DTN.	It was considered to define the architecture.	Not discussed in the architecture	Yes. The architecture is based on development of an NDT.	The paper proposes a software-defined NDT architecture integrated with DT function virtualization. The proposed architecture is service-aware and provides flexible DT resource management approaches, which can adapt to the varying demand of 6G services.



D1.1 Architecture and technical foundations (Initial)

3 SIMULATION FRAMEWORKS AND SIMULATORS

Network simulators are crucial tools for evaluating and analysing the performance of networks, protocols, and applications in lab environments. Software-based discrete-event network simulators are widely used and offer a rich set of features for simulating various types of wireless networks, protocols, and applications are widely used in academia, research institutions, and industry for network protocol development and performance evaluation. This also include network emulators, that focus specifically on emulating the network. Emulators use real hardware or virtualized environments to replicate the behaviour of actual network devices. This includes base stations, user equipment, and the interactions between them. Unlike simulators, emulators execute real software and protocols, providing a highly realistic testing environment. This is crucial for validating the performance of radio technologies, testing signal processing algorithms, and ensuring interoperability with real-world devices.

The issues facing simulators include ease-of-use, scalability, realism, and accuracy in an increasingly complex RAN environment with increasing number of technologies, antenna, introduction of NTN, all of which need to be deployed and operated in a cost-effective manner.

3.1 Network simulator to support NDT

6G-TWIN aims to develop a digital replica of physical live RAN environments, including RF propagation in a virtual environment for AI/ML model training and performance assurance purposes. In particular, this will include generation of synthetic datasets that are typical of traditional network simulators but will extend these with an ML model that can employ reinforced learning methodologies that adapt and learn when deployed in live networks.

6G-TWIN targets to deliver an emulation-based DT blueprint, designed to replicate key performance characteristics of a given RAN service on any given day. RF propagation models will be combined with emulated virtual RAN and Core services and real-time monitoring information, to learn as it goes with the innovate application of reinforcement. The resulting platform will support management and configuration of continuous learning, as well as continuous flow of realistic data for AI/ML model training.

A literature review has been performed on existing related works and with a special focus on simulation frameworks that facilitate coupled simulators with communication. Our primary objective is to meticulously examine the state-of-the-art in simulation frameworks and simulators, particularly those that incorporate Hardware In the Loop (HIL), real-time system simulation, federated simulation frameworks, and various forms of vehicular, robotic, and Unmanned Aerial Vehicle (UAV) simulations. This exploration aims to understand the current advancements and methodologies utilized within the domain from 2008 to 2023, with a special emphasis on coupled frameworks that enable communication.

Our review was restricted to English-language articles that detail simulation frameworks, their structure, the integration of different simulators, and the enablement of wireless communications. This focus ensured we examined frameworks adept at simulating the complexity and heterogeneity of real-world communication systems. The overall literature review can be sub-divided into various small sub-groups: Real time, High Level Architecture (HLA), Aerial vehicles, Robotic and Vehicular Simulators.

These intended sub-groups broadens our knowledge in existing simulation frameworks and simulators to support a heterogeneously federated NDT simulation framework that intends to simulate networks covering space, aerial, terrestrial and undersea. Furthermore, the subdivision also intends to capture good existing practices used in literature to reduce federation overhead, e.g. real-time simulators.



3.2 Simulation taxonomy

In the realm of advanced simulation technologies, various types of simulators play a crucial role in different fields, enhancing the development, testing, and optimization of complex systems. Real-time simulators provide immediate feedback, vital for systems testing and training. HLA based simulators enable interoperability and synchronization across diverse simulation systems. Aerial vehicle simulators focus on the dynamics and communication systems of UAVs, supporting advancements in unmanned flight operations. Robotic simulators are essential for developing and testing robotic systems, offering insights into a wide range of applications beyond robotics. Lastly, vehicular simulators replicate the dynamics and interactions of ground vehicles, facilitating the design and evaluation of traffic management strategies and safety protocols. Each category brings unique benefits and specialized applications, contributing significantly to their respective domains. The following subsections will dive in each of the different types of simulators.

3.2.1 Real time simulation

Real-time simulation refers to simulators that can execute a model at the same rate as actual time (or near actual time), often used for systems testing and training where immediate feedback is crucial. This includes HIL setups, where real components are tested within a simulated environment, ensuring high fidelity in results. Additionally, some simulators can perform faster than real-time, allowing for extensive testing over shorter periods, thus accelerating development cycles and enabling efficient system analysis and optimization. The Table 2 provides a list of literature that is related to real-time simulation:

Table 5. Real time simulators

Title	Coupled components and purpose	Taxonomy
Bridging Worlds: Integrating Hardware-in-the-Loop Testing with Large-Scale VANET Simulation [99].	This work integrates the components, Hardware-in-loop Automotive Simulation Models (ASM), Ego vehicle interface (EVI) and VANET simulator (Veins and SUMO). This work demonstrates a possible way of using a discrete event simulator (DES) for simulating real-time systems.	Heterogeneous federation of real time systems
Demo Abstract: Integrating a Driving Simulator with City-Scale VANET Simulation for the Development of Next Generation ADAS Systems [100].	Combining a VANET Simulator with a 3D Driving Simulator, this study streamlines real-time ADAS simulation for next-gen system development, enabling city-scale testing of VANET applications with real user engagement.	Heterogeneous federation of real time systems
Towards Real-Time Interactive V2X Simulation [101].	This demonstrates the hindrance of using discrete event simulator for the simulation of real time systems and propose a solution of only simulating ROI (region of interest) for this purpose.	Real time System
Accelerating the Simulation of Wireless Communication Protocols using Asynchronous-Parallelism [102].	This works shows that using multicore systems and performing isolated computation in the background the DES can be tuned for performing real time simulation.	Real time System
INTEGRATION Large-Scale Modelling Framework of Direct Cellular Vehicle-to-All (C-V2X) Applications [103].	This framework merges a network simulator, based on an analytical model, with the INTEGRATION traffic simulator, achieving two-way dynamic coupling at variable intervals. This setup is designed for large-scale simulations, with the analytical model replacing a standard network simulator and variable intervals enhancing performance, enabling the system to run faster than real time.	Integrated simulation framework with real time support



3.2.2 Simulation with High Level Architecture

This subgroup of tables categorizes the literature centred on co-simulation tools that draw inspiration from High-Level Architecture. HLA serves as a standard for enabling disparate simulation systems to interact and operate collectively. Studies within this subgroup detail the adoption of HLA principles to achieve interoperability, synchronization, and a cohesive simulation environment across various domains. The Table 3 captures the literatures that uses HLA.

Table 6. Simulators with high level architecture

Title	Coupled components and purpose	Taxonomy
Realistic Simulation of V2X Communication Scenarios [104]	The framework VSimRTI, drawing inspiration from HLA, integrates with SUMO for traffic simulation, JiST/SWANS for network modelling, and eWorld for environmental context, creating a cohesive system for realistic V2X communication simulation.	Heterogeneous federation
Extending the V2X simulation environment VSimRTI with advanced communication models [105]	VSimRTI, coupled with OMNeT++ and CCMSim, provides a comprehensive simulation framework that addresses the communication domain across two federates: OMNeT++ simulates the higher layers of the communication stack, while CCMSim handles the physical layer and radio channel. This integration facilitates a detailed exploration and testing of network protocols and signal transmission.	Heterogeneous federation
Coupled simulation of mobile cellular networks, road traffic and V2X applications using traces [106]	VSimRTI serves as the coupling mechanism in a simulation ensemble with SUMO for traffic modeling, OMNeT++ for cellular network simulation, and VSimRTI_App for V2X application simulation. The purpose is to create a trace-based simulation environment capable of emulating cellular network communication for V2X applications using real-world data.	Heterogeneous federation
Extensible Co-Simulation Framework for Supporting Cooperative Driving Automation Research [107]	The integration of Carla, MOSAIC, and SUMO establishes an extensible co-simulation framework tailored for autonomous vehicles (AV) and cooperative AV systems, enhancing the testing and development of advanced vehicular technologies.	Heterogeneous federation
A Large-Scale Traffic Scenario of Berlin for Evaluating Smart Mobility Applications [108]	The framework integrates MATSim for traffic scenario calibration, MOSAIC for co-simulation facilitation, and SUMO for execution, highlighting the transformational process essential for smart mobility application evaluations.	Heterogeneous federation

3.2.3 Aerial vehicles simulation

In this section, we review UAV simulation tools that encompass flight dynamics and communication systems, essential for testing and advancing UAV operations in complex simulated environments. The Table 4 captures the simulation tools for simulation of aerial networks.

Table 7. Aerial vehicles simulators

Title	Coupled components and purpose	Taxonomy
Towards an Open Source Fully Modular Multi Unmanned Aerial Vehicle Simulation Framework [109].	AirMobiSim, paired with OMNeT++ and SUMO, offers a simulation framework for the integrated operation and communication of road vehicles and UAVs, tailored for smart city applications. It presents a modular approach to study the dynamics of UAVs, supporting an arbitrary number of both aerial and road vehicles, while simulating their interactions and wireless communications.	Heterogeneous federation
Demo: SkyRoute, a Fast and Realistic UAV Cellular Simulation Framework [110].	"SkyRoute" incorporates a base station deployment database and the NS3 network simulator, focusing on using ground base stations to provide high-speed wireless connectivity to UAVs. This simulation framework aims to improve cellular network interactions with UAVs, ensuring robust communication capabilities in various operational scenarios.	Integrated full-stack simulation framework



<p>UTSim: A framework and simulator for UAV air traffic integration, control, and communication [111].</p>	<p>UTSim, leveraging the Unity game engine, is a modular simulator crafted for the in-depth study of UAV air traffic integration, control, and communication within varied environments. Its design allows for extensive customization and extension, enabling researchers to simulate a wide range of UAV operations and scenarios. This flexibility supports the exploration of critical UAV issues such as sense and avoid mechanisms, communication protocols, and navigation algorithms, making UTSim an invaluable tool for advancing UAV traffic management research.</p>	<p>Integrated simulation framework</p>
<p>Performance Evaluation of Direct-Link Backhaul for UAV-Aided Emergency Networks [112]. Evaluation of flying caching servers in UAV-BS based realistic Environment [113]. Evaluation of Beam steering performance in MultiuserMIMO UABS networks[114].</p>	<p>The Green Radio Access Network Design (GRAND) is a Java-based tool developed by the Waves research group to reduce energy consumption in cellular wireless networks. Initially designed to evaluate 4G macro and micro-networks with a focus on energy efficiency and human exposure, the tool has evolved to include drone-aided networks, including access and backhaul networks, human exposure-aware aerial networks, UAVs using caching servers to reduce backhaul usage, and UAV-aided networks for moving ground users; as well as IoT sensing for agricultural scenarios.</p>	<p>Integrated simulation framework</p>

3.2.4 Robotic Simulation

This section explores robotic simulators, essential for developing and testing robotic systems. Beyond their core use in robotics, these simulators also hint at broader applications, touching on diverse fields. This versatility reflects the expanding role of simulation in technology and interdisciplinary research. Table 5 captures the simulation tools for perform robot simulation or that uses robotic simulators.

Table 8. Robotic simulators

Title	Coupled components and purpose	Taxonomy
<p>RoboNetSim: An integrated framework for multi-robot and network simulation [115].</p>	<p>The framework combines the ARGoS simulator, tailored for swarm robotics, with NS2 and NS3 for a comprehensive approach to simulating networked multi-robot systems. It's particularly valuable for researching robotic tasks where collaboration is key, contrasting with simulations focused on individual robots. Simulating robotic elements (like sensors and actuators) is performed in ARGoS and communication components (including radio propagation and network protocols) are simulated in NS2/NS3.</p>	<p>Heterogeneous Federation</p>
<p>An Integrated Architecture for Autonomous Vehicles Simulation [116].</p>	<p>Combining SUMO for realistic traffic scenarios with USARSim, a robotics simulator that models autonomous vehicles, sensors, and actuators, this architecture offers a comprehensive environment for autonomous vehicle research. USARSim, leveraging a game engine, provides immersive 3D animations of vehicles and their interactions with the environment through advanced physics and visualization modules. This integration ensures detailed simulation of autonomous vehicle behaviour and their sensor and actuator responses in dynamic traffic conditions.</p>	<p>Heterogeneous Federation</p>
<p>A Novel Simulation Framework for the Design and Testing of Advanced Driver Assistance Systems [117].</p>	<p>This simulation framework integrates CarMaker with Robot Operating System (ROS)TI to create a platform for efficient ADAS testing, leveraging CarMaker's driving dynamics and ROS's middleware capabilities. It enables automated ADAS testing in various real-world scenarios, reducing costs and emphasizing the value of virtual test drives. The framework also explores the impact of collective perception and V2X communication on enhancing traffic safety and efficiency.</p>	<p>Heterogeneous Federation</p>



3.2.5 Vehicular Simulation

This subsection focuses on vehicular simulators, with a particular emphasis on ground vehicle simulation tools. These simulators are designed to replicate the dynamics, behaviours, and interactions of vehicles within various environments, from urban streets to highways. Through detailed modelling of vehicle mechanics, traffic patterns, and driver behaviours, these tools play a critical role in the development, testing, and optimization of vehicle systems, traffic management strategies, and safety protocols. Table 6 captures the literatures which facilitates the simulation of ground vehicles.

Table 9. Vehicular simulators

Title	Coupled components and purpose	Taxonomy
Co-simulation Framework for Control, Communication and Traffic for Vehicle Platoons [118].	This co-simulation framework integrates SUMO, NS3, and Matlab to tackle vehicle platooning challenges, merging traffic, network simulations, and control algorithm development. It allows for the consideration of network congestion, traffic dynamics, and control strategies early in the platooning design process. A case study within the framework demonstrates its utility in assessing platoon performance under various traffic conditions, supporting the development, testing, and validation of platoon strategies.	Heterogeneous federation
An integrated simulation environment for testing V2X protocols and applications [119].	A simulation framework that merges VISSIM for traffic modelling, MATLAB for managing traffic applications, and NS3 for simulating communication networks, focusing on V2X technologies. This setup enables the testing and analysis of V2X protocols and applications within a realistic simulation framework, offering insights into the deployment of V2X technologies in various scenarios. It highlights the environment's capacity to model real-world traffic and vehicle communication, supporting the development and implementation of V2X technologies effectively.	Heterogeneous federation
Simulation of V2X Applications with the iTETRIS system [120].	The paper highlights the iTETRIS system's capability to simulate V2X applications, integrating SUMO for traffic simulation, NS3 for communication, and iCS for application control. This setup offers a holistic view of V2X technology in urban environments, aiming not only to emulate V2X application behaviour but also to explore traffic management solutions facilitated by vehicular communication. This dual focus supports the development of more efficient and effective traffic strategies through the integration of advanced vehicular communication systems.	Heterogeneous federation
Co-simulation Platform for Developing InfoRich Energy-Efficient Connected and Automated Vehicles [121].	The framework combines VIREs for environmental simulation, InfoRich for integrating sensor, communication, and map data, and Simulink for simulating vehicle dynamics and powertrains, focusing on energy-efficient autonomous driving systems. InfoRich serves as a platform for exploring eco-autonomous driving technologies in connected and automated vehicles, emphasizing the use of comprehensive data to improve energy efficiency.	Heterogeneous federation
Design of V2X runtime emulation framework for evaluation of vehicle safety applications [122].	The V2XREF framework integrates SUMO for traffic simulation, a system controller, and QualNet for network simulation, providing an efficient platform for evaluating vehicle safety applications. Designed as a cost-effective solution for entities lacking resources for physical test environments, it couples network and traffic simulations to emulate realistic road conditions. By adapting communication stacks to IEEE 802.11p and WAVE protocols, V2XREF enables comprehensive testing of vehicular safety technologies in simulated scenarios.	Heterogeneous federation



Customized Co-Simulation Environment for Autonomous Driving Algorithm Development and Evaluation [123].	The paper introduces a customized co-simulation environment that combines Carla, SUMO/VISSIM, CarSim/MATLAB, Autoware, and ROS Bridge to support the development and evaluation of autonomous driving algorithms. This integration aims to offer a realistic setting for testing vehicle dynamics, traffic simulations, and sensor fusion applications, contributing to the advancement of autonomous driving technology.	Heterogeneous federation
Development of a Co-Simulation Framework for Systematic Generation of Scenarios for Testing and Validation of Automated Driving Systems [124].	The paper introduces a Co-Simulation Framework that synergizes a Simulation Controller, CarMaker, and VISSIM to create scenarios for testing and validating automated driving systems. Leveraging calibrated traffic models based on real-world Austrian test road data and integrating with CarMaker, this framework facilitates the generation of realistic scenarios, particularly focusing on the Highway Chauffeur function. The aim is to support systematic, controlled virtual testing of automated driving technologies.	Heterogeneous federation
Evaluation of CACC string stability using SUMO, Simulink, and OMNeT++ [125].	The article focuses on utilizing a combined simulation environment comprising OMNeT++/MiXiM, SUMO, and SIMULINK to assess the effects of packet loss rate and beacon sending frequency, particularly in the context of Cooperative Adaptive Cruise Control (CACC) string stability for platoon vehicles. This setup allows for a detailed evaluation of communication and behaviour dynamics within vehicle platoons, emphasizing the critical role of network and traffic simulations in understanding and improving platoon vehicle stability and safety.	Heterogeneous federation
Artery-C: An OMNeT++ Based Discrete Event Simulation Framework for Cellular V2X [126].	The Artery-C framework combines SimuLTE with Artery, enriching SimuLTE's user plane for evaluating cellular V2X applications. It introduces a dedicated sidelink interface that focuses on dynamic mode switching and incorporates advanced 5G network features such as variable numerologies. This setup is specifically designed for a detailed performance analysis of cellular V2X applications.	C-v2x simulation framework-Heterogeneous simulation
Design and Implementation of a Co-Simulation Framework for Testing of Automated Driving Systems [127].	The framework integrates MATLAB/Simulink with CarMaker and VISSIM, establishing a co-simulation environment for evaluating Automated Driving Systems (ADS) in realistic traffic conditions. Utilizing a Model-View-Controller (MVC) design pattern, it effectively generates relevant scenarios to enhance ADS testing approaches and strengthen safety validation processes.	Heterogeneous Federation
OpenCV2X Mode 4: A Simulation Extension for Cellular Vehicular Communication Networks [128].	The paper introduces "OpenC-V2X," the first open-source simulation model for the 3GPP Release 14 C-V2X standard, utilizing the Artery framework that integrates OMNeT++ and SUMO. This setup, enhanced by the Vanetza framework for the ETSI ITS-G5 standard, provides a comprehensive tool for simulating cellular vehicle-to-everything communications alongside road traffic, facilitating advanced C-V2X research and development.	Heterogeneous Federation
Flexible multi-node simulation of cellular mobile communications: the Vienna 5G System Level Simulator [129].	The Vienna 5G System Level Simulator, a standalone tool with a modular design, is introduced for simulating large-scale, multi-tier 5G cellular networks. It offers flexibility and efficiency, allowing researchers to explore network performance through detailed modelling of network geometry, propagation models, and Monte-Carlo simulations within an object-oriented MATLAB environment. This simulator stands out for its comprehensive approach to analysing 5G network dynamics and performance.	Heterogeneous network simulator

3.3 Simulation tools

In the dynamic landscape of network planning and optimization, simulation tools are essential for both industrial and research applications. Industrial-focused tools, typically operating under licensed software models, are designed to meet the rigorous demands of commercial



deployment, ensuring efficient network design, deployment, and optimization. These tools address real-world challenges such as coverage analysis, capacity planning, and KPI support. On the other hand, research-focused tools, often open-source, facilitate detailed exploration and innovation within academic and experimental settings. They enable comprehensive modelling and simulation of network protocols and technologies, supporting the advancement of new innovations in telecommunications. Together, these tools play a crucial role in the continuous evolution of network technologies.

3.3.1 Industrial Focused tools

Most of the industrial-focused planning tools work under a licensed software model.

The ASSET suite is one of the most complete 5G network planners in the market, able to validate several of the 5G business models. 5G New Radio (5G NR) modelling is provided by enhanced propagation models, complex antenna arrays, comprehensive multi-technology 3D coverage and capacity simulations, including human exposure analysis [130]. Similarly, the Atoll 5G NR module offers operators a flexible and evolving framework for designing and deploying 5G networks [131]. This wireless network design and optimisation software includes multi-RAN modelling for 5G networks, including outdoor and mmWave propagation based on ray tracing techniques. It is based on Monte Carlo simulations that offer accurate planning with the capability of revising planning data based on measure campaigns. Capgemini Engineering delivers a 5G planning solution which consists of several 5G tasks to create a continuous optimisation framework for operators working in sub 6 GHz and mmWave bands aiming to support the operators' KPIs [132].

The Cell Designer tool [133] provides network modelling and coverage analysis for 5G and other wireless technologies, using multi-vendor specific equipment modelling. On the other hand, the Hamina tool provides a cloud-based robust network planner for WiFi, Private 5G and Bluetooth Low Energy (BLE). The web-based technology provides fast network designs for sub-6GHz networks with accurate 3D planning [134]. Hardware vendors like Huawei provide a 5G network planner for its partner operators to solve 5G challenges such as precision propagation models for urban and rural scenarios, accurate coverage prediction, automatic site planning and planning for novel services [135]. iBwave design enterprise is a 3D network design tool for Wi-Fi and small cell cellular private networks that can be merged with a detailed site aesthetic to perform network design. It works mainly in indoor sub-6 GHz bands to predict optimal node location placements [136].

Another tool is the LSTelecom planning tool, which can map existing sites and optimise network operation with interference assessment, providing the maximum possible capacity of already deployed and upgraded 5G networks [137]. The NetSim uses the 5G NR library to simulate end-to-end across all layers of the 3GPP protocol stack. This tool is used for industry and research. It can evaluate existing implementations and validate future extensions in emulated scenarios, being the only industrial tool capable of simulating aerial networks [138]. The Terragraph project provides an open-source Link-Level network planning tool with Software Defined Network (SDN) capabilities for a 60 GHz mesh network backbone for an FWA use case. This software is intended to provide network planning for cloud-based network real deployments with commercial-off-the-shelf (COST) equipment under the open-software methodology, using either SDN or Software Defined Radio (SDR) for low-cost implementation [139], [140].

3.3.2 Research Focused tools

The range of research tools is extensive and depends on the specific objectives the research teams investigate. They can range from channel modelling to link-level simulators. Still, a complete protocol stack simulator needs optimisation functions to reduce the complexity and



provide accurate results. About 50 5G simulator tools are available in the literature, according to [141]. The following is an overview of some of the most popular tools.

The 5G Air simulator is an open-source system-level tool that models key 5G NR elements such as MaMIMO, extended multi-cast and broadcast, enhanced random access procedure, and NB-IoT, as well as support for performance analysis of reference 5G scenarios with varying mobility, traffic load, and deployment configurations [142]. Similarly, the 5G K-Simsys, an open-source software system-level simulator, evaluates the performance of 5G networks, particularly the new improvements of 5G NR, such as beamforming in MaMIMO systems. Several antenna configurations are implemented to evaluate the mmWave performance of the 3GPP Rel 16 standard [143]. CGA Simulation produced an online replica of Kensington, Liverpool, utilising the 'digital twin' technology with 5G network planning tool. This tool enables 5G network planning to examine an area by visualising LoS 5G receivers and working around constraints such as trees or tall buildings. It models the IEEE 802.11ad protocol working at 60 GHz to evaluate the network links' Packet Error Rate (PER) and compare them with test-bed measurements, providing comparable results [144].

Discrete-event network simulators, such as OMNeT++ [145], [146], OPNET [147] or NS-3 [148], are some of the most popular simulation tools. While these are essentially generic network simulators, specific modules such as 5GSim, LTESim, and Simu5G can simulate LTE and 5G networks. These tools are packet-based and mimic substantial sections of the protocol stack due to their event-driven nature. In terms of computational complexity, this makes simulating vast networks with many network nodes prohibitively expensive. OMNeT++ includes the 4GSim, 5GSim and Simu5G modules to perform cellular network simulations focused on the Radio Resource Allocation (RRA) procedures and data plane simulations in 4G and 5G networks. Similarly, the NS-3 network simulator with the 5G-LENA module aims to solve real-world issues, including several 5G technologies such as hybrid beamforming, vertical handover, V2X communications and Multi-Tier Heterogeneous Networks. Then, OPNET simulates the physical, MAC and Link layer of the Open Systems Interconnection (OSI) model, featuring comprehensive hardware models that consider resource allocation and protocol testing for realistic Monte Carlo simulations.

The OpenAirInterface is a Network simulator that integrates the Core network with the RAN to perform complex simulations that can support 3GPP Rel 8 and other improvements such as 5G NR and OpenRAN [149]. Finally, the Vienna 5G Simulator performs system-level simulations abstracting the physical and MAC layers to model the complete protocol stack in a simplistic object-oriented implementation. By doing this, the Vienna 5G simulator can simulate thousands of 5G nodes in complex scenarios, including 3D Channel modelling, MaMIMO and mmWaves [129], [150].

3.4 Tools Planned to use in 6G-TWIN

The 6G-TWIN project plans to use a set of tools provided by different partners and open sources. The investigation or decision of these tools is still in early stages, however a quick description of these are mentioned as follow.

3.4.1 TU Dresden Simulation Framework Scope

TU Dresden, as WP3 ("Open and Secured Simulation Framework") leader, will investigate the use of the following simulation software with the simulation framework to be built in 6G-TWIN. All the subsequently mentioned software is available as open-source software.

The simulation engine OMNeT++ [145], [146], [151] is a discrete event simulation engine geared towards network simulation and forms the basis of many of the discussed models as shown in Figure 6. SUMO [152] is a traffic simulation software that is a good fit for use case 1: teleoperated driving. SUMO allows to simulate the mobility of vehicles with a variety of vehicle



and driver models, topology and behaviour constraints, platooning controllers, etc as depicted in Figure 7. Carla [153] is an alternative used for research in autonomous driving. There are similarities between Carla and SUMO, but in detail the simulation tools are different and provide different functionalities. Such traffic simulation software is commonly used to simulate (subsets of) ready-made mobility scenarios for traffic demand modelling. Examples of established scenarios are the SUMO LuST Scenario [154] for unimodal mobility and the SUMO MoST Scenario [155] for multimodal mobility.

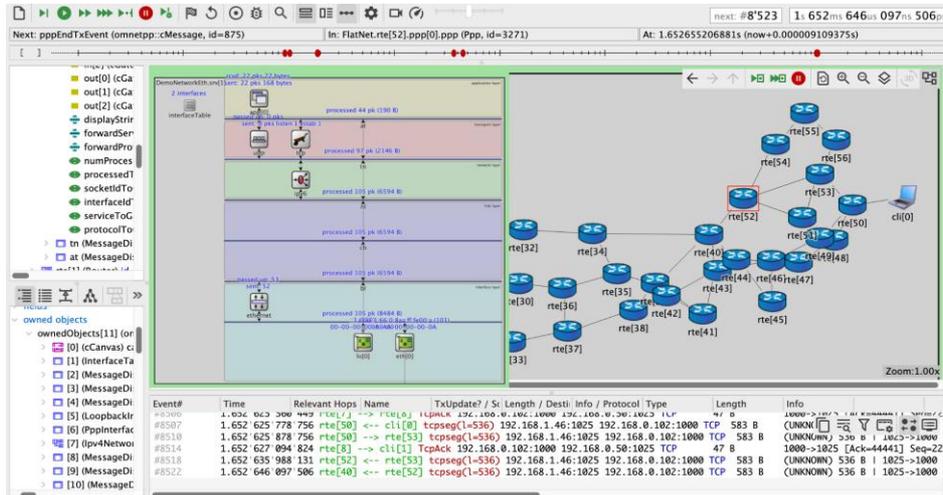


Figure 6. OMNeT++ INET [151]

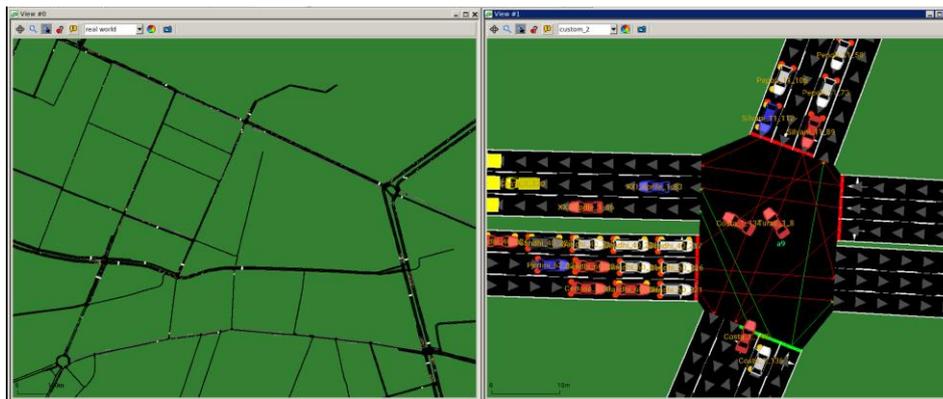


Figure 7. SUMO Simulator [152].

Veins [156] combines SUMO and OMNeT++ to simulate cooperative driving, i.e., the mobility and the network data exchange can modify each other's behaviour during the simulation run. Additionally, Veins contains models of network protocols typical for connected driving. Similarly, Veins_Carla [157] connects Veins and Carla. The space_Veins [158] tool extends Veins by introducing the simulation of satellites and the communication between vehicles and satellites.

The INET [159] model suite is based on OMNeT++ and contains detailed simulation models of many network protocols and standards, containing Ethernet, WLAN, TCP, IP etc. INET-GPL [160] extends these models by more representations provided under the GPL license. Simu5G [146] is based on OMNeT++ and INET and extends it by adding 5G network models.

The Unreal Engine [161] is a 3D graphics engine that is useful for visualization of simulated scenarios. Management of simulations can be supported by containers and virtual machines, as supported by Docker Desktop [162], Podman Desktop [163], or Oracle VM VirtualBox [164].



3.4.2 ACCELLERAN dRAX

Accelleran's dRAX™ platform is a robust, cloud-native solution designed to facilitate the deployment and management of O-RAN for 5G networks. This platform incorporates the principles of cloud-native architecture, leveraging containerized microservices that ensure flexibility, scalability, and efficiency. Each microservice operates independently, allowing for asynchronous communication and seamless scaling across various deployment scenarios, from small office environments to large-scale network infrastructures with features like multi-node clustering and geo-redundancy.

The dRAX platform is fundamentally built on disaggregating key RAN control plane functions into distinct service entities, such as the CU-CP, CU-UP, and the RIC. This disaggregation supports modular and flexible network management, enabling operators to customize and optimize network operations efficiently. The modularity of the dRAX components enhances interoperability within a multi-vendor ecosystem, allowing operators to integrate and manage components from different suppliers seamlessly.

Figure 8, presents the general components of the dRAX platform. At the top, the dRAX SMO provides management and orchestration capabilities, integrating with the O1 and O2 interfaces. The SMO also hosts the Non-RT RIC, responsible for controlling RAN elements on a timescale of seconds. At the bottom, the dRAX Near RT RIC is shown, featuring the E2 interfaces and proprietary brokers for the Y1 and A1 interfaces. On the left, the x/rApp applications and the SDK are depicted, enabling developers to create these applications.

As mentioned before, the dRAX RIC, provides a comprehensive platform for developing and deploying xApps and rApps. These applications utilize real-time data and artificial intelligence to enhance RAN intelligence and automation. The RIC facilitates the onboarding and lifecycle management of these apps, which can perform a variety of tasks, from optimizing network performance to managing resources dynamically. This capability allows network operators to introduce new functionalities and services into their networks, significantly improving network efficiency and user experience. In addition to its intelligent control capabilities, dRAX includes advanced tools for service management and orchestration. These tools provide an intuitive GUI and open APIs, making it easier to monitor, configure, and manage RAN elements. The dynamic instantiation of RAN microservices is supported, ensuring that network resources are utilized efficiently and effectively. This orchestration capability is further enhanced by the platform's integration with popular orchestration frameworks like Kubernetes, allowing for precise control over network service deployment and management.

The dRAX platform also excels in its integration capabilities with various DUs and RUs from Accelleran's ecosystem partners. It supports different architectural splits, such as Split 7.2 and Split 2, ensuring a modernized and interoperable deployment process. This flexibility allows operators to tailor their network architecture to meet specific deployment needs, whether in urban, suburban, or rural environments.

Other dRAX components include the platform's dRAX Grafana component which provides powerful visualization capabilities, allowing users to explore and monitor the dRAX system easily. It is equipped with a Grafana dashboard that can be accessed via a web interface, providing insights into system health, performance metrics, and other vital data. Additionally, the dRAX API serves as the API gateway, offering easy integration and comprehensive documentation of all exposed APIs. It supports services such as the O2 Service Orchestrator for onboarding and lifecycle management, O1 for discovery and configuration, and O1 VES for monitoring. The API endpoints are well-documented and accessible via a Swagger page, ensuring developers have the necessary resources to integrate and utilize the platform effectively.

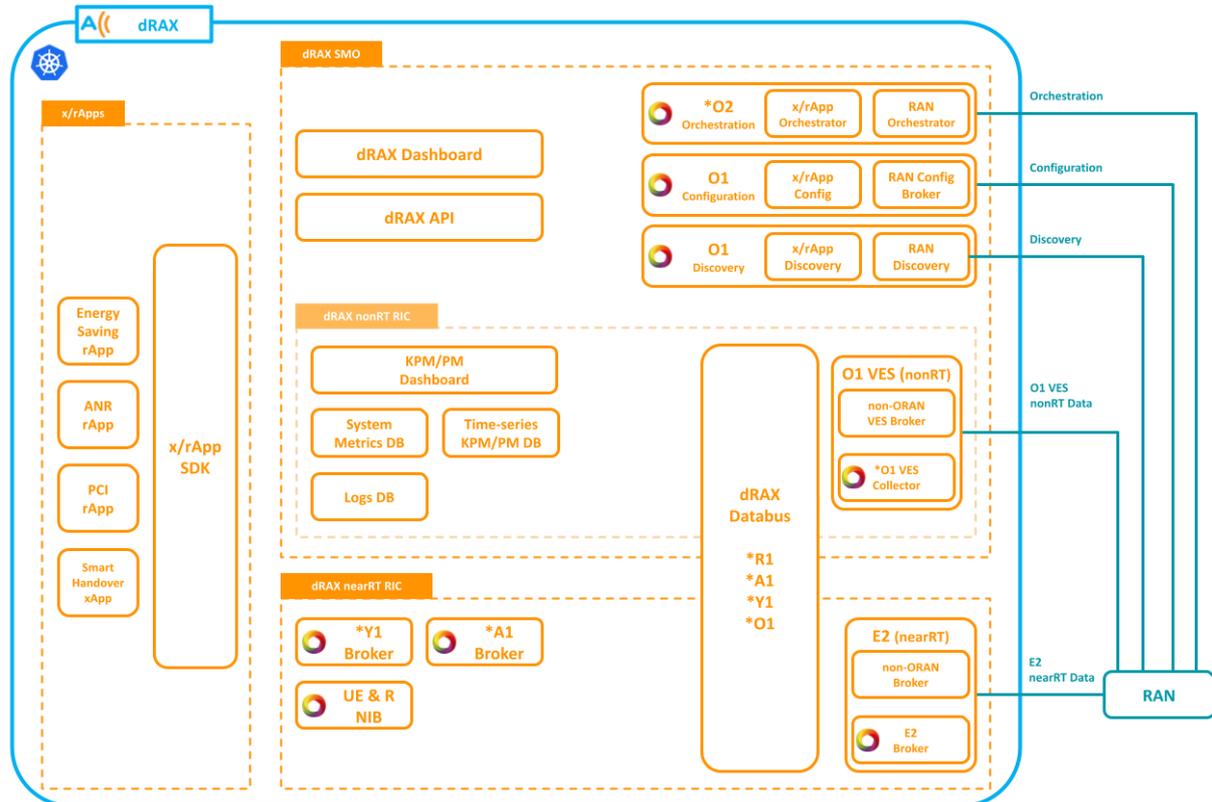


Figure 8. Accelleran dRAX Platform

Central to the platform is the dRAX Databus, a Kafka-based system that facilitates data exchange between components. It acts as the internal R1, A1, and O1 interface and is also exposed externally as the Y1 interface, allowing external systems to publish and subscribe to data. This data exchange system supports real-time data streaming and integration, essential for monitoring and managing network operations.

To support the integration of third-party systems and applications, dRAX offers detailed documentation and example code. The dRAX Integration Guide provides step-by-step instructions for connecting to the dRAX Databus, using the dRAX API, and configuring the platform's various components. It includes practical examples, such as using Python to query Prometheus for RAM usage or setting up Kafka consumers to listen to dRAX Databus topics.

3.4.3 VIAMI RIC Tester

The Viavi RIC Test Tool, shown in Figure 9, provides a solid foundation for RAN Digital Twin (RDT), as it enables comprehensive training and test capabilities for wireless networks, covering various standards and protocols such as ORAN, 4G, and 5G. It emulates RAN topologies in real-world network conditions and user scenarios, providing accurate insights into network performance under different environments, user densities, and mobility patterns. This enables developers to train AI/ML models, for Traffic Steering, Energy Savings, Admission Control, and other Mobility Load Balancing (MLB) use-cases and this is uniquely positioned to develop custom RDTs to optimize operators' networks and RAN spectrum. It achieves this by creating and running millions of RAN simulations with KPIs generated per UE, per beam and per Cell on a regular interval (e.g. 10ms, 1 second or thirty seconds). Such KPIs include PRB Utilization, Throughput, RSRP, RSRQ and SINR.



Hardware and software implementations will be conducted by deploying low (C-band) and high frequencies (sub-THz) gNBs across various network topologies and user equipment locations to gather real-channel state information and power consumption measurements. This data will be used to transform RDT synthetic data into more realistic NDT models, followed by developing management, control, and optimization algorithms for training and predicting network performance. The NDT will incorporate the Viavi RIC Test using O1 and E2 interfaces to generate real-time network configuration optimizations through rApp and xApp. An O-RAN-based network, utilizing the Accelleran dRAX described in the previous section, will be established to configure experimental scenarios, measure system performance, and generate data sets. Simulated calls on the DT, based on live network configuration and call data, will train the ML model and test inferences. The Viavi RIC-Test tool, which emulates the RAN network and subscriber population, will provide a DT of real network configuration, subscriber mobility, and traffic patterns. This tool will generate various RAN scenarios, train ML models for power-control and energy-saving optimization, and measure cell energy and power consumption against QoS objectives, supporting both short-term and long-term energy savings.

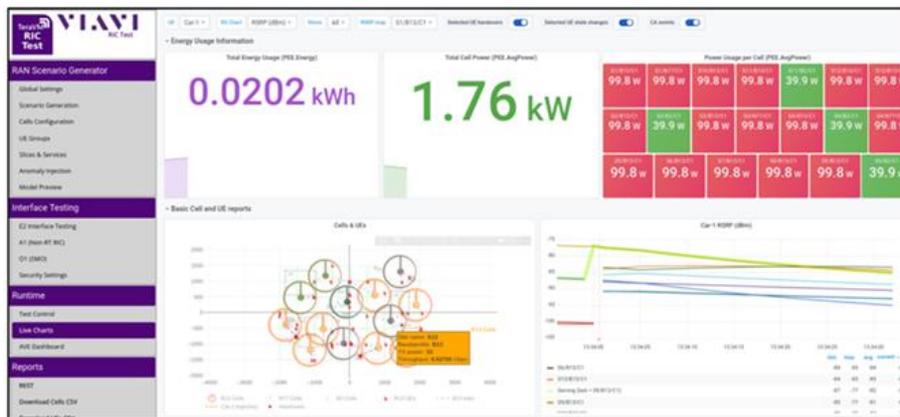
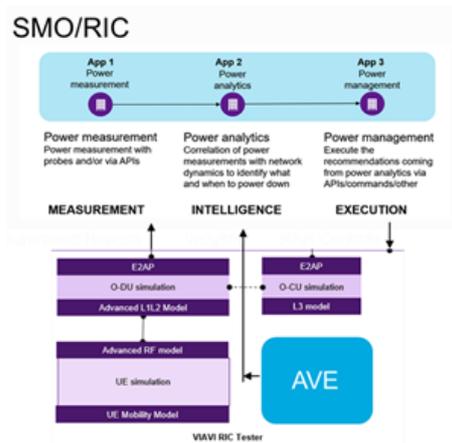


Figure 9. Viavi Solutions. a) Viavi Ric Tester architecture. b) Viavi RIC Tester GUI.

4 FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS

As the telecommunications industry progresses towards the deployment of 6G networks, their complexity and scale necessitate advanced management and optimization techniques. An NDT, as a sophisticated virtual replica of the physical network, simulates, analyses, and optimises network operations in real-time. Accurately modelling the network's topology, behaviours, and environmental factors allows for advanced simulations and scenario testing. real-time data integration and AI-driven analytics empower the DT to predict network conditions, optimise resource allocation, and proactively address potential issues.

The integration of AI and machine learning is a game-changer for the DT's capabilities, making zero-touch resource management a reality—a key feature of 6G networks. This automation significantly reduces the need for human intervention, ensuring efficient and reliable network operations. Moreover, the DT's support for network slicing, virtualization, and edge computing reflects the flexible and distributed nature of 6G architecture.

Ultimately, NDT in 6G are not just tools but the key to achieving the network's goals of ultra-high data rates, near-zero latency, and pervasive connectivity. They also ensure security, privacy, and sustainability. By harnessing these advanced digital replicas, network operators can drive innovation and maintain superior performance in the rapidly evolving landscape of telecommunications.

In this mind, the development of 6G networks promises unprecedented technological advances in connectivity, speed, and integration. To fully harness these capabilities, in **6G-TWIN**, we will create an NDT, which emerges as a critical tool. The NDT will be a virtual replica of the physical network and will simulate, predict, and analyse the network's performance and behaviour. Our work focuses on four fundamental concepts within the realm of NDT for 6G:

- **Data Collection:** Data collection (DC) is not just a foundational process but a continuous and urgent one in creating a digital network twin for the **6G-TWIN** project. The process connects and gathers information from the physical network to feed into the DT. In the context of **6G-TWIN**, data collection is not just a task but a mission that must be continuous, comprehensive, and real-time to capture the network's dynamic nature. The requirements are not just guidelines but the key to enabling a scalable and distributed data exposure and collection framework, empowering effective monitoring of the physical network infrastructure.
- **Zero-touch Management:** Zero-touch management (ZSM) is not just a term but a concept that holds the potential to revolutionise network operations. It refers to the automation of network operations with minimal human intervention. In the **6G-TWIN**'s NDT, zero-touch management is not just a feature but a game-changer that will enable end-to-end automation while focusing on privacy and controlled access. Moreover, the zero-touch network management and control requirements are not just rules but the stepping stones to allow AI-based NF and NS to control domain-specific resources, paving the way for a more efficient and secure network.
- **Federated MANO:** In **6G-TWIN**, federated MANO (FMANO) refers to the decentralised approach to managing and orchestrating network functions across diverse infrastructures and domains. The requirements shall guide the federated management and orchestration of AI-based NF and NS that perform their lifecycle management and



provide mechanisms to guarantee end-to-end convergence (e.g., coordinate decisions, solve conflicts, share knowledge).

- **Simulation Frameworks:** The simulation framework will be a crucial component for the NDT, connecting the tools necessary to model, analyse, and predict network behaviour. Overall, the requirements shall point to an open and secure NDT modelling, simulation, and management framework to build and effectively use NDTs to support what-if analysis and the creation of AI-based functionalities.

In Section 4.5, we outline the high-level system architecture for integrating all the necessary components. The interplay between the different components creates a scalable, robust and fault-tolerant ecosystem for the 6G-TWIN NDT. As seen, the NDT plays a pivotal role in enhancing network performance, reliability, and efficiency. It highly relies on data collection, gathering and processing, to feed all of the other components and allow the NDT to react and enable AI-based NF/NS to work. The Federated MANO layer bootstraps the interaction between all of the infrastructures and domains, while creating standard ways to seamlessly integrate all of the underlying services without compromising security. The integration of the different layers creates the backbone of 6G-TWIN.

During this chapter, we describe all the components in detail.

4.1 Data collection

The development and implementation of data collection systems in the upcoming 6G networks are critical as we transition toward a service-based architecture. To develop a high-fidelity NDT, a comprehensive data strategy is essential. This involves collecting a balanced set of data from the physical network, ensuring both quality and quantity are maintained to avoid unnecessary redundancies and minimize communication overhead and storage use. The data collection must align with existing standardized interfaces along all network domains, including the O-RAN E2 interface, which include different service models under the E2 Service Model (E2SM) and E2 Application Protocol (E2AP) protocols. A reliable data management framework is crucial for maintaining the long-term stability and adaptability of the NDT within the network environment. This framework should encompass the entire lifecycle of data, from collection and storage to maintenance and retrieval. Optimal data management involves automation and incorporates essential features like security, accurate record-keeping, traceability, and data integrity while being supported by MLOps. These elements ensure the proper handling of sensitive network data while maintaining accuracy, completeness, and consistency, thereby supporting the robust functioning of the NDT [34], [165], [166], [167], [168].

In the context of 6G, data collection becomes even more sophisticated and integral. The RAN telemetry framework within 6G networks is designed to capture extensive data from various network elements, including RUs, DUs, and CUs. This data is crucial for creating accurate digital representations of the physical RAN. However, the same procedure is valid for all the network domains, e.g., UE and CN. These digital twins enable seamless interaction between the physical and virtual environments, thus supporting various use cases such as network optimization, energy saving, and enhanced user experiences. Moreover, the integration of AI/ML with DTs in 6G networks enhances their capability to manage and optimize network operations dynamically. AI/ML models require substantial amounts of data to function effectively, which can be initially supplemented by data generated from DTs or network emulators. This creates a continuous cycle of data exchange where the digital twin supplies data to train AI/ML models, which then optimize network configurations. These configurations are applied to the real network, and the resulting performance data is fed back into the digital twin to further refine the models.



One way to manage the integral data collection is the telemetry framework, which is developed to facilitate data communications across various segments of the radio network within the context of O-RAN. Given the dual nature of O-RAN deployment, it addresses the needs of both fully standardized O-RAN implementations and those with proprietary or partially standardized components. In fully standardized O-RAN setups, products adhere strictly to established protocols and interfaces. However, many companies still maintain some closed or proprietary implementations, resulting in Radio Units (RUs), Distributed Units (DUs), and Central Units (CUs), that are not fully compliant with O-RAN standards. The telemetry framework, hence, serves as a crucial intermediary in this heterogeneous environment. Its primary purpose is to manage, translate, and convey data metrics and control information within the RAN. This ensures seamless communication and coordination between the non-standardized radio components and the control entities such as the RIC.

In the context of 6G-TWIN, the data collection framework should be able to support the following Functional requirements (Table 10) and Non-Functional requirements (Table 11), that are specified in T1.2 and D1.2.

Table 10. Functional requirements regarding data collection

ID	Requirements
FR.DC.01	The data collection framework shall allow a seamless integration of capabilities and data sources across multiple data domains, extending the service-based architecture model to the Cloud-to-Far-Edge continuum.
FR.DC.02	The data collection framework shall provide a distributed model for sharing and storing data, regulated by access policies, stored across multiple locations to enhance fault tolerance, improve data access speeds, and ensure scalability.
FR.DC.03	The data collection framework shall enforce robust access policies to control who can access the data, ensuring privacy and security.
FR.DC.04	The data collection framework shall support for multiple communication protocols to ensure that the design of the NDT is able to support legacy integration where many existing devices and systems operate on older protocols.
FR.DC.05	The data collection framework shall provide mechanism to harmonized data formats and standards to maintain consistency and accuracy, reducing the likelihood of errors and misinterpretations when data is exchanged across different parts of the network.
FR.DC.06	The data collection framework shall provide mechanism to ensure integration of data from various sources.
FR.DC.07	The data collection framework shall provide the mechanism to ensure a more efficient data processing, analysis, and utilization across different applications and services.

Table 11. Non-Functional requirements regarding Data Collection

ID	Requirements
NFR.DC.01	6G-TWIN 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.
NFR.DC.02	The data collection framework must be able to handle data generated by a set of heterogenous connected devices, including sensors, IoT devices, user equipment, and network infrastructure (interoperability).
NFR.DC.03	The data collection framework should be able to process and analyse data in real-time to support dynamic and responsive network operations (performance).
NFR.DC.04	The data collection framework should be compatible with various devices and technologies to facilitate seamless data collection and integration (interoperability)
NFR.DC.05	Strong security measures to protect data from unauthorized access, breaches, and other cyber threats (security and privacy)
NFR.DC.06	The data collection framework should ensure minimal delay in data transmission and access to support applications that require real-time data (performance)
NFR.DC.07	The data collection framework should comprise open interfaces so interoperability, cost efficiency and flexibility are achieved (Interoperability)
NFR.DC.08	The data collection framework should utilize system resources (CPU, memory, and network bandwidth) efficiently to minimize overhead and ensure optimal performance. (Efficiency)



An extended information about data collection and data management can be found in deliverable D2.1.

4.2 Zero-touch management

Taking into account the works in T1.3, the 6G-TWIN Zero-Touch Management services will significantly impact traditional control layers into a closed-loop control one. Such services are powered by the NDT AI-based functions that will automate network management and infrastructure control on the heterogeneous deployments we will find. The core objectives of scoping out the functional and non-functional requirements for the Zero-Touch Network and Services Management (ZSM) are inspired by the need to manage and control multiple time scales and cross-domain services while reducing human intervention to minimise errors.

According to ETSI, the functional requirements of such a solution shall focus on three core areas:

- Data concerning collection, generation, and processing.
- AI/ML based functions.
- Automation and continuous integration and deployment.
- The non-functional requirements, still according to ETSI, shall be focused on (1) Performance, (2) Scalability, and (3) Security and Privacy. With this in mind, we will unfold the different specific functional and non-functional requirements for the NDT in the context of 6G-TWIN.

In the context of 6G-TWIN, the ZSM service component will focus on the following requirements (Table 12 and Table 13), which task description is specified in T1.3 and D1.3 will present its results:

Table 12. Functional requirements regarding ZSM

ID	Requirements
FR.ZSM.01	The ZSM shall allow for the implementation of a fully automated network management system where the different data points can be integrated.
FR.ZSM.02	The ZSM shall allow for the autonomous and automatic monitoring of the real-time status of the NDT.
FR.ZSM.03	The ZSM shall enable the management and orchestration of network resources to allow the AI functions on the NDT to optimise and dynamically allocate network resources.
FR.ZSM.04	The ZSM service shall have standard APIs to ensure the minimum interoperability requirements between the new and existing services.
FR.ZSM.05	The ZSM service must enable the integration of AI-based Network Functions (NF) and Network Services (NS), following the best practices for CI/CD and automation while promoting the correct deployment and placement of the workloads.
FR.ZSM.05	The ZSM service should support programmable interfaces that AI-based functions and the NDT ecosystem of apps can control.
FR.ZSM.06	The ZSM system must be able to protect its APIs and resources with the necessary authorization tokens. All the AI-powered functions shall communicate with the ZSM service in a secure and authorised manner to enable security, auditing, and reliability across the network.
FR.ZSM.07	The ZSM system must be able to protect its APIs and resources with the necessary authorization tokens. All of the AI-powered functions shall communicate with the ZSM service in a secure and authorised manner to enable security, auditing, and reliability across the network.
FR.ZSM.08	The ZSM service shall allow itself to be discovered in the network. Because of its appearance on the network, it shall be able to register itself on a common control plane (e.g., the NDT control plane).



Table 13. Non-Functional requirements regarding ZSM

ID	Requirements
NFR.ZSM.01	6G-TWIN 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.
NFR.ZSM.02	6G-TWIN KPI2.5 Support the integration of Network planning & what-if analysis, Network management and control, Network traffic analysis operations.
NFR.ZSM.03	The ZSM service shall be able to handle complex networks across multiple domains and time scales (scalability).
NFR.ZSM.04	The ZSM service shall be able to handle failures and have failover mechanisms (reliability)
NFR.ZSM.05	The ZSM service shall be able to ensure low latency and be able to handle AI-based workloads (performance)
NFR.ZSM.06	The ZSM service shall adhere to the NDT requirements around security and privacy to enable a compliant environment and network (Security and privacy).
NFR.ZSM.07	All of the ZSM APIs and interfaces shall be interoperable and standard (Interoperability)
NFR.ZSM.08	The ZSM service shall have an energy-aware mode. (Efficiency)
NFR.ZSM.09	The ZSM service shall be able to be adapted and maintained by the NDT AI-based functions and the DevOps tooling (Adaptability and Maintainability)

4.3 Federated MANO

Under the guidance of 6G-TWIN's T1.4, we need to scope out the requirements to design and implement a federated MANO framework that would support the AI-based NF/NS in the context of 6G-TWIN. The federated MANO framework will be responsible for enabling a decentralised approach to the M&O of the network, its services and functions. And since we are on the federation, the concept expands beyond a single network onto a federation of several networks and, therefore, several more M&O points. Additionally, the requirements and ways of working shall adhere to the best practices of the cloud-native community.

Designing such a framework requires that all underlying systems are interconnected and interoperable and understand each other. Also, the framework shall be able to deploy and orchestrate workloads that will run on the network and processing units on this network, which essentially entails a specific set of requirements that scope this component to not only be an orchestrator but also have tight integrations with source control systems to allow for the automatic integration and deployment of new apps and services. Below, we outline the requirements for such a solution (Table 14 and Table 15), which task description is specified in T1.4 and D1.3 will present its results

Table 14. Functional requirements regarding F-MANO

ID	Requirements
FR.FMANO.01	The F-MANO shall support, when necessary and possible, intelligent strategies for life cycle management of AI-based NF/NS in cross-domain and multi-time scale distributed networks.
FR.FMANO.02	The F-MANO framework shall be able to remotely manage, deploy and orchestrate the workloads that contain the AI-based algorithms across the network it operates.
FR.FMANO.03	The F-MANO framework shall provide a standardised way of storing and retrieving AI models in an MLOps-oriented manner.
FR.FMANO.04	The F-MANO Framework shall allow for an automated way of updating the AI models in real-time as soon as a new version is available.
FR.FMANO.05	The F-MANO shall expose a comprehensive and standardised API for the other services in the 6G-TWIN ecosystem to communicate.
FR.FMANO.06	The F-MANO shall provide mechanisms such as coordination, conflict detection and resolution, and knowledge sharing between AI-based NF/NS in cross-domain and multi-time scale distributed networks without losing privacy of the data.
FR.FMANO.07	The F-MANO framework shall support the allocation of AI-based NF/NS in cross-domain and multi-time scale distributed networks.



Table 15. Non-Functional requirements regarding F-MANO

ID	Requirements
NFR.FMANO.01	6G-TWIN 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.
NFR. FMANO.02	6G-TWIN KPI1.3: Provide at least three AI-based NF/NS for data analytics or/and decision-making to optimise network performance per use case.
NFR. FMANO.03	The F-MANO shall support simultaneously network elements and digital twin instances across multiple network domains (scalability).
NFR. FMANO.04	The F-MANO should efficiently scale AI model training and inference as network demands increase (scalability).
NFR. FMANO.05	The F-MANO shall ensure low-latency operations for management, orchestration, and real-time decision-making (performance)
NFR. FMANO.06	The F-MANO should seamlessly integrate with various AI models, network elements, and third-party systems (Interoperability).
NFR. FMANO.07	The F-MANO should optimize energy consumption, especially when managing large scale AI workloads and digital twin instances (Efficiency).
NFR. FMANO.08	The F-MANO should comply with relevant industry standards and regulations. (Adaptability and Maintainability)
NFR.FMANO.09	The F-MANO framework shall be able to maintain the running state of the services in the other components of the NDT based on GitOps, DevOps and MLOps guidelines.
NFR.FMANO.10	The F-MANO shall follow a cloud-native approach and architecture to manage the lifecycle of the workloads better.

For the Federated MANO Framework, several implementation considerations should be mapped out, as follows.

- The Federated aspect of the solution entails several data privacy and security concerns. In this sense, the F-MANO framework shall assume that the nodes it's managing will have storage and processing capabilities and will only share the necessary data across the network. The nodes should be in charge of data security at rest.
- The F-MANO Framework also assumes that the Data Collection Framework will be responsible for the anonymisation and protection of data in transit.
- The F-MANO Framework requires that the nodes comply with a standard set of underlying tooling to be orchestrated. The ZSM services shall bootstrap such tooling in the edge nodes or any other nodes.
- The F-MANO Framework shall follow a cloud-native approach and architecture to manage the lifecycle of the workloads better.
- The F-MANO Framework shall adhere to the MLOps best practices regarding the deployment, storage, training, and monitoring of AI models.

4.4 Simulation framework

The simulation framework is developed for combining different 6G network simulation models realized in different simulation tools. Therefore, the simulation framework must make sure that the interaction between the different simulators works as intended. This requires specifications of the communication between the simulation framework and the simulators as well as the data exchange between the simulators, if this is done directly.

Furthermore, the simulation framework is configured by the "closed-loop optimization framework" to test and optimize different parametrizations of a combined model. For this purpose, also the communication between the simulation framework and the closed-loop optimization framework must be specified.

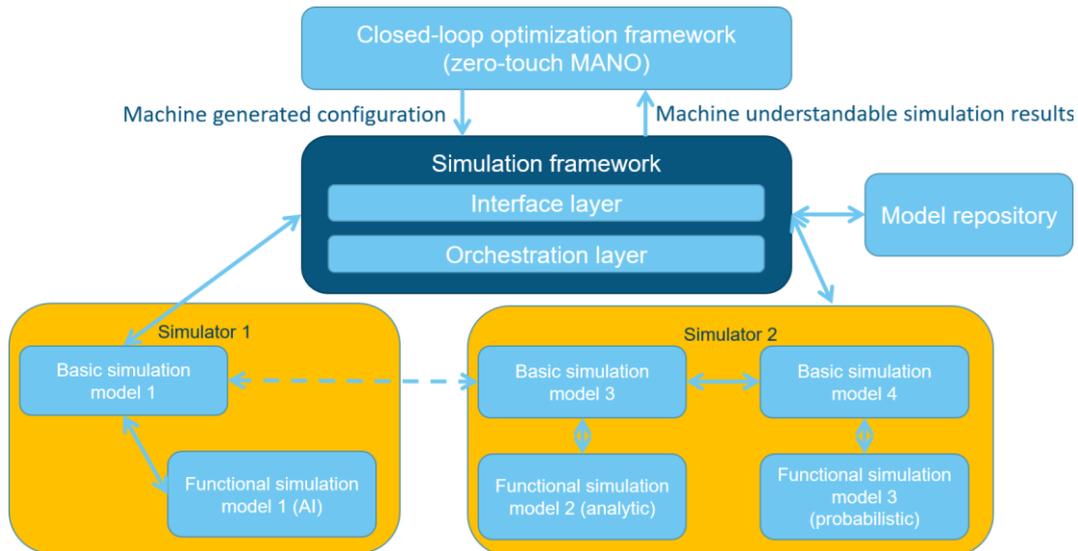


Figure 10. Logical view of the interaction of the simulation framework with other components

All of that has the additional challenge that different simulation models and the closed-loop optimization framework might be executed on different computers in different places in Europe or the earth. So, besides the logical communication between the models, also secure communication between the physical platforms of the combined simulation must be realized. All these tasks result in requirements.

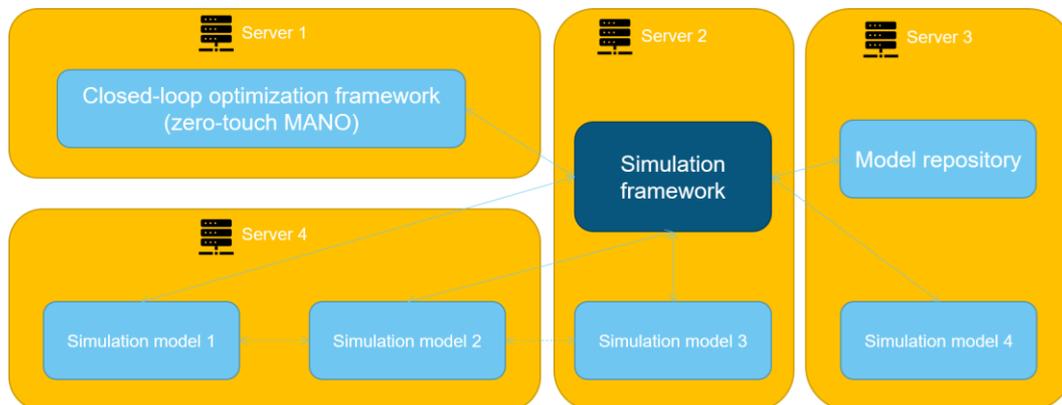


Figure 11. Example of distributed simulation setup

First, what the simulation framework requires from the components that it uses is specified described in Table 16.

Table 16. Functional Requirements regarding components that are used by the simulation framework

ID	Used Component	Requirements	Further specified in task/deliverable
FR.SF.01-05	Simulators	(1) specifications of the communication protocols between the simulation framework and the simulators that are coordinated by the simulation framework (2) specification of data structures used for communication between the simulation framework and the simulators (3) semantic description of the data structures that are relevant for simulation setup and computation of metrics (4) time management service for synchronizing the simulators for reaching high efficiency without violating dependencies between the simulators (5) specification of exception handling	Task 3.1 D3.1



FR.SF.06	Basic models	implementation of basic models as available in common simulators, or custom-built compatible to them	Task 2.2, task 3.1 D2.2, D3.1
FR.SF.07	Functional models	implementation of functional models as available in common simulators, or custom-built compatible to them	Task 2.3, task 3.1 D2.3, D3.1
FR.SF.08-13	Model repository	(8) machine-readable description of available models (9) functionalities for selecting appropriate models according to a machine-readable specification of simulation goals (10) functionalities to deploy (instantiate) models (11) functionalities to parameterize, start and stop model instances (12) functionalities to gather metrics from deployed models (13) machine-readable description of computing and storage requirements	Task 3.1 D3.1

The simulation framework is used by other components, primarily by the closed-loop optimization framework. Also in that direction, there are functional (Table 17 and Table 18) and non-functional requirements (Table 19).

Table 17. Functional requirements regarding components that use the simulation framework

ID	Component that uses simulation framework	Requirements	Further specified in task/deliverable
FR.SF.14-16	Closed-loop optimization framework which does zero-touch MANO	(14) specification of the protocol between the closed-loop framework and the simulation platform (15) semantic description of the parametrization information that is transferred from the closed-loop framework to the simulation platform ("Machine-Generated Configuration") (16) semantic description of the metrics that are transferred from the simulation platform to the closed-loop framework ("Machine-Understandable Simulation Results")	Task 1.3, task 1.4, task 2.4, task 3.1 D1.3, D3.1

The simulation framework also contains two internal layers, the interface layer and the orchestration layer, see Figure 10. These internals don't have to be known by the external components (simulators and closed-loop framework), but specifications about their functionalities are required to develop them together and to make them replaceable.

Table 18. Functional requirements of the internal layers of the simulation framework

ID	Layer	Requirements
FR.SF.17-18	Interface layer	(17) abstract specification of the subdivision procedure of configurations, in order to be used by the closed-loop framework (18) abstract specification of the result collection procedure
FR.SF.19 - 21	Orchestration layer	(19) specification of the time management service for synchronization of simulators, providing synchronous, asynchronous, and perhaps speculative mode (20) specification of an event distribution service for simulators that are not directly coupled (21) specification of a global state repository for coupling heterogeneous simulators

Finally, besides the interaction with other components, also the simulation framework itself must fulfil specific functional and non-functional requirements, mainly fitting to the KPIs from section 2.2.4.

Table 19. Non-Functional Requirements of the simulation framework itself

ID	Requirement	Further specified in task/deliverable
NFR.SF.1	KPI3.1: abstract interface (for platform-independent solution that allows the integration of new frameworks)	Task 3.1 D3.1



NFR.SF.2	KPI3.2: federation overhead of no more than 15% for moderately complex simulations (and less for complex ones)	Task 3.4 D3.2
NFR.SF.3	KPI3.3: federation interface is available for at least two programming languages (one compiled, one interpreted)	Task 3.1 D3.1
NFR.SF.4	KPI3.4: reference implementation of the federation interface as Open-Source software	Task 3.1 D3.1
NFR.SF.5	Parametrization of simulations	Task 3.1, task 5.1 D5.1, D3.1
NFR.SF.6	Output of metrics	Task 3.1, task 5.1 D5.1, D3.1
NFR.SF.7	Secure communication between components	Task 3.2 D3.2
NFR.SF.8	Verification and validation	Task 3.3, task 3.4, task 4.2, task 4.3, task 4.4 D4.2, D3.1

In conclusion, the specification of protocols and data structures are the most essential tasks for the collaboration of simulation tools via the simulation framework developed in **6G-TWIN**. Regarding the reference implementation, a small federation overhead and openness via different programming languages and open-source software is necessary.

4.5 Requirements considerations

In 6G networks, self-healing, self-optimising, and self-organising capabilities are essential for managing complexity and enhancing performance. Self-healing networks automatically detect, diagnose, and recover from failures without human intervention, ensuring continuous service through automated fault detection, root cause analysis, and dynamic rerouting. Self-optimising networks dynamically adjust parameters and configurations to optimise performance and efficiency, using real-time performance monitoring and AI-driven optimization to manage resources and enhance user experience. Self-organising networks autonomously configure, manage, and optimise operations, reducing the need for manual intervention by enabling automatic configuration of new elements, continuous self-optimization, and dynamic topology management. These capabilities rely on integrating AI and ML for predictive analytics and autonomous decision-making, distributed intelligence for localised processing, and advanced automation frameworks. The benefits include enhanced reliability, improved performance, cost efficiency, and scalability, making these features fundamental to the vision of 6G networks.

Morphing traditional network simulators into RAN Digital Twin components, requires the following items:

- **Orchestration:** Have a working Digital Twin CI/CD configuration that automates test and delivery of AI based applications.
- **Data ingestion:** Conversion of network data via a wide range of interfaces (EMS, SNMP, E2, O1 etc) into InfluxDB and/or Kafka
- **Data lake design/spec:** Based around applications such as KubeFlow , having a homogeneous access to heterogeneous data sources
- **RAN Models infrastructure (train & run):** KubeFlow framework.
- **RAN Simulation based on VIAVI RAN Scenario Generator**
- **RIC Twin, RIC Platform or Similar**



The requirements that we've pointed out during this chapter will aid in the development of the use cases. In other words, these requirements are the baseline for any of the use cases and shall depict the core functionalities of a 6G-enabled NDT or app.

5 REFERENCE USE CASES AND KPIS

In this chapter, we will delve into the essential use cases and the KPIs that are pivotal to the 6G-TWIN project. We will begin by discussing the foundational KVs and KVIs within the context of European projects, highlighting how these elements guide the strategic objectives and actions of the 6G-TWIN initiative. The relationship between KVs and KVIs will be explored to demonstrate how abstract values are translated into measurable outcomes, ensuring alignment with broader societal goals such as sustainability, inclusiveness, and innovation.

Following this, we will present the KPI family and specific KPIs relevant to the 6G-TWIN project. This section will detail the methodology used to derive these KPIs, ensuring they are aligned with the project's objectives. Additionally, these will be mapped into the two primary use cases that the project will implement: teleoperated driving and energy savings in dense deployments. Each use case will be described in detail, outlining the expected functionalities, technical requirements, and the specific KPIs that will be used to measure success. These use cases will demonstrate the practical applications of the 6G-TWIN architecture and its potential to enhance network performance and efficiency in real-world scenarios.

5.1 KVIs and KPIs Within European Projects

5.1.1 Key Values

Key Values are fundamental principles or standards that guide the strategic objectives and actions of organizations and projects. These values often originate from broader societal goals established by international bodies such as the UN and the ITU. For instance, the UN promotes values such as sustainability, human rights, and social equity, which are crucial for ensuring inclusive and equitable development. The UN's 17 Sustainable Development Goals (SDGs) provide a comprehensive blueprint for global development, addressing issues such as poverty, hunger, health, education, and climate change as shown in Figure 12. Each SDG encapsulates specific targets and indicators that align with broader KVs, thereby ensuring a holistic approach to development [169].

The ITU focuses on universal connectivity, innovation, and cybersecurity, aiming to bridge the digital divide and foster a secure and innovative technological environment. These efforts are directly aligned with several SDGs, including Goal 9 (Industry, Innovation, and Infrastructure) and Goal 17 (Partnerships for the Goals), which emphasize the importance of technological advancement and global cooperation. By promoting these values, the ITU contributes to building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation.



Figure 12. UN 17 Sustainable Development Goals to map KVs [169]



The relationship between KVs and KVIs is intrinsic and critical for translating abstract values into measurable outcomes. KVs provide the foundational principles, while KVIs are the specific metrics used to assess the extent to which these values are being upheld. For example, the KV of sustainability can be translated into KVIs such as carbon footprint reduction and energy efficiency. These indicators allow organizations to measure their progress toward achieving sustainability goals in a tangible manner, aligning with SDGs like Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action).

Furthermore, KVs help align the objectives of various stakeholders by providing a common framework of values that everyone agrees to uphold. This alignment is crucial in large-scale projects like 6G-TWIN, where multiple stakeholders may have differing priorities. By establishing clear KVs, organizations can ensure that their actions are consistently aimed at achieving shared societal goals. The KVIs, in turn, provide a way to measure and demonstrate this alignment, ensuring accountability and continuous improvement.

In the context of 6G-TWIN, KVs such as innovation, inclusiveness, and environmental sustainability are paramount. These values guide the project's overarching goals and inform the development of specific initiatives and strategies. By relating these values to measurable KVIs, the project can effectively monitor its impact and ensure that it is contributing positively to broader societal objectives. This approach not only enhances the project's credibility but also ensures that it delivers meaningful and sustainable outcomes.

Hence, to correctly identify the KVs/KVIs that perfectly suit the 6G-TWIN use cases, we first review the KV/KVI methodology derivation for some 2nd call Stream B/Stream D SNS-JU projects. KVI values are generally dressed for specific use cases. Then, we summarize in Table 20 some examples of use cases for different Stream B/D projects that are representative of the different classes of applications (verticals) targeted by the 6G networks. Each use case in Table 20 is referred by its Ucl (Use case Identification) that follows the following format “SNS_UCx.y”, where *x* is the project reference in Table 20 and *y* is the use case number for a given project [170].

Table 20. SNS JU Stream B/ D projects use case examples aligned with verticals

Project reference	Project Name	Vertical	Use case name	Use case Identification (Ucl)
1	DETERMINISTIC6G [171], [172]	Industry 4.0	Exoskeleton in the Industrial Context	SNS_UC1.1
		Agriculture and forestry	Mobile Automation: Smart Farming	SNS_UC1.2
2	HEXA-X-II [13], [173]	Industry4.0	Cooperating Mobile Robots	SNS_UC 2.1
3	FIDAL [174], [175]	Media	DT for first responders	SNS_UC3.1
		PPDR	City security incident	SNS_UC3.2
4	TrialsNet [176], [177], [178], [179]	Transport and logistics	Smart Traffic Management	SNS_UC4.1
		eHealth	Smart Ambulance	SNS_UC4.2
		Culture, Education Entertainment	Service Robots for enhanced passengers' experience	SNS_UC4.3
5	6GTandem [180]	eHealth	Mixed Reality Surgery	SNS_UC5.1
		Industry4.0	DT in industrial environment	SNS_UC5.2
		Transport and logistics	Crowd scenarios in public transportation	SNS_UC5.3

In Table 21, we briefly describe the KV/KVI mapping methodology used by for some projects use cases. For instance, for projects like DETERMINISTIC6G [172] or FIDAL [175], the process begins by KV categorizing in the three high level categories (social, economic and environmental). Then, key value criteria/goals are explicitly defined in each category. KV



indicators are then defined for each use-case and can be expressed or not with a quantitative value as a target or with potential KPIs as a metric [181]. For projects like HEXA-X-II, the deliverable D2.1 [173] details for each use case the sustainability analysis that defines the Key values as footprints (costs) and handprints (benefits). To assess the technical and the sustainability performance of the 6G systems, a PoC (Proof of Concept) analysis [173] is undertaken for the different use cases and KVIs (like trustworthiness) are derived. KVIs can be evaluated quantitatively through common KPI performance parameters (like latency) or qualitatively using proper socio-economic paradigms (like resilience).

5.1.2 KPI family and KPIs

The 6G SNS Test, Measurement, and Validation (TMV) of KPIs Working Group (WG) [182] is one of the three Smart Networks and Services Joint Undertaking (SNS JU) WGs that aims to formalize KPI/KVI concepts and their generalization to the greatest number of projects. As KVIs, KPIs rather focus on the technical performance of a given system/architecture and are generally expressed as quantitative target values. In the context of 6G mobile networks and depending on the abstraction layer for which the performance are derived, KPIs can either be the user plane latency or the packet loss rate for example. To facilitate the categorization of KPI values, the TMV WG proposes to regroup KPI values into KPI families as shown in Table 13 to allow the SNS JU European projects to easily pick the performance indicators among the list proposed in Figure 13 and also to harmonize these parameters among the different projects hence rendering a prospective comparison between the different projects performance possible.

Thus, the TMV WG defines the information to be collected by the research projects, related to the KPIs definitions, target values, as well as information relevant to the context of these definitions.

In accordance with the reference KPI families identified in Figure 13, each project should identify a subset or a comprehensive list of KPIs referenced in this table, and eventually other KPIs that are proper to each project/use case definition.



Table 21. Examples of use case's KV/KVI definitions for SNS JU Stream B and D projects

Project	Ucl	KV categorization	Key Value theme/criteria	Key Value enabler (cost)	Key Value enabler (benefit)	KVI
DETERMINISTIC 6G	SNS_UC1.1	Social and economic	Personal health and protection from harm			Reduction of the costs for the care of work-related injuries
						Reduction of number work-related injuries
HEXA-X-II	SNS_UC2.1	Environment		Increased efficiency in production processes Reduced need for multiple machines due to function integration	Increased material and energy consumption throughout full life cycle of the robots and associated services. Increased electronic waste	
		Social		Improved accessibility from tasks beyond human capabilities. Safer working environments. M2H support	Elimination of jobs. Uneven distribution of benefits from robots and cobots. Unauthorized use of sensors and associated privacy concerns	
		Economic		Enhanced productivity and competitiveness. New business and job opportunities	Barriers for small businesses Monopolization risks financial loss in case of service failure or cyber-attacks	
FIDAL	SNS_UC 3.1	Environment	Compliance Quality Standards			Engage certification processes
			Mitigation Strategies			Greater understanding of environmental challenges from tech
			Environmental Sustainability			Reduced energy consumption, air pollution
		Economic	Business Value			Solve existing and emerging problems, reduce resources needed to engage
		Social	Safety			Greater protection of vulnerable people, improved feeling safe, and increased operational efficiency for saving lives
			Security			Decrease system vulnerabilities
Healthier community				Improved satisfaction and access to services		



	SNS_UC 3.2	Environment	Environmental Sustainability			Reduction of energy consumption, decreased energy degradation
			Waste Management			Re-used and re-purposed existing equipment
		Economic	Economic Sustainability			Reducing costs by using existing systems rather than building new one
			Business Value			Perception of problems solved business plans
			Responsibility			Accountability for system behaviour, enables alternative approaches
		Social	Flexibility			Optimal resource allocation, re-use of existing systems, ability of AI systems to adapt
			Healthier community			Improved relationships with organisations, improved health
				Knowledge		

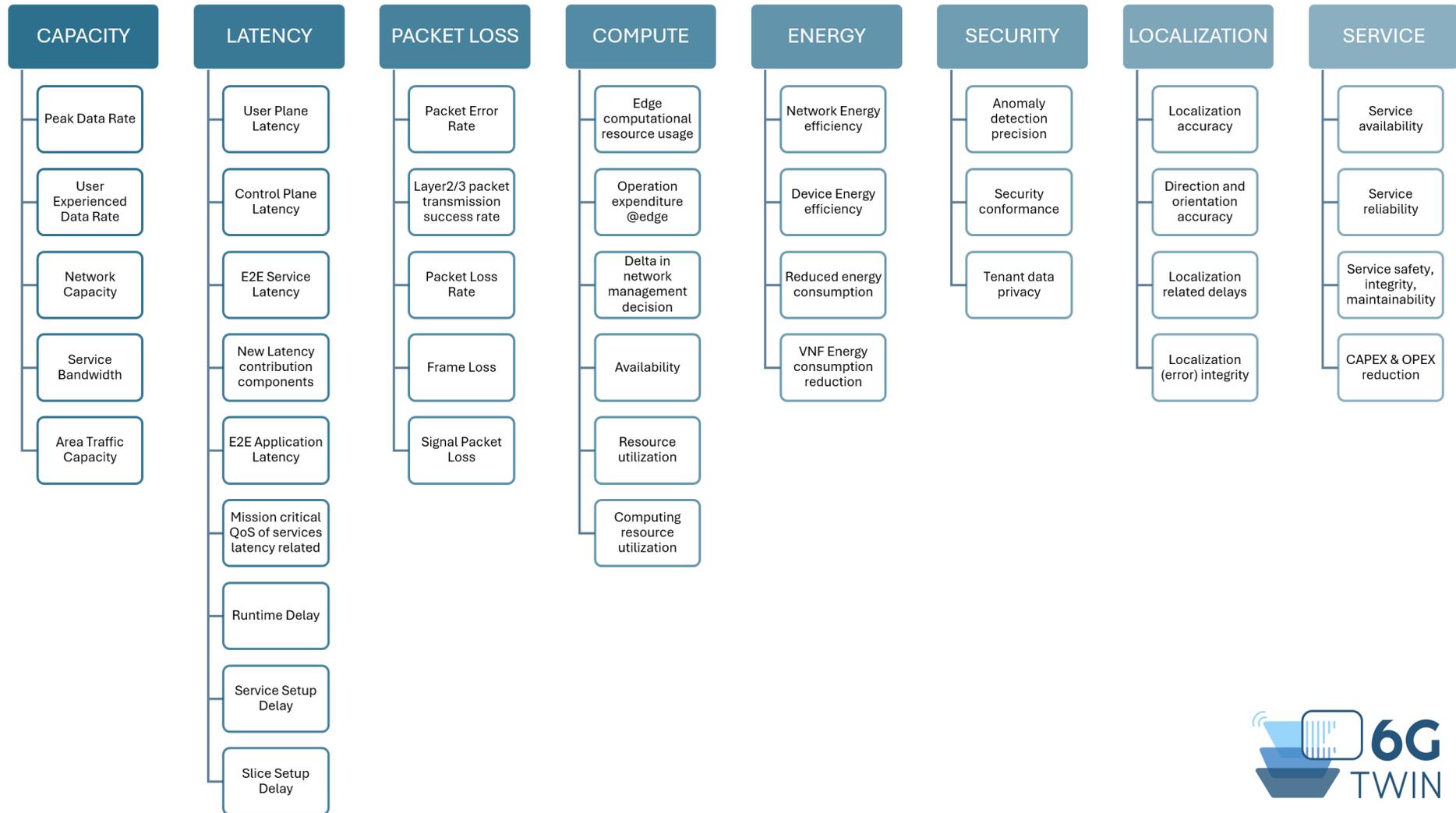


Figure 13. KPIs grouped in KPI families.





In Table 22, we focus on the use cases SNS_UC2.1 already defined in Table 20 that respectively correspond to the “Cooperating Mobile Robots” use case in HEXA-X-II project and the SNS_UC4.1 “Smart Traffic Management” use case in TrialsNet project. For these two use cases, we show the target KPI values grouped by KPI families.

For instance, the use case SNS_UC2.1 aims to achieve an “end to end service latency”, which belongs to the “Latency” KPI family less than 0.8 ms. Whereas, in the context of the “Service” KPI family the use case SNS_UC4.2 intends to ensure a “Service reliability” of 99,99%. For both use cases, some KPI values are not applicable. For instance, the “Security” KPI family is not applicable for both use cases.

Table 22. Examples of KPI values for several 6G SNS Stream B/D project use

Ucl	KPI Family							
	Capacity	Latency	Packet Loss	Compute	Energy	Security	Localization	Service
SNS_UC2.1	User experienced data rate (10 Mb/s)	E2E service latency (<0.8 ms)					Localisation accuracy (<0.1 m)	Service reliability (99.999-99.999)
	Area traffic capacity (<0.1 Mb/s/m2)							
SNS_UC4.1	Uplink user experience data rate (14 Mbps)	Application-level latency (<100ms)						
	Downlink cell capacity (1.5 Gbps)	E2E latency (<50ms)						Reliability (99%)
	Uplink cell capacity (150 Mbps)							Service availability (99%)
SNS_UC4.2		Application round trip latency (800ms)		Precision 0,8				Service reliability (99,99%)
				Recall 0,6				Service availability (99,99%)
				F1 score 0,68				

5.1.3 Relation between KVI and KPIs

A KPI is a measurable value that demonstrates how effectively an organization is achieving its key business objectives. KPIs are essential tools for performance management, providing insights into various aspects of organizational performance and helping to drive strategic decision-making. In the context of 6G-TWIN, KPIs are used to measure the effectiveness of various initiatives and ensure that they are aligned with the project's overall goals and values. The relationship between KVIs and KPIs is fundamental in ensuring that the values upheld by an organization are effectively translated into actionable and measurable outcomes. While KVIs measure the adherence to key values, KPIs provide specific metrics that can be monitored over time to gauge performance. For instance, a KVI related to environmental sustainability might be measured through KPIs such as energy consumption, carbon emissions, and waste reduction. This mapping ensures that the organization's values are not only articulated but also systematically tracked and improved upon.

The SNS TMV WG [182] outlines a structured approach to deriving KPIs from KVIs, ensuring that each KPI is directly linked to the underlying values. This process involves identifying the



use case stakeholders, articulating their challenges and needs, defining the key values for the use cases, and then developing specific indicators to measure these values. The indicators are then used to set measurable KPIs that align with the project's goals and timelines.

Table 23. Relation between KVIs and KPIs for some SNS projects.

KVI	KPI
Environmental Sustainability	Energy consumption, CO2 emissions, waste reduction
Inclusiveness	Service availability to diverse demographics
Innovation	Number of patents filed rate of new technology adoption
Safety and Security	Incident response time, number of security breaches
Economic Growth	Cost efficiency, profitability, market penetration
Good Health and Safety	Patient waiting time, accuracy of health monitoring
Privacy and Confidentiality	Number of data breaches, compliance with privacy regulations
User Experience	User satisfaction scores, adoption rates

5.1.4 KPIS in 6G-TWIN

In the context of 6G-TWIN, the two use cases (teleoperated driving and energy savings will be implemented in the form of demonstrators to test the solutions and assess their relevance. The design of such solutions will be done with respect of a list of KPIs potentially shared with other projects funded under STREAM-C and B of SNS JU Phase 1 (2022) and with respect to KPI family classification given in Figure 13. The project will analyse these KPIs in more details and map them into their respective families as shown in Table 24. All KPIs will be measured for each of the use cases and their scenarios. Specific targets are indicated in the description of each use-case, later on in this section.



Table 24. Prospective KPI family and names for 6G-TWIN

Ucl	KPI family								
	Capacity	Latency	Packet Loss	Compute	Energy	Security	Localization	Service	
UC1: Teleoperated driving	User experienced data rate Network capacity Connectivity density	E2E service latency E2E application latency New component latency contribution	Packet error rate Frame Layer 2/3 packet transmission success rate	Edge computational resource usage Delta in network management decision Availability Resource utilisation Computing resource utilisation	Network efficiency Device efficiency NFV efficiency energy energy energy	Anomaly detection precision Security conformance Tenant data privacy	Localisation accuracy Direction accuracy localization-related delays localization integrity	Service availability Service reliability Service safety, integrity and maintainability	
UC2: Energy savings	User experienced data rate Network capacity Connectivity density			Edge computational resource usage Delta in network management decision Availability Resource utilisation Computing resource utilisation	Network efficiency Device efficiency NFV efficiency energy energy energy	Anomaly detection precision. Security conformance Tenant data privacy	Localisation accuracy. Direction accuracy localization-related delays localization integrity	Service availability Service reliability Service safety, integrity and maintainability	



5.2 Teleoperated Driving

The first use case centres on teleoperated driving supported by a predictive DT, as illustrated in Figure 14.

Here, *teleoperated driving* means moving the driver of a road vehicle out of their car/truck/etc. and into a (remote) control centre – either partly or fully. This requires vehicle sensors capable of sensing the environment and transmitting this real-time information (e.g., detected objects, Light Detection and Ranging -LIDAR- point clouds, video streams) to the remote operator over the mobile network. It also requires data fusion and pre-processing on edge servers to overcome the limited computing capabilities of the vehicles while limiting the amount of information transmitted (i.e., reducing network load). Such a system is particularly interesting for public transport, remote hailing, or remote parking – even more so when combined with some autonomous functions of the vehicle.

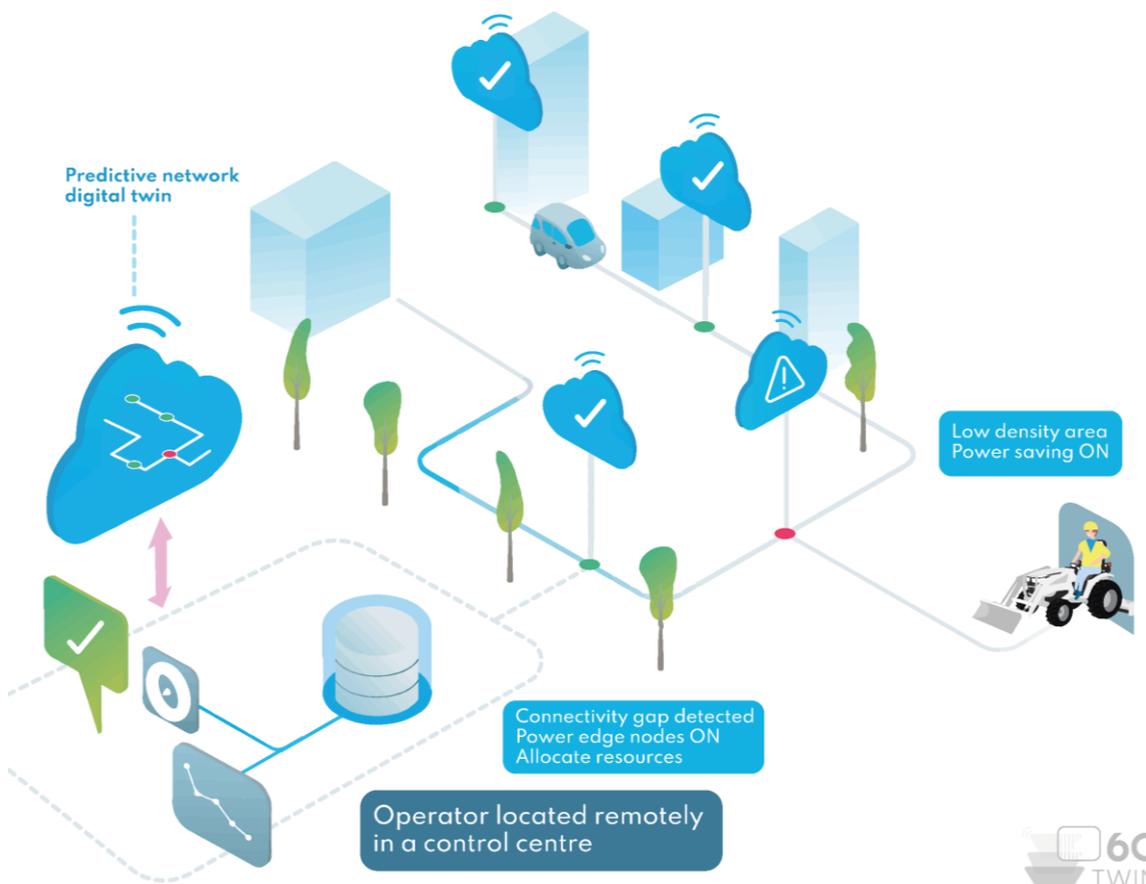


Figure 14. Illustration of the Teleoperated Driving Use Case.

The teleoperation of a vehicle has high demands on the network, such as extreme reliability, low latency, and high throughput. Often-quoted values are 99.999% reliability and latencies below 20 milliseconds. This is in contrast to our assumption that the full capacity of the network is not always deployed throughout. In particular, we assume that edge servers at different locations can be turned off and virtual network functions might be undeployed during periods of inactivity, e.g., in rural areas. Before the journey of a teleoperated vehicle can begin, the vehicle is therefore first driven virtually, in a simulation, to ensure adequate resources are available – to investigate changes that would ensure they are – and to then realize these changes before the trip of the vehicle commences.



We envision two realizations of this use case:

- **2D network planning**, where a single mobile platform representing a vehicle is teleoperated wirelessly in a lab environment via an O-RAN network. Before the vehicle starts its trip, the network (1) reasons about quality-of-service levels of the vehicle when connecting to various edge computing nodes along its route, (2) allows to examine various trade-offs in how to improve service (e.g., deploying edge computing capacity or virtual network functions), then (3) supports the realization of a selected optimization.
- **3D network planning**, which augments the network with satellites or drones as both additional access and edge computing options – and replaces the single real mobile platform with multiple simulated ones.

5.2.1 Expected functionalities

To realize the described use case, the designed system must, given a planned trip (as defined by its start/end location), allow to conduct automatic what-if analyses, exploring and weighing options, then be able to realize the required changes in the real network.

For this, three components need to interact: a *closed-loop optimization framework* and a *simulation framework*, both having a shared understanding of which components (might) exist in the system and how they are configured (that is, a *data and model repository*). The optimization framework keeps the data and model repository current with the state of the real network and allows to manifest desired changes in the real network.

For conducting a what-if analysis, the optimization framework assembles a machine-generated system configuration (a *scenario*) from the data and model repository, modified by changes to be investigated, and sends it to the simulation framework.

The simulation framework must then conduct the what-if analysis of the scenario – instantiating, interconnecting, and managing many interrelated simulations, e.g., potentially many mobility simulations, RAN simulations, and a core network simulation. These individual simulations must be useful approximations of system behaviour, in particular with respect to involved basic and functional models of the network. It must be possible to execute individual simulations on different machines in potentially different locations without compromising the security or integrity of data.

Upon conclusion of a simulation, the simulation framework must then return machine-understandable simulation results to the optimization framework. The optimization framework must then reason about the results and either conduct more what-if analyses or actualize the investigated changes in the real network.

5.2.2 KPIs

Key performance indicators for a successful demonstration of the *teleoperated driving* use case must be aligned with a 2D network planning for teleoperated driving providing full end-to-end connectivity to teleoperate a real mobile platform. The performance of the network can be visualized in terms of at least four metrics. Connectivity in the system can be subjected to imperfections in deployment, which can be addressed by changes in the network. The optimization framework can investigate the impact of potential changes to the network, then realize a beneficial change.

Results from the real mobile platform of the 2D network planning realization of the use case can be replicated in the purely virtual 3D network planning realization. The optimization framework can then investigate potential improvements brought about by the integration of satellites or drones and can serve multiple vehicles planning upcoming trips.



The use case is connected to the following project-wise KPIs as described in Anex 1:

- **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.
- **KPI4.1 (pt1):** Set up the teledriving testbed to provide full E2E connectivity for the successful transmission of control signalling and user traffic from the remote driving apps.
- **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.
- **KPI4.4:** 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.

Table 25 lists reference KPIs that have to be guaranteed according to the literature [183]. They serve as a baseline for the derivation of concrete specifications during the project.

Table 25. Reference KPIs for Use Case 1.

KPI family	Target	Baseline ref
Latency	Uplink from vehicle: ≤ 100 ms. Downlink to vehicle ≤ 20 ms Depending on speed	[184], [185]
Capacity	Uplink from vehicle ≥ 32 Mbit/s (video streaming) Downlink to vehicle ≥ 400 kbit/s (commands) Depending on number of cameras and sensor data richness	[185]
Reliability	Uplink from vehicle ≥ 99 % Downlink to vehicle ≥ 99.999 % Depending on driving situation	[185]
Compute/Energy	Reduction of up to 30% Compared to knowledge-expert agent with guarantee of zero violation of minimal latency	[186]

5.3 Energy savings in dense deployments

Sustainability will be one of the guiding aspects of the 6G era. In 2030, our networks will not only refine the way we live and work, but they must also directly impact how we care for the planet. One obstacle to building a sustainable 6G system is the fact that 6G will need to deliver much more data at faster rates than today's networks, while still fulfilling very stringent energy-efficiency goals. This means that the required energy for transmitting a bit must be significantly reduced. Additionally, energy is one the main OPEX costs of running mobile networks, so saving energy is also a strong business driver. The use-case targets a green approach of mobile networks, which provides increased efficiency and better energy usage by optimising network resources. Data-driven networks, mainly empowered by AI/ML, or hybrid approaches between ML, analytical models and mathematical models, will be required to optimise performance in such complex scenarios and supported by open architectures to avoid vendor locks, enhance flexibility and increase innovation and adoption.

The representation of the Energy savings use-case is shown in Figure 15. The NDT is fed by data collected across the network (RAN, Edge, Core). Specifically, it uses QoS parameters



defined for the end users, system performance data provided by in-band monitoring, and localization/sensing data (e.g., user poses and locations). The NDT generates a range of RAN scenarios replicating real-life traffic patterns and generates the ORAN O2 data set to train the DRL agent. The DRL agent triggers x-/r-apps related to changing power consumption at different levels with the objective of saving energy in densely populated areas. The near-RT xApps implemented in near-RT RIC are responsible for Cell and Beam level optimizations on short-term (milli-second), while rApps are responsible for non-RT long-term actions, such as nightly power-down management.

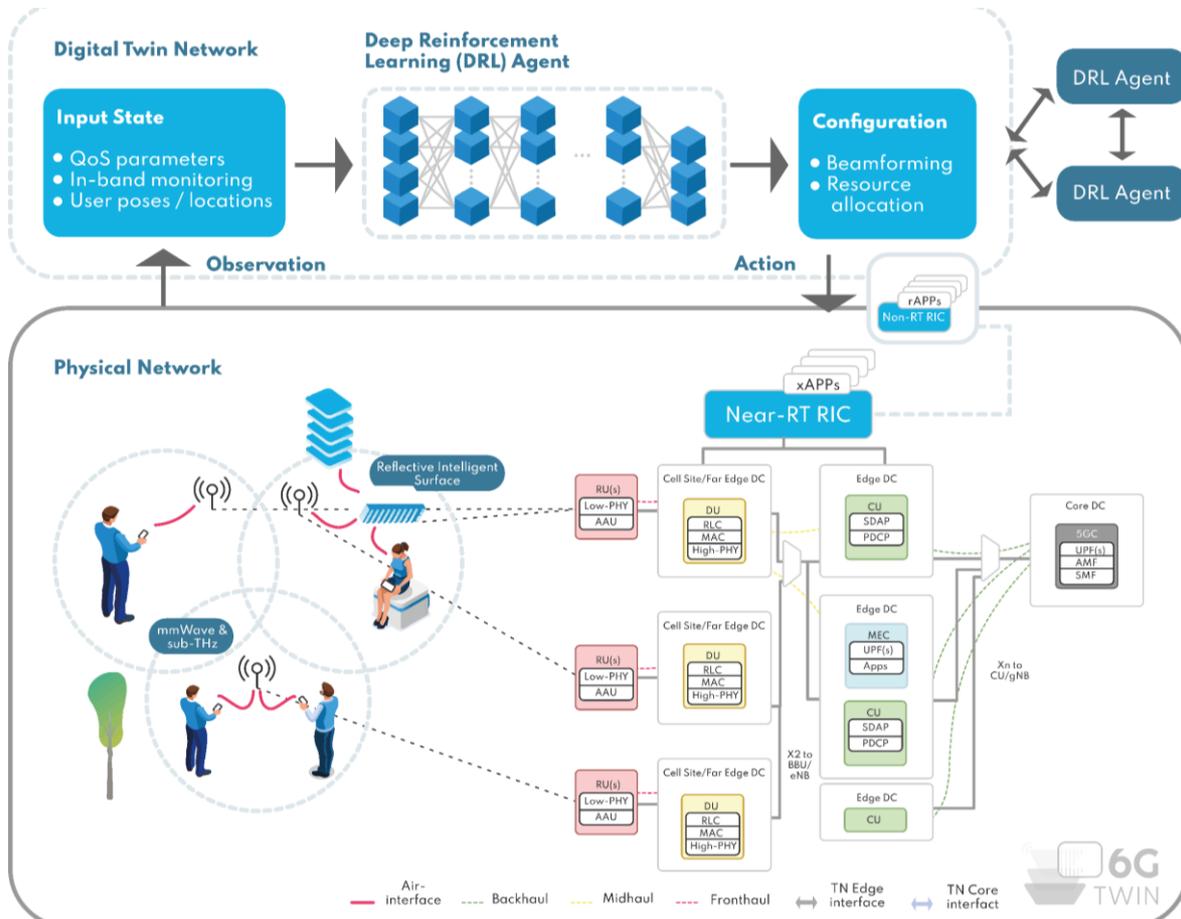


Figure 15. Illustration of the Energy Savings Use Case.

Three complementary scenarios of increasing complexity will be explored to evaluate the energy efficiency (number of radio access technologies and domains covered):

- **Optimisation in 6G radio access technologies (Scenario 1):** The objective of this scenario is to design a precise and low complex *beam selection scheme* to enable UEs and multiple gNBs to find their best set of beam pairs by combining the concept of RIS and therefore providing continuous communication links *at sub-THz frequencies*. For this purpose, optimisation and control algorithms will be investigated and designed to provide a UE location-aware beam management system aligned with the ISAC concepts for a dense sub-THz network.
- **Network management and control with heterogeneous radio access technologies (Scenario 2):** The objective of this scenario is to design an energy-efficient, flexible and proper network management method where *heterogeneous radio technologies* are deployed to serve a variety of user's QoS requirements. In addition to the sub-THz radio access as in Scenario 1, traditional radio access technologies in lower frequencies (such



as C-band at 3.5GHz) will be added to increase coverage and ensure minimal capacity. In this scenario, optimisation and control algorithms will be designed and developed to: 1) select the best radio gNB and radio technology that can guarantee the user's QoS requirements, 2) determine the best set of beam pairs between UEs and gNBs that provide sub-THz access (based on Scenario 1), and 3) ensure that the final selection is energy-efficient.

- **Federated cross-domain radio and computing resource optimisation (Scenario 3):** The objective of this scenario is to extend the previous scenarios to cover multiple domains (RAN, Edge, Core) in such a way that the *energy efficiency* is achieved in an *end-to-end* fashion. For this, edge and cloud computing resources that are required to deploy the virtualised network components of RAN and Core will be managed and controlled in such a way that they 1) allocate the required computing resources to the edge (for RAN) and to the cloud (for the Core) to process the network traffic, 2) ensure end-to-end users' QoS, and 3) perform management and control across network domains in a federated manner in order to collect data and shared services while preserving privacy and data locality and seamless interoperability.

5.3.1 Expected functionalities

To realize the use case, the following hardware and software components will be developed:

- Hardware and software implementations will be performed. Real-channel state information and power consumption measurements will be gathered by densely deploying low (C-band) and high frequencies (sub-THz) gNBs for various network topologies and various locations of UEs. This data will be used to create the NDT models. Subsequently, a suitable set of management, control and optimisation algorithms will be developed using the data collected for the training and predicting procedure.
- NDT built-in Viavi RIC tester based on an O1 and E2 (open) interface that feeds an rApp and xApp that generates the optimisations for the network configuration in real time.
- B5G Open RAN-based network (using ACC dRAX cloud-native RAN NFs) will be realised to configure experimental scenarios and to measure system performance and generate and measure data sets.
- Simulated calls on DT based on the configuration and call data from the live network to train the ML model and test the inferences.
- GPU-accelerated hardware capable of running the NDT and optimisation models.

The algorithms will be deployed that perform control/optimisation (AI, non-AI, or hybrid) for:

- Energy optimisation in RAN
- End-to-end energy optimisation
- Power control of gNBs and servers
- Optimal beam pair finder
- Coverage optimiser
- gNB selection (low vs. higher frequency radio access)
- Network and service data analytics



The following functionalities will be provided:

- Intelligent connectivity (including 6G radio access technologies) across heterogeneous domains.
- Providing the mechanisms that will allow the optimal exploitation of intelligent mechanisms for the control and management of the infrastructure.
- Technologies enabling the connectivity and service infrastructure to be programmable with a single, unifying and open controllability framework.
- Internet-like architecture(s) supporting much higher dynamics and versatility for its topology and service instantiation while significantly lowering energy consumption.

5.3.2 KPIs

The aim of the use case is minimising the long term network energy consumption while guaranteeing minimum QoS in terms of data rate and latency by optimising the UE-gNB association and its beamforming design and computing resource allocation in dense cell deployments considering higher (sub-THz frequencies scenario 1, scenario 2) and lower frequencies (C-band, scenario 2 and scenario 3) under three different city-like environments, to be fully specified during the project: City Skyscraper, City Market hall and City Main Shopping Street. It is connected to the following project-wise KPIs described in Anex 1:

- **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.
- **KPI4.1 (pt2):** 1) Set up the energy-saving testbed to provide connectivity and successful communication via O1, E2 and A1 to the third-party RIC (Accelleran); 2) Target three environments: City Skyscraper, City Market hall and City Main Shopping Street.
- **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.

Further expanding KPI1.2, we foresee the following use-case specific KPIs:

Table 26. Reference KPIs for Use Case 2

KPI family	Target	Baseline Ref
Capacity	With RIS assisted functionality: 20% increase with respect to state of the art schemes. 30% increase of available bandwidth in dense deployment when combining C-band and subTHz/mmWave radio access. Spectral efficiency (bps/Hz) increased by 30% using higher frequencies compared to optimised lower frequencies in dense deployments.	[187], [188]
Packet loss	99.9999% reliability of connectivity via smart coordination of heterogeneous radio access and dynamic resource allocation of computing resources across multiple domains.	[186], [189]
Compute	Reduction of up to 30% in the usage of computing resources compared to knowledge-expert agent with guaranteed minimum service level agreement.	[186]
Energy	RIS assisted functionality: 20% decrease of energy consumption with respect to state of the art schemes. E2E energy consumption reduced of at least 30% compared to knowledge-expert agents with guaranteed minimum service level agreement.	[190]



For performance evaluation, we will rely on TeraVM RIC-Test tool provided by Viavi for the testbed as it has the proven O-RAN O1-based measurements used by RIC-based energy saving algorithms. The Viavi RIC-Test emulates the RAN network and subscriber population, providing a DT of real network configuration, subscriber mobility and traffic patterns. RIC-Test generates a range of RAN scenarios replicating real-life traffic patterns and generates the O-RAN O2 data set to train the ML models in the SMO/RIC that are dedicated to power-control and energy-saving optimisation, such as the ACC dRAX cloud-native RAN. RIC-Test compares the RAN configuration and records the improved Cell Energy consumed (kWh) and Cell Average Power consumed (Watts) (as defined in ETSI ES 202 336-12) [191] and compares it with the QoS objectives of throughput and data volume per subscriber and cell. RIC-Test works with Cell and Beam level optimisations on short-term (milli-second) and long-term (Nightly Cell power-down management) energy savings.

Finally, a demonstrator will be developed. First, we will develop a demonstrator in a laboratory with one macro and three hybrid small/pico cells. In a second iteration, more advanced scenarios will be developed, and we will use an emulation platform to increase the number of cells and users connected.

6 6G-TWIN SYSTEM ARCHITECTURE

In the previous sections we have explored how (i) Digital Twins have been used to offer services such as simulation, analysis, or prediction at industries where the actual implementation of a feature is too expensive, including the telco industry (Section 2), and (ii) the roadmap for 6G includes the deep integration of Artificial Intelligence (AI) in its architecture, constituting what is known as AI-native network architectures (Section 2.3). On the one side, communication networks will become extremely complex and dynamic in nature, thus needing additional (if not fully) automated management solutions – still with human oversight. On the other side, creating digital, real-time replicas of these network elements, their topology, and their services allows the creation of a safe sandbox for closed-loop network automation and facilitates the optimal planning, management, and control of these resources.

Moving towards a DT architecture has been proven to be an excellent way of reducing the gap between network complexity and performance – all the while potentially enhancing user experience in real time – across multiple domains. However, to date, very few initiatives have focused on developing a reference architecture for NDTs. As stated in Section 2.2, the ITU-T has proposed a high-level model for Manufacturing use case [31], but so far nothing else has been designed, developed, and tested for more complex applications. Therefore, there is a need to take a major leap forward and propose new methods, simulation, and modelling tools around the concept of NDTs and demonstrate their interest in tangible use cases. An important opening towards open communities is also needed to ensure these solutions' adoption and future exploitation.

Additionally, to integrate the general technical components into the 6G-TWIN proposed architecture, we foresee leveraging four main components, as detailed below and illustrated in Figure 16. This approach is designed to effectively utilize the technical elements necessary for creating an NDT. This approach has been deeply discussed in [192], [193]

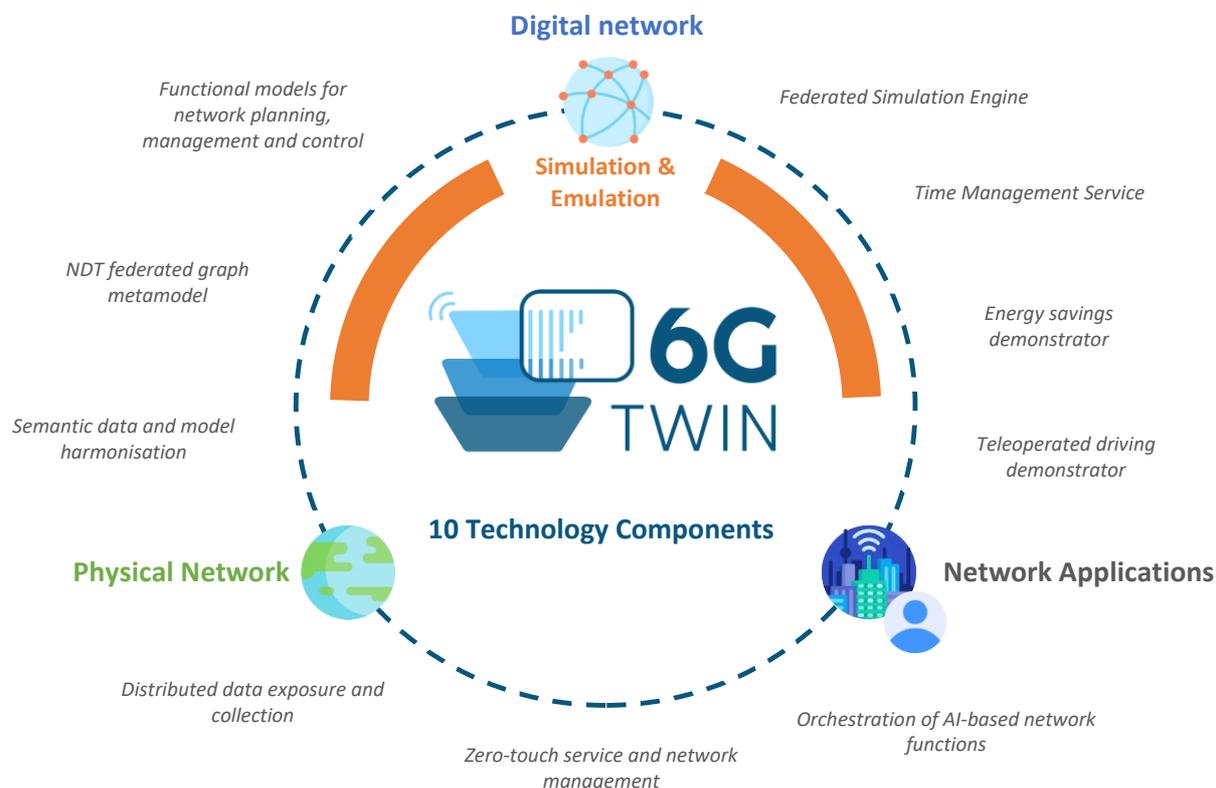


Figure 16. Technical components that leverage an NDT.



- **6G Physical Network Architecture Components:** The 6G physical network architecture components are crucial for building a secure and efficient network infrastructure. These include the secured, scalable, and distributed data exposure and collection framework, which consists of algorithms for decentralized and privacy-aware data collection, ensuring secure storage and access across multiple domains. Additionally, the zero-touch service and network management framework, powered by AI-based network functions, aims to achieve full automation of network tasks such as planning, management, and control. Another key component is the federated management and orchestration of AI-based network functions, designed to manage the lifecycle of AI-driven network functions and deploy distributed machine learning workflows across various domains in a federated manner.
- **Network Digital Twin Components:** NDTs are pivotal in simulating and optimizing network performance. The semantic data and model harmonization component ensures consistent operation of models and data across different domains, managing uncertainty and providing a consistent DT graphical representation. The NDT federated graph metamodel describes the elements populating the NDT, leveraging standards and expert knowledge, and includes an API for exposing models and harmonized data. Functional models for network planning, management, and control involve a set of algorithms, both analytical and AI-based, to simulate the NDT behaviour, assess its performance under various conditions, and optimize the network accordingly.
- **Simulation Components:** Simulation components are essential for testing and validating the network's capabilities. The federated simulation engine is designed to manage multiple federated simulators, both homogeneous and heterogeneous, to provide a consistent view of simulation results via an open API. This engine helps in finding the best configurations for the physical network. Complementing this is the time management service, which ensures synchronization across all federated simulators, maximizing efficiency and ensuring dependencies regarding event processing are not violated. These components evolve from established concepts in literature to high-performance software prototypes, tailored for the needs of NDTs.
- **Network Applications & Demonstrators:** The network applications and demonstrators showcase the practical implementations of the 6G-TWIN technologies. The teleoperated driving demonstrator leverages NDT solutions to predict network behaviour and ensure high-quality service and network resource availability for teleoperated vehicles. This demonstrator is designed, implemented, and tested in a lab environment to anticipate and manage network conditions. Similarly, the energy savings demonstrator uses NDT solutions to optimize end-to-end energy efficiency in near real-time, adapting network behaviour to reduce energy consumption. Both demonstrators are developed and tested in a laboratory setting, highlighting the potential of NDT solutions to enhance network performance and sustainability.

In this context, and based on the ITU-T reference architecture (cf. Figure 4) and the technical components described above, the 6G-TWIN project aims to propose and validate a unified AI-native architecture with support for NDTs that consists of three distinct layers, as shown in Figure 17.

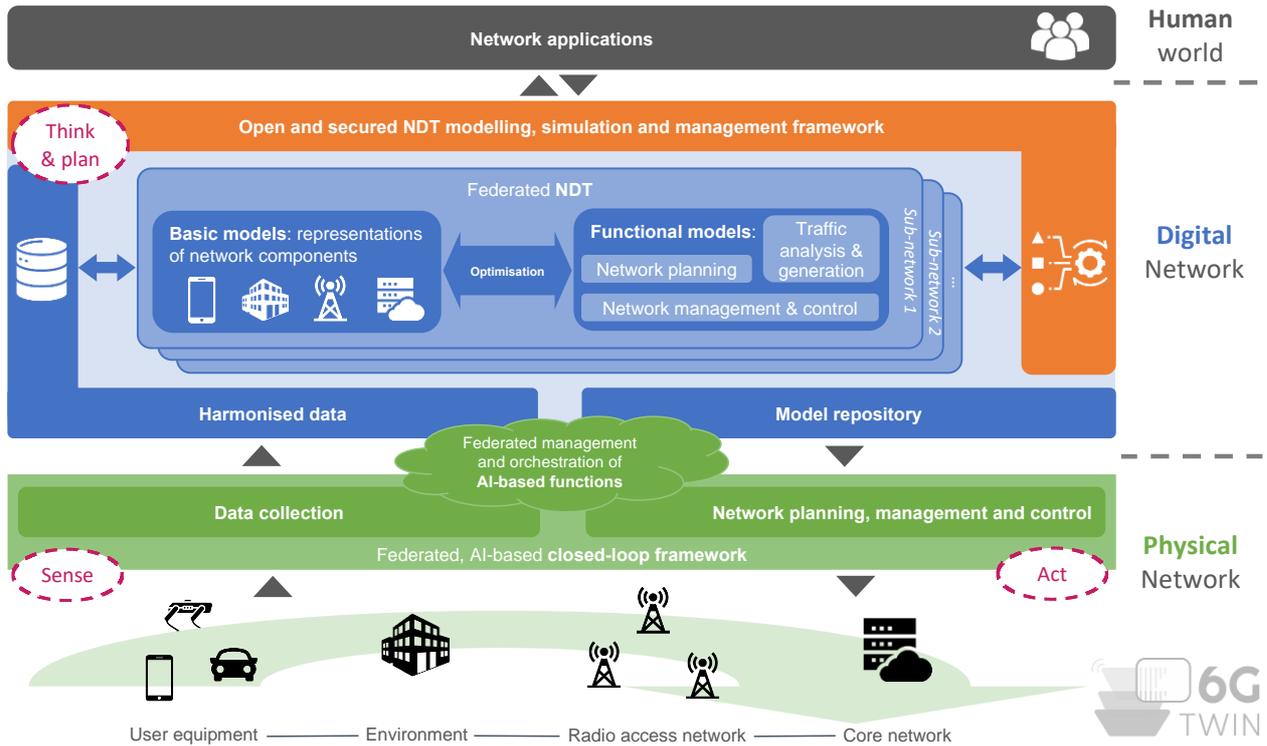


Figure 17. High-level architecture of 6G-TWIN

6.1 Layer 1: Physical Network – AI-based Architecture

The base of Figure 17 represents the physical network in green and the operations performed on it. This includes UE, the surrounding environment that can influence the propagation patterns, the RAN and the CN. Each of these components is supported by computing and networking resources deployed at the (far) edge and cloud data centers. Although these domains already exist from previous network generations, the future 6G network architecture is expected to be significantly different from its predecessors in terms of its design principles and operating mechanisms.

The 6G network architecture proposed by 6G-TWIN will be built from the ground up with AI as an integral part of its design and operation. This AI-based network architecture by design, as described in Figure 18, will enable the deployment of AI-based NFs and NSs to automate various tasks, optimize network performance, and enhance the user experience. 6G-TWIN will go beyond state of the art [85] (Section 2.3) by also integrating NDTs as part of its AI-native architecture, which will provide a safe sandbox to train and validate AI-based NF/NS before they are deployed on the real network, as shown in orange part of Figure 18.

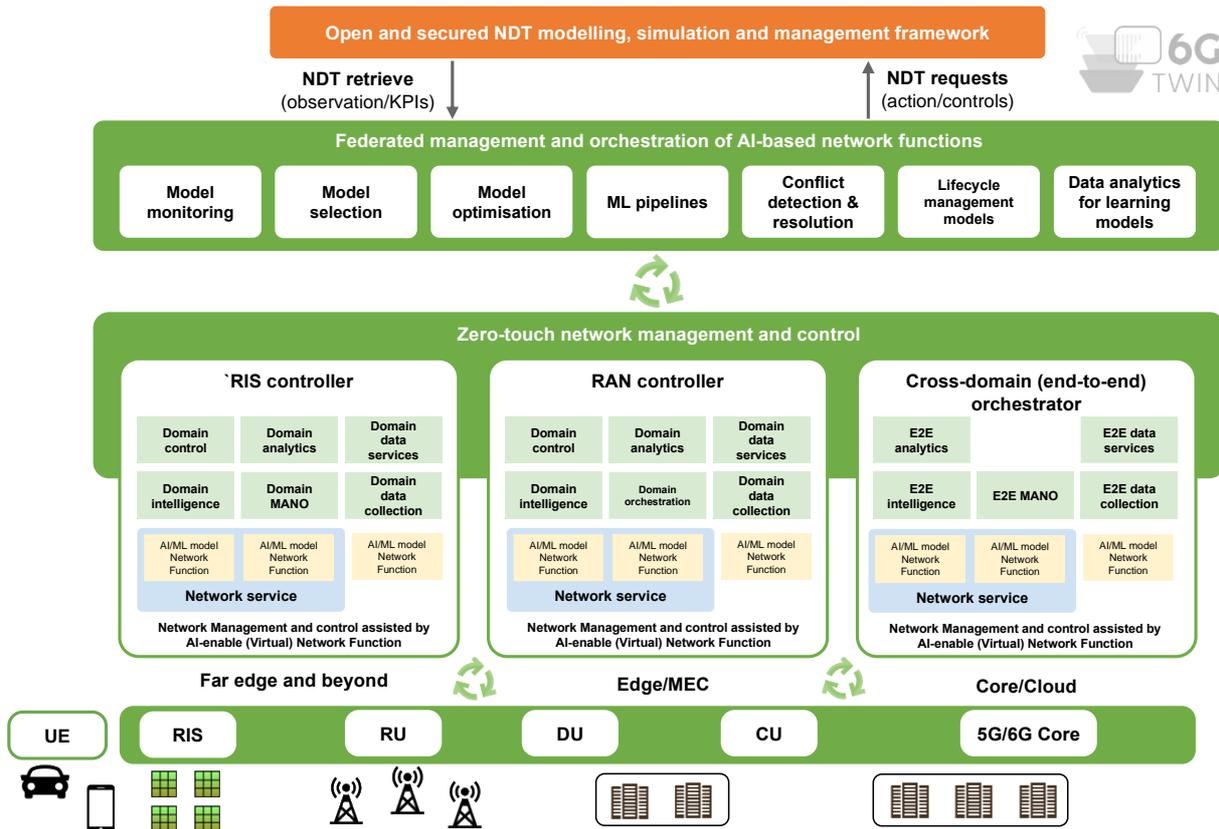


Figure 18. High-level architecture of 6G-TWIN, with a focus on the AI-native components

6G-TWIN will also evolve the traditional MANO frameworks for NF/NS towards a framework that not only performs the traditional lifecycle management of NF/NS (onboarding, deployment, scaling, termination), but also includes the mechanisms to perform the orchestration and management of AI-based NF/NS (training, deployment, and monitoring of AI models). This will be achieved by providing a novel MANO framework that supports operations such as the lifecycle management of the AI-based NFs and NSs, orchestrating the composition of advanced AI-based NF/NS and coordinating interactions between their inner models. This is fundamental since the performance of an AI-based NF/NS does not only depend on networking KPIs – e.g., Quality of Service (QoS), Quality of Experience (QoE) – but also on learning-related KPIs – e.g., accuracy, loss, cumulative reward.

To enable these AI-based NFs/NSs to observe and interact with the network (e.g., controlling it), two main aspects are needed:

- **Network programmability:** Novel mechanisms to increase network programmability and support closed-loop management strategies. These will enable AI-based NFs/NSs to learn (e.g., using an NDT or with continual learning in physical networks) and adapt in real-time in order to automate network provisioning, configuration, and optimisation. This is a fundamental step forward that can significantly reduce operational costs, enable rapid network deployment, achieve high scalability, and increase network reliability and availability.
- **Efficient Data Collection:** Introducing novel mechanisms for efficient data collection and processing pipelines for monitoring information, including handling diverse data formats, protocols, and traffic patterns; as well as cryptographic methods and privileged access management protocols for enhanced security and privacy. These mechanisms harness parallel processing and distributed computing techniques for scalability, accommodating more users, devices, and data streams without sacrificing performance



or reliability. Workload distribution across multiple nodes will also be exploited to ensure optimal performance and availability.

6G-TWIN will explore and obtain inspiration from novel concepts on different network segments and investigate and innovate in big data telemetry subsystems and data lake functionalities, such as 3GPP 5G Core, NEF, WAIF 6G, 3GPP NWDAF and its evolution towards the split Network Management Function (NWMF) / Network Function Automated Framework (NAAF), the O-RAN Y1 interface for exposing RAN analytics information to internal and/or external functions, and the High Velocity Virtual Event Streaming (HV-VES) collector functionality in the service and network management layer.

6.2 Layer 2: Digital Network – Data and Models.

The middle part of Figure 17 in blue represents the NDT, which is at the heart of the project, and which has been designed in line with the preliminary work on the topic. According to [31], the ITU specifies two core notions: (i) basic models that consist of the representation of the network topology and elements and (ii) functional models composed of functions related to the behaviour of the system. These functions include traffic analysis, network diagnostic, and prognostic, but are described at a high level.

An approach broken down into two areas has been drawn up to consider this architecture: data and models. The data area enables the collection, governance, and harmonization of the data collected. This will ensure a unified, data space-based foundation, regardless of the communication technologies, domains, or network elements involved. More details are provided on Deliverable D2.1 Data governance, privacy, and harmonization [194].

The DT model area consists of a set of models to best and dynamically represent the network elements (basic models) and their behaviour (estimated and predicted using AI approaches, i.e., functional models). Instantiation and execution of these models relies on the harmonized data collected and will be developed to optimize network planning, management, and control issues, as well as to provide meaningful KPIs and metrics to operators. These DT models are federated in several layers, allowing complex, interconnected, and dynamic topologies to be imagined depending on the applications to be served.

Our approach to NDT will be based on several technical components aiming to provide a holistic representation of the cyber-physical elements related to the real network. As illustrated in Figure 19, basic models are a central component for establishing a link to the physical world, as well as for internal operations within the NDT components, fuelling functional models and enabling data and model harmonisation.

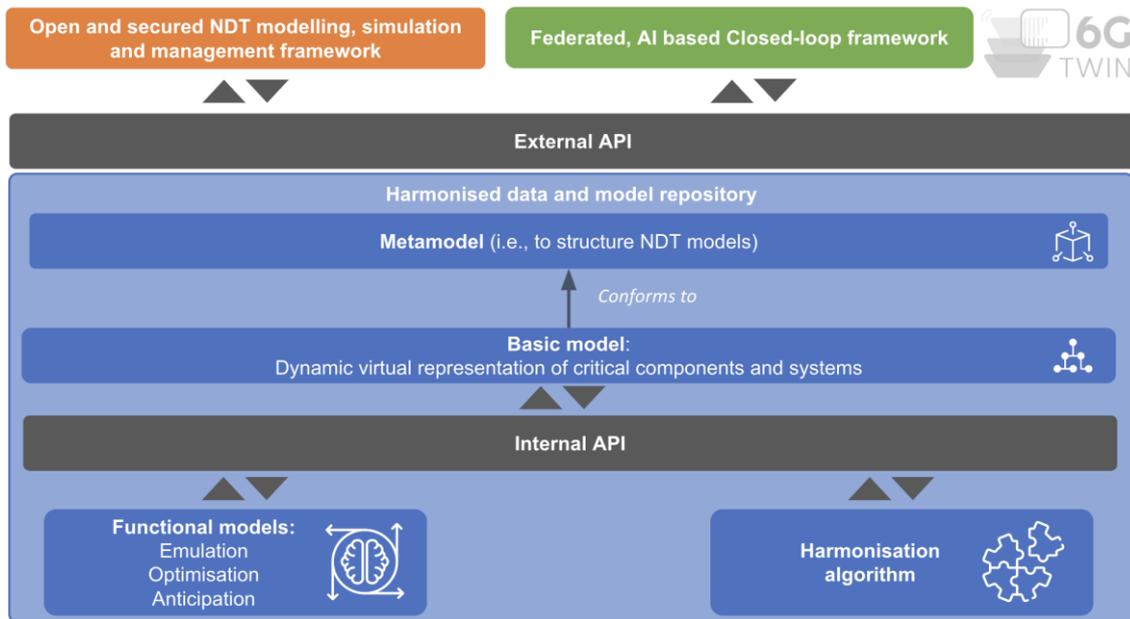


Figure 19. Relation of Basic Model and Functional models

6.2.1 Basic models

A basic model aims to be a consistent representation of the cyber-physical network system. In the project, it will consist of a typed graph that represents the network elements (e.g., topology, servers, terminals). It should be used to either reflect a current state of the real network or in isolation from reality for simulation, projection scenario, etc; as explained in the 6G-TWIN D2.1 Deliverable [194].

The first phase for building basic models will imply establishing a graph structure with multiple inter-related metamodels in a common graph-enabled modelling framework that will be able to support some flexibility in its definition. It will be based on the different references and standards (e.g., ETSI, 3GPP TS 23.501, 5GPPP), ontologies [195] and other metamodels available in the sector (e.g., OASIS TOSCA). Multiple inter-related metamodels will be necessary to cover the different sub-domains of network systems and related assets. Such modularity will allow easier maintenance and better support of local evolution. Moreover, we assume that each metamodel corresponds to a sub-domain community that has already reached consensus and forms a coherent whole. Once this ecosystem of metamodels reaches a stable state, our objective is to propose it for standardisation, as a smart data schema [45] for the Network in the Fiware community. This metamodel will then be our network reference metamodel.

In a subsequent phase, a relationship will be established between the reference metamodel, and the data and information provided by the 6G architecture to provide a first typed graph (i.e., a knowledge model) that describes the network, at a given state. The data in this phase is not yet harmonised (see "Harmonised data and model repository" below). Within the selected modelling framework, our metamodel will be used as the basis for the development of the API within the federated simulation framework, while allowing communication with the physical network data. This API will serve for any exploitation of the graph, including harmonisation and functional model processing.

Basic models typically include, but are not limited to:

- **Topology model:** This includes the topographic information of the RAN area considered for the NDT, but also between servers across a geographical area (RAN to Core).



- **Computing model:** This provides the representation of computing resources such as servers and their properties (Central Processor Unit -CPU-, memory) and their underlying connectivity topology.
- **gNBs model:** This includes aspects related to the deployment of gNBs (e.g., position, height), configuration (e.g., operating frequency, bandwidth configurations, numerologies, beamforming model) and operation (e.g., packet conformance at different levels).
- **UEs model:** This provides a representation of the UEs capturing physical aspects such as position, height, antenna gain or noise figure. It also includes aspects such as UE type (e.g., pedestrian, vehicular, sensor) and/or the UE QoS requirements (e.g., minimum bit rate, latency, reliability).

6.2.2 Functional models

Functional model [31] refers to various data models such as network analysis, emulation, diagnosis, prediction, assurance, etc., which are established by making full use of the network data in a unified data repository for specific application scenarios. The functional models can be constructed and expanded by multiple dimensions: by network type, there can be models serving for single network domain or multiple network domains; by function type, it can be divided into state monitoring, traffic analysis, security drill, fault diagnosis, quality assurance and other models; by generality, it can be divided into a general model and special-purpose model. Specifically, multiple dimensions can be combined to create a data model for a more specific application scenario. For example, the traffic balance optimization model can be created on the core switch of one campus network, and the model instance can be used to serve the corresponding network applications.

A functional model includes different forms of analytics and AI that handle the basic models. They are drastically different from the basic models as they depict behaviour. In **6G-TWIN**, we consider three types of functional models:

- **Emulation:** Functional models that comprise the operations on the basic model to mimic reality: these are the basic behavioural models. This can include, for instance: propagation models; mobility models; radio and computing performance models, providing KPI measurements in terms of radio (e.g., Bit Error Rate -BER-), networking (throughput, delay), and computing, etc.
- **Optimisation:** Functional models that can improve the system. These can limit themselves to the operations possible on the physical network allowing them to provide an output configuration that can be applied by the 6G architecture within the network planning, management, and control components.
- **Anticipation:** Functional models that represent diverse kinds of external operations and network configurations that can go beyond the current capability or limits of the physical network.

Functional models primarily rely on data, and their implementation involves categorizing them into three classes: analytical models, AI models, and ML models, based on the techniques used in their development.

- **Analytical models**, which are models produced from human knowledge and expertise. They are usually abstractions, trying to be as close as possible to the real system behaviour. For instance, an example of an analytical model would be a mathematical representation of radio propagation in 6G networks.



- **Traditional AI models**, which are based on logic, inference probabilistic or search approaches (e.g., heuristics and metaheuristics). They are “white or grey” box models, which means that they can be more easily explained: for instance, a decision tree can trace the path and explain why, according to a given input parameter, it provided a specific answer. Beyond being more trustable (due to explanation), such AI models can either adapt their behaviour or anticipate it.
- **Machine-learning models**, notably deep-learning (DL) models, which are the modern approach of ML that is gaining increasing interest and proving its efficacy across various domains, particularly in networking and communications. For instance, a functional model based on neural networks that predicts the future state of a network element in the context of 6G NDT. ML/DL based functional models rely on massive data collection to be accurate and to have a good functional coverage. They will first inevitably rely on the proper structuration of collected data.

A functional model may consist of a set of specific-purpose functional models, each utilizing different techniques. For instance, a functional model aimed at proactively optimizing the deployment of 6G NFs may employ a search approach (e.g., metaheuristic) and leverage a DL-based model to predict the network load and expected QoS.

The 6G NDT will leverage various functional models for different applications spanning network analysis, emulation, diagnosis, prediction, and more. These models introduce additional KPIs to the design of the NDT, including but not limited to, accuracy in representing the real behaviour of network elements, the complexity of the models in terms of inference time and storage resources, and the training cost of ML models.

6.2.3 Harmonised data and model repository

A harmonised data and model repository will serve as the core source of information to populate basic models and will be used as the training set for functional models. In addition, the harmonised repository should be properly governed, such as a digital space, including data privacy and sovereignty.

Providing a unified metamodel, as described in basic models, will not be sufficient. In addition, using data-fusion algorithms and entity resolution will help reduce the dimensions of the data and models to be harmonised. A semantic model associated with a pragmatic representation (i.e., the rationale and the context of the data and models) is also necessary to preserve the meaning behind each piece of collected data. The harmonisation will have to consider semantic (pragmatic and conceptual) drifts and mismatches. It will define a concrete process, based on graphs and logic, to identify the drifts and propose solutions to overcome its impact on data and models. D2.1 [194] explores in more detail how the data collection, data harmonization and data space creation are carried out in the project.

6.3 Layer 2: Digital network – Federated simulation framework

The top part of Figure 17 in orange represents the simulation framework, which manages the lifecycle of the DT, in order for the closed-loop optimization framework (zero-touch MANO) to conduct what-if analyses, driving realistic network applications (Figure 17, grey). Such an open source, secured, and federated simulation framework will also be developed to provide the scientific community with a tangible tool to test their own approaches.



What is needed for executing a 6G NDT is a federated simulation engine which is able to couple a wide variety of the many existing simulators, from road traffic to AI-based network management, each focusing on a specific domain or scale, and which is able to simulate large-scale scenarios with heterogeneous granularity.

Our approach to a simulation framework will be based on the following principles: Instead of re-implementing existing models from a large number of specialized domains, we will explore a federated simulation engine concept following an agent-based approach and coupling existing simulators. By necessity, this simulation engine will allow both homogeneous (same simulator, different agent) and heterogeneous (same agent, different simulator) simulation and the inclusion of closed-source simulators across different languages and execution platforms while ensuring privacy and security.



7 FINAL REMARKS

In the following section we will cover some of the final remarks needed to conclude this deliverable. We will provide a general review of the open challenges that the construction of Network Digital Twin faces and a general idea on how to overcome them. Then some conclusions are drawn from the analysis of the state of the art in the architecture, the NDT fundamentals and the supporting simulator tools. Next, we map the project use cases into the functional and non-functional requirements. The conclusion section will also cover the most important topics related with the creation of an architecture of an NDT. Finally, this section will explore the future work related with the **6G-TWIN** architecture and the direction that the future version of this document will take.

7.1 Open challenges.

While the proposed architecture advances beyond current models by integrating a unified AI-native system with support for NDT, there are significant challenges to its large-scale implementation. Although the DT concept is established, widespread adoption in various sectors remains complex due to numerous existing challenges. This section enumerates some of those challenges and presents initial ideas on how to tackle them.

7.1.1 Security

As noted in previous sections, AI-based algorithms will not only be at the core of the next generation of NF/NS but will also be used to create new network applications and services such as NDTs. However, recent evidence suggests that AI/ML models are susceptible to security breaches [197]. Even minor, often unnoticed alterations in data samples can lead to inaccurate predictions by cutting-edge classifiers during the inference phase. Due to the complexity and distributed nature of networks, the possibility of adversarial attacks in telecom environments persists. This poses a significant risk considering AI's anticipated role in 6G communication systems. Previous research indicates that adversarial attacks, optimized for perturbations, can disrupt telecommunication networks or services [198]. Thus, effective defensive strategies are imperative to mitigate such threats.

To address these challenges, studies propose leveraging adversarial training and explainable AI (XAI) [199]. While conventional AI/ML models providing predictions, recommendations, or decisions lack transparency in their decision-making processes, black-box AI algorithms offer promising security solutions for 6G networks [200]. However, their opaque decision-making processes present challenges. Explanations play a critical role in understanding the vulnerabilities of adversarial machine learning [201]. XAI enhances the transparency and accountability of black-box AI models, enabling explanations for any performance degradation, thereby facilitating proactive identification of issues in model training or data quality. Incorporating transparency-enhancing XAI techniques not only bolsters defensive strategies but also enhances trust by clarifying the decision-making processes of AI/ML systems. Such transparency is often considered essential for ensuring the reliability of 6G communication systems [202].

Following the pivotal role of DT technology within 6G communication systems, considerations of security and privacy emerge as critical components that require careful attention. While DTs are instrumental in facilitating error-intolerant industrial processes, by leveraging data and models for decision-making, they also introduce challenges related to uncertainty and trustworthiness within DT systems. Furthermore, the storage and synchronization of sensitive user data between the DT and its PT counterpart, pose significant security and privacy risks. Therefore, it is necessary to identify and detect vulnerabilities and associated threats and



implement robust security and privacy measures within both the PT and DT. Unauthorized access to the DT could potentially enable manipulation of the associated PT, raising serious concerns regarding data exposure and exploitation without proper authorization. To address these concerns, robust security measures must be implemented, including end-to-end encryption for data transmission between the DT and PT, integration checks, and anomaly detection mechanisms to safeguard against potential attacks. Additionally, establishing optimal authentication mechanisms for DT owners to access the 6G network infrastructure, real-time monitoring of DT-specific events, and leveraging advanced machine learning-assisted solutions for managing APIs and information exchange between these systems are imperative. By addressing these security and privacy challenges, the deployment of DT technology within 6G networks can proceed with confidence, ensuring the protection of sensitive data and the integrity of network operations. To address the security and privacy aspect the following roadmap will be considered:

Threat landscape with respect to data security and privacy

- Data Collection and Management
 - *Challenges with Data Volume and Complexity:* As telecommunication networks, particularly in 6G environments, will rely on AI-based algorithms, they generate massive volumes of data. The increased data collection creates complexity in managing sensitive information, which raises risks of data leakage, improper storage, and unauthorized access.
 - *AI/ML Data Vulnerabilities:* AI/ML models used for network services and applications require large datasets for training, which might contain sensitive information. If not properly managed, these datasets can become a target for attackers seeking to exploit AI vulnerabilities.
- Data Exposure
 - *Risks from Adversarial Attacks:* Adversarial attacks can subtly manipulate input data to affect AI/ML predictions. This will potentially pose a significant risk to 6G network operations and could lead to inaccurate decision-making in critical applications.
 - *Data Leaks and Insider Threats:* Data exposure can occur due to leaks from internal or external sources. Insider threats, where employees or partners with access to sensitive data misuse their privileges, also contribute to this risk.
- Distributed Scenario
 - *Distributed Network Challenges:* In 6G communication systems, data will often be distributed across various physical and virtual locations, complicating security management. This distribution will increase the surface area for potential attacks and introduce variability in compliance requirements across different regions.
 - *Security in Digital Twin Systems:* DT technology, used to model and simulate real-world systems, requires synchronization with their PT counterparts. The distributed nature of DT systems creates additional security and privacy challenges, as sensitive user data must be transmitted and stored securely.

Requirements of data security and privacy

- Confidentiality, integrity, and privacy



- *Ensuring Data Confidentiality*: Measures must be in place to ensure that only authorized personnel have access to sensitive information. This includes robust encryption for data storage and transmission, as well as strict access controls.
- *Maintaining Data Integrity*: It is essential to ensure that data is not altered or tampered with during transmission or storage. This involves the use of cryptographic hashing and other methods to verify data integrity.
- *Preserving Data Privacy*: Data privacy regulations like General Data Protection Regulation (GDPR) and California Consumer Privacy Act (CCPA) require that personal information is protected. Compliance with these laws is ensured by implementing privacy policies and obtaining consent for data collection.
- Privacy-Enhancing Methods
 - *Homomorphic Encryption*: This technique allows computations on encrypted data without decrypting it, providing an additional layer of security. It enables AI/ML applications to process sensitive data without exposing it to risk.
 - *Secure Multi-Party Computation (SMPC)*: SMPC allows multiple parties to collaborate on computations without revealing their inputs. This is useful for distributed learning environments where data privacy is crucial.
 - *Differential Privacy*: By adding noise to data sets to obscure individual identities, differential privacy helps protect sensitive information while enabling broader data analysis.
- Distributed Learning Methods
 - *Federated Learning*: Federated learning enables collaborative learning without centralizing raw data. This is beneficial for 6G networks as data remains on local devices, reducing the risk of exposure while enabling collective AI model training.
 - *Edge Computing*: By processing data at the edge of the network, edge computing minimizes the need to transmit sensitive information across long distances, reducing the risk of interception or unauthorized access.

By combining privacy-enhancing methods with distributed learning approaches, organizations can mitigate security and privacy risks in 6G networks and AI-based applications. This approach provides a pathway to building resilient and trustworthy systems, ensuring data confidentiality, integrity, and privacy in a distributed and complex environment.

7.1.2 Openness integration

In the dynamic world of telecommunications, the evolution from 5G to 6G signals significant changes not only in speed and connectivity but also in network infrastructures' architecture and openness. Such changes prompted the emergence of O-RAN technology, a disruptive innovation poised to surpass traditional openness integration approaches. O-RAN's disaggregated architecture and standardized interfaces fundamentally alter the dynamics of network element interactions, enabling heightened flexibility, scalability, and efficiency. By decoupling hardware and software components, O-RAN cultivates a diverse vendor ecosystem, fostering competition, innovation, and cost-effectiveness. Thus, O-RAN's disruptive potential transcends conventional integration methods, driving the advantages of an open market forward.



In the context of 5G networks, the pursuit of openness and flexibility has been a driving force shaping network architectures. Conventional integration methods often hinge on closed, monolithic systems, constraining interoperability and stifling innovation. However, the advent of O-RAN technology disrupts this status quo, ushering in a more collaborative and open approach in the 5G and 6G architectures. Through its disaggregated structure and standardized interfaces, O-RAN nurtures a thriving ecosystem of vendors and developers, fuelling competition and expediting innovation. This embrace of openness not only amplifies flexibility and scalability but also empowers operators to tailor network deployments to their specific needs, enhancing efficiency and cutting costs.

One transformative tool complementing the principles of openness and flexibility in network management is the concept of NDT. Serving as virtual replicas of physical networks, NDTs capture their structure, behaviour, and functionalities in a digital environment. By leveraging real-time data across physical, RIC, and SMO layers, and employing advanced AI/ML-based analytics, NDTs offer network providers and operators unparalleled insights into network operations and performance for dedicated use cases. These insights enable proactive and optimized resource allocation and informed decision-making, ultimately enhancing the reliability and efficiency of telecommunications networks.

The disaggregated nature of O-RAN architectures facilitates seamless integration with NDTs, enabling the exchange of data and insights between virtual and physical environments.

7.1.3 AI Integration and Orchestration

Besides integrating AI deeply in the network architecture, the intelligence should be properly orchestrated, supporting its entire lifecycle. Effective workflows for AI lifecycle management are aligned with Machine Learning Operations (MLOps) [203]. The existing MLOps frameworks strive to automate and operationalize ML processes, ensuring the delivery of production-ready software. The workflow is intended to be model- and platform-agnostic. However, this integration is very challenging in practice.

On the one hand, common ML applications use well-defined input data such as images, text, or audio. Conversely, ML algorithms designed for networking add extra complexity regarding data velocity and variety. For instance, network applications like traffic classification may involve diverse input data types, ranging from images [204] to time series [205]. On the other hand, the dynamic and constantly evolving nature of future networks introduces additional challenges. This variability can lead to data drift [206], impacting the ML model performance and potentially degrading the performance of the managed network as well.

For effective network management, a unified data collection framework is essential to accommodate various data formats, protocols, and traffic patterns. To address data drift, two approaches are often recommended: first, enhancing ML models' generalization through zero-shot learning techniques [207] or hierarchical reinforcement learning [208], allowing models to handle unseen classes during testing. Second, incorporating data drift detectors [209], [210] into the ML models' lifecycle management. These strategies support the goals of zero-touch management, enabling networks to autonomously adjust operations with minimal human supervision.

7.1.4 Distributed ML and Federated Management

The inherently distributed nature of telecommunication networks, now a heterogeneous amalgam of diverse devices, technologies, and stakeholders, makes it impossible to have a one-size-fits-all solution. This complexity necessitates the collaboration of multiple targeted solutions to approach an optimal outcome. A common challenge across many studies is the heterogeneity of devices and communications, requiring sophisticated, distributed systems to work together effectively. Federated Learning [211], [212] emerges as a promising method,



enabling collective model training while maintaining data privacy at each local node, effectively addressing the needs of diverse network environments. Nevertheless, significant challenges such as effectively sharing knowledge among different models, resolving potential conflicts that may destabilize the system, and synchronizing shared knowledge to minimize communication overhead, still need addressing to enhance system stability and efficiency.

Moreover, ensuring data privacy and security in federated learning settings presents a complex challenge. As data is distributed across multiple network domains, maintaining confidentiality becomes paramount. Designing robust privacy-preserving mechanisms, such as secure aggregation, differential privacy, and encryption techniques, is essential to protect sensitive information while allowing collaborative model training. Additionally, exploring techniques for federated learning model evaluation and validation without compromising data privacy is crucial for building trust and compliance with regulations.

These challenges highlight the necessity for innovative strategies in both distributed ML and federated management. These strategies are aimed at overcoming hurdles associated with heterogeneous environments, privacy issues, and regulatory conformity. Tackling these challenges will advance the development of efficient AI-Native network architectures and facilitate the seamless integration of NDTs for enhanced network optimization and management. Notably, forthcoming deliverables of **6G-TWIN**, such as D1.3, will explore the implications of orchestrating AI-driven functionalities on network optimization and management across multiple network domains.

7.2 Conclusions

The Digital Twin concept involves creating a virtual representation of a physical object or system to simulate, analyse, and optimize its performance. The NDTs variation, which models mobile networks, represents a significant advancement, enabling networks to benefit from AI-native capabilities and gain a higher level of autonomy. NDTs have various practical applications, including network planning, monitoring, optimization, and fault prediction and prevention, enhancing the efficiency and reliability of network management and operations.

The architecture of NDTs comprises three main layers: Physical network, Digital network and Human world. The Physical Network comprises the infrastructure to operate the communication network, including the radio equipment, the core network and the sensing and acting capabilities over it. It also encompasses the data collection and the management and control interfaces to be linked with the following layer. The Digital Network layer, collect the data by using a harmonized data interface to feed information to the basic and functional models. The Digital Network layer host the NDT and applies optimized solutions to the physical network layer using model repositories and action policies. On top of them, the Human World layer, interact with policies made by in humans and the network application the support new use cases.

This whole architecture is enlarged by the implementation of AI-Native architectures. In order to deliver a **6G-TWIN** AI-Native NDT system architecture, we review the state-of-the-art in AI-Native architectures from both industry and academic perspectives. While integrating AI/ML solutions into these architectures is considered essential, integrating NDTs is often seen as a supplementary benefit. Moreover, aspects like security and decentralized/distributed management are mentioned but not thoroughly addressed. The integration, orchestration, and management of AI in network systems are crucial issues. AI integration within networks should be deeply embedded and well-orchestrated to support the entire AI lifecycle, aligning with MLOps frameworks to automate ML processes. However, challenges such as managing varied and dynamic data in networks suggest methods like zero-touch learning and data drift detectors to maintain model performance. Additionally, learning techniques must be aware of the natural distribution of networks, with Federated Learning highlighted as a method to enable collaborative model training while preserving data privacy, despite challenges in knowledge sharing and system stability.



AI-based algorithms will be pivotal in the evolution of AI-Native NDT by enabling new applications and services. However, AI/ML models are vulnerable to adversarial attacks, posing significant risks to network integrity and operation. Robust defensive measures, such as adversarial training and explainable AI, are essential to enhance the transparency and accountability of AI systems.

Functional models are essential for describing the layer 2 functionalities of the 6G-TWIN system architecture, incorporating various forms of analytics and AI. To align with other SNS JU Stream B/D projects, KPIs must be defined for each use case, demonstrating how they can be mapped from KVIs to meet social, environmental, and economic requirements. Data models are crucial for operating DTs, with basic models representing fundamental physical entities and functional models providing detailed behavioural traits for simulations.

Network simulators are essential for the analysis and evaluation of NDTs. Instead of developing new simulators, coupling existing simulators is planned. The new simulation framework developed in 6G TWIN must ensure proper interaction between simulators and secure communication between distributed physical components, such as simulation servers. Defining communication protocols and data structures to be exchanged between simulators is also a critical task.

Finally, the development and implementation of NDTs are influenced by standard development organizations, industry initiatives, and academic research, each contributing unique perspectives and advancements, leading to a nuanced and comprehensive evolution of NDT technologies.

7.3 Future work

The future work for the 6G-TWIN project within the D1.1 and WP1 encompasses several critical areas, each aimed at advancing the project's objectives through detailed and coordinated efforts. The following activities are gathered by specific topics related to the future version of this document.

Network Digital Twin Layer

The specification and evolution of the NDT layer will be a primary focus. As of June 2024, parallel work has been completed on the data management aspects of the NDT, including the definition of a smart data model and explanations about data flows, privacy, security, and harmonization processes (D2.1). Following this, further specifications will address the detailed models encapsulated within the NDT, covering both basic and functional models, leading to subsequent deliverables (D2.2 and D2.3). Additionally, the federation of NDTs and their integration with the current architectural concepts in WP1 will be established (D2.4). Ongoing updates to D1.1 will reflect these advancements in the NDT layer.

AI-Based Functionalities, Models, and Coordination

Efficient coordination and orchestration of AI-based functionalities will be prioritized, aligning with MLOps frameworks. This involves addressing challenges related to the exchange of knowledge among diverse models, resolving conflicts that could disrupt system stability, and synchronizing shared knowledge to minimize communication overhead. These efforts are crucial for enhancing overall system stability and efficiency. Concurrently, ongoing work is focused on developing 6G-TWIN analytic and AI-based functional models to meet the requirements of the teleoperated driving use case, as part of post-doctoral research in UBOU.

Simulation Framework Integration

The integration and specification of the simulation framework will be detailed within WP3. This includes outlining the integrated simulators and necessary simulation models for closed-loop



optimization. The initial simulation models will be developed in alignment with the specific requirements of the use cases, ensuring that they meet the project's objectives.

Demonstration Infrastructure

The integration of use cases into the demonstration infrastructure is essential for supporting the creation of the NDT. This involves developing the necessary infrastructure to demonstrate the practical applications and benefits of the 6G-TWIN solutions.

Security Enhancements

Several key areas will be addressed to enhance the security of the 6G-TWIN project. Advanced techniques for detecting and mitigating adversarial attacks on AI/ML models and data in telecommunication networks will be developed, including real-time monitoring systems and automated response mechanisms. Research and implementation of sophisticated XAI techniques will improve the transparency and interpretability of AI/ML models in 6G networks. Privacy-preserving AI algorithms, such as homomorphic encryption and SMPC, will be investigated to ensure sensitive data can be processed without compromising privacy. Comprehensive security frameworks for DT systems within 6G networks will be created, addressing synchronization, data transmission, and storage issues. Optimal authentication mechanisms tailored for 6G network infrastructures will be designed and tested to ensure secure access for DT owners and authorized users. The scalability of proposed security measures will be researched to ensure effective implementation across large-scale, distributed 6G networks without compromising performance or user experience. Additionally, a telemetry framework will be implemented to support data collection from the physical world and integrate it into the defined architecture.



REFERENCES

- [1] Ericsson, '6G - Follow the journey to the next generation networks'. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.ericsson.com/en/6g>
- [2] C. Dietzel, '6G: A glimpse into the future beyond 5G', TechRadar. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.techradar.com/pro/6g-a-glimpse-into-the-future-beyond-5g>
- [3] 'IMT towards 2030 and beyond', ITU. Accessed: May 24, 2024. [Online]. Available: <https://www.itu.int:443/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx>
- [4] ATIS, 'AI-Native Wireless Networks', Washington, DC, Apr. 2023. Accessed: May 24, 2024. [Online]. Available: https://nextgalliance.org/white_papers/ai-native-wireless-networks/
- [5] J. Hoydis, F. A. Aoudia, A. Valcarce, and H. Viswanathan, 'Toward a 6G AI-Native Air Interface', *IEEE Commun. Mag.*, vol. 59, no. 5, pp. 76–81, May 2021, doi: 10.1109/MCOM.001.2001187.
- [6] G. Wikström, P. Persson, et al., "'6G-Connecting a cyber-physical world," White Paper GFTL-20:001402,' Ericsson, Feb. 2022.
- [7] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, 'An Overview of Massive MIMO: Benefits and Challenges', *IEEE J. Sel. Top. Signal Process.*, vol. 8, no. 5, pp. 742–758, 2014, doi: 10.1109/JSTSP.2014.2317671.
- [8] V. Petrov, T. Kurner, and I. Hosako, 'IEEE 802.15.3d: First Standardization Efforts for Sub-Terahertz Band Communications toward 6G', *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 28–33, 2020, doi: 10.1109/MCOM.001.2000273.
- [9] Y. Liu *et al.*, 'Reconfigurable Intelligent Surfaces: Principles and Opportunities', *IEEE Commun. Surv. Tutor.*, vol. 23, no. 3, pp. 1546–1577, 2021, doi: 10.1109/COMST.2021.3077737.
- [10] M. Giordani and M. Zorzi, 'Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities', *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, 2021, doi: 10.1109/MNET.011.2000493.
- [11] ITU. *IMT-2030, Framework and overall objectives of the future development of IMT for 2030 and beyond*. [Online]. Available: <https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/Pages/default.aspx>
- [12] ATIS, 'Roadmap to 6G', Washington, DC, Feb. 2022.
- [13] Hexa-X, 'Main - Hexa-X'. Accessed: Apr. 19, 2024. [Online]. Available: <https://hexa-x.eu/>
- [14] 'Hexa-X-II - European level 6G Flagship project'. Accessed: May 31, 2024. [Online]. Available: <https://hexa-x-ii.eu/>
- [15] ITU-R, 'Rec ITU-R M.2160-0: Framework and overall objectives of the future development of IMT for 2030 and beyond', Geneva, Nov. 2023. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2160-0-202311-1%21%21PDF-E.pdf
- [16] R. L. Aguiar, D. Bourse, A. Hecker, J. Huusko, and A. Pouttu, 'NetworkEurope Strategic Research and Innovation Agenda 2022', Zenodo, Dec. 2022. doi: 10.5281/ZENODO.7454872.
- [17] M. K. Bahare *et al.*, 'The 6G Architecture Landscape - European perspective', Feb. 2023, doi: 10.5281/ZENODO.7313232.
- [18] D. Allen, 'Digital Twins and living models at NASA', presented at the Digital Twin Summit, Nov. 2021. Accessed: Apr. 19, 2024. [Online]. Available: https://ntrs.nasa.gov/api/citations/20210023699/downloads/ASME%20Digital%20Twin%20Summit%20Keynote_final.pdf
- [19] V. Thomas, W. Neckel, and S. Wagner, 'Information technology and product lifecycle management', in *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment (Cat. No.99CH36357)*, May 1999, pp. 54–57. doi: 10.1109/ISEE.1999.765848.
- [20] K. Lyytinen, B. Weber, M. C. Becker, and B. T. Pentland, 'Digital Twins of Organization: Implications for Organization Design', *J. Organ. Des.*, pp. 1–17, 2023.
- [21] M. Grieves and J. Vickers, 'Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems', *Transdiscipl. Perspect. Complex Syst. New Find. Approaches*, pp. 85–113, 2017, doi: 10.1007/978-3-319-38756-7_4.
- [22] A. Ladj, Z. Wang, O. Meski, F. Belkadi, M. Ritou, and C. Da Cunha, 'A knowledge-based Digital Shadow for machining industry in a Digital Twin perspective', *J. Manuf. Syst.*, vol. 58, pp. 168–179, 2021.
- [23] J. Deng, L. Yue, H. Yang, and G. Liu, 'A Digital Twin Network Approach for 6G Wireless Network Autonomy', in *2023 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2023, pp. 415–420. doi: 10.1109/ICCWorkshops57953.2023.10283539.
- [24] DTC, 'Digital Twin Consortium', Digital Twin Consortium. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.digitaltwinconsortium.org/>
- [25] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, 'Digital Twin in Industry: State-of-the-Art', *IEEE Trans. Ind. Inform.*, vol. 15, no. 4, pp. 2405–2415, 2019, doi: 10.1109/TII.2018.2873186.
- [26] M. Dalibor, J. Michael, B. Rumpe, S. Varga, and A. Wortmann, 'Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits', in *Conceptual Modeling*, vol. 12400, G. Dobbie, U. Frank, G. Kappel, S. W. Little, and H. C. Mayr, Eds., in Lecture Notes in Computer Science, vol. 12400. , Cham: Springer International Publishing, 2020, pp. 377–387. doi: 10.1007/978-3-030-62522-1_28.
- [27] ISO, 'ISO 23247-2:2021: Automation systems and integration — Digital twin framework for manufacturing', 2021. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.iso.org/standard/78743.html>
- [28] E. Ferko, A. Bucaioni, and M. Behnam, 'Architecting Digital Twins', *IEEE Access*, vol. 10, pp. 50335–50350, 2022, doi: 10.1109/ACCESS.2022.3172964.
- [29] A. Macías, E. Navarro, C. E. Cuesta, and U. Zdun, 'Architecting Digital Twins Using a Domain-Driven Design-Based Approach*', in *2023 IEEE 20th International Conference on Software Architecture (ICSA)*, L'Aquila, Italy: IEEE, Mar. 2023, pp. 153–163. doi: 10.1109/ICSA56044.2023.00022.



- [30] E. Evans, *Domain-driven design: tackling complexity in the heart of software*. Boston: Addison-Wesley, 2004.
- [31] ITU-T, 'Rec. Y.3090 : Digital twin network - Requirements and architecture'. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.itu.int/rec/T-REC-Y.3090>
- [32] ETSI, 'ETSI GR ZSM 015 V1.1.1 Zero-touch network and Service Management (ZSM); Network Digital Twin'. Accessed: Apr. 19, 2024. [Online]. Available: <https://cdn.standards.iteh.ai/samples/64372/106e37af9bf648a8b6f924c1d4a4248b/ETSI-GR-ZSM-015-V1-1-1-2024-02-.pdf>
- [33] L. Hui, M. Wang, L. Zhang, L. Lu, and Y. Cui, 'Digital Twin for Networking: A Data-Driven Performance Modeling Perspective', *IEEE Netw.*, vol. 37, no. 3, pp. 202–209, May 2023, doi: 10.1109/MNET.119.2200080.
- [34] X. Lin, L. Kundu, C. Dick, E. Obiodu, T. Mostak, and M. Flaxman, '6G Digital Twin Networks: From Theory to Practice', *IEEE Commun. Mag.*, vol. 61, no. 11, pp. 72–78, Nov. 2023, doi: 10.1109/MCOM.001.2200830.
- [35] I. Turcanu, G. Castignani, and S. Faye, 'On the Integration of Digital Twin Networks into City Digital Twins: Benefits and Challenges', in *2024 IEEE 21st Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, USA: IEEE, Jan. 2024, pp. 752–758. doi: 10.1109/CCNC51664.2024.10454704.
- [36] B. Li, S. Zhao, R. Zhang, Q. Shi, and K. Yang, 'Anomaly detection for cellular networks using big data analytics', *IET Commun.*, vol. 13, no. 20, pp. 3351–3359, Dec. 2019, doi: 10.1049/iet-com.2019.0765.
- [37] M. S. Mollel *et al.*, 'A Survey of Machine Learning Applications to Handover Management in 5G and Beyond', *IEEE Access*, vol. 9, pp. 45770–45802, 2021, doi: 10.1109/ACCESS.2021.3067503.
- [38] Z.-Q. Luo *et al.*, 'SRCON: A Data-Driven Network Performance Simulator for Real-World Wireless Networks', *Comm Mag*, vol. 61, no. 6, pp. 96–102, Jun. 2023, doi: 10.1109/MCOM.001.2200179.
- [39] E. Ak, B. Canberk, V. Sharma, O. A. Dobre, and T. Q. Duong, 'What-if Analysis Framework for Digital Twins in 6G Wireless Network Management'. arXiv, 2024. doi: 10.48550/ARXIV.2404.11394.
- [40] 3GPP, '3GPP TR 28.915 V0.1.0; Management and orchestration; Study on management aspects of Network Digital Twin (Release 19)', 28.915, Feb. 2024.
- [41] C. Zhou *et al.*, 'Network Digital Twin: Concepts and Reference Architecture', Internet Engineering Task Force, Internet-Draft draft-irtf-nmrg-network-digital-twin-arch-05, Mar. 2024. [Online]. Available: <https://datatracker.ietf.org/doc/draft-irtf-nmrg-network-digital-twin-arch/05/>
- [42] X. Wang, X. Li, and V. C. M. Leung, 'Artificial Intelligence-Based Techniques for Emerging Heterogeneous Network: State of the Arts, Opportunities, and Challenges', *IEEE Access*, vol. 3, pp. 1379–1391, 2015, doi: 10.1109/ACCESS.2015.2467174.
- [43] R. Dong, C. She, W. Hardjawana, Y. Li, and B. Vucetic, 'Deep Learning for Hybrid 5G Services in Mobile Edge Computing Systems: Learn From a Digital Twin', *IEEE Trans. Wirel. Commun.*, vol. 18, no. 10, pp. 4692–4707, Oct. 2019, doi: 10.1109/TWC.2019.2927312.
- [44] Y. Zhou, R. Zhang, J. Liu, T. Huang, Q. Tang, and F. R. Yu, 'A Hierarchical Digital Twin Network for Satellite Communication Networks', *IEEE Commun. Mag.*, vol. 61, no. 11, pp. 104–110, Nov. 2023, doi: 10.1109/MCOM.001.2200864.
- [45] I. Vilà, O. Sallent, and J. Pérez-Romero, 'On the Design of a Network Digital Twin for the Radio Access Network in 5G and Beyond', *Sensors*, vol. 23, no. 3, p. 1197, Jan. 2023, doi: 10.3390/s23031197.
- [46] N. P. Kuruvatti, M. A. Habibi, S. Partani, B. Han, A. Fellan, and H. D. Schotten, 'Empowering 6G Communication Systems With Digital Twin Technology: A Comprehensive Survey', *IEEE Access*, vol. 10, pp. 112158–112186, 2022, doi: 10.1109/ACCESS.2022.3215493.
- [47] Spirent, 'Simplifying 5G with a Network Digital Twin. White paper', Nov. 2022. [Online]. Available: <https://www.spirent.com/campaign/5g-network-digital-twin>
- [48] 'Wireless Network Digital Twin as a Service Technology White Paper 5.0'.
- [49] D. Chen, H. Yang, C. Zhou, L. Lu, P. Lü, and T. Sun, 'Classification, Building and Orchestration Management of Digital Twin Network Models', in *2022 IEEE 22nd International Conference on Communication Technology (ICCT)*, 2022, pp. 1843–1846. doi: 10.1109/ICCT56141.2022.10073109.
- [50] H. Haddadi, M. Rio, G. Iannaccone, A. Moore, and R. Mortier, 'Network topologies: inference, modeling, and generation', *IEEE Commun. Surv. Tutor.*, vol. 10, no. 2, pp. 48–69, 2008, doi: 10.1109/COMST.2008.4564479.
- [51] H.-Y. Zhou, D.-Y. Luo, Y. Gao, and D.-C. Zuo, 'Modeling of Node Energy Consumption for Wireless Sensor Networks', *Wirel. Sens. Netw.*, vol. 03, no. 01, pp. 18–23, 2011, doi: 10.4236/wsn.2011.31003.
- [52] M. Ferriol-Galmés *et al.*, 'Building a Digital Twin for network optimization using Graph Neural Networks', *Comput. Netw.*, vol. 217, p. 109329, Nov. 2022, doi: 10.1016/j.comnet.2022.109329.
- [53] J. Wen, B. Gabrys, and K. Musial, 'Toward Digital Twin Oriented Modeling of Complex Networked Systems and Their Dynamics: A Comprehensive Survey', *IEEE Access*, vol. 10, pp. 66886–66923, 2022, doi: 10.1109/ACCESS.2022.3184801.
- [54] Y. Wu, K. Zhang, and Y. Zhang, 'Digital Twin Networks: A Survey', *IEEE Internet Things J.*, vol. 8, no. 18, pp. 13789–13804, 2021, doi: 10.1109/JIOT.2021.3079510.
- [55] S. Mihai *et al.*, 'Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects', *IEEE Commun. Surv. Tutor.*, vol. 24, no. 4, pp. 2255–2291, 2022, doi: 10.1109/COMST.2022.3208773.
- [56] ITU, 'AI for Good', AI for Good. Accessed: May 24, 2024. [Online]. Available: <https://aiforgood.itu.int/>
- [57] 'ML5G Challenge', AI for Good. Accessed: May 24, 2024. [Online]. Available: <https://aiforgood.itu.int/about-ai-for-good/aiml-in-5g-challenge/>
- [58] 3GPP, '3GPP TS 23.288 V18.5.0; Architecture enhancements for 5G System (5GS) to support network data analytics services (Release 18)', Mar. 2024.
- [59] 3GPP, '3GPP TS 23.501 V18.5.0; System architecture for the 5G System (5GS); Stage 2 (Release 18)', TS 23.501, Mar. 2024.
- [60] 3GPP, '3GPP TS 23.502 V18.5.0; Procedures for the 5G System (5GS); Stage 2 (Release 18)', TS 23.502, Mar. 2024.
- [61] X. Lin, 'Artificial Intelligence in 3GPP 5G-Advanced: A Survey'. arXiv, May 08, 2023. doi: 10.48550/arXiv.2305.05092.



- [62] X. Lin, 'An Overview of the 3GPP Study on Artificial Intelligence for 5G New Radio'. arXiv, Aug. 09, 2023. doi: 10.48550/arXiv.2308.05315.
- [63] 3GPP, '3GPP TS 23.503 V18.5.0; Policy and charging control framework for the 5G System (5GS); Stage 2 (Release 18)', TS 23.503, Mar. 2024.
- [64] 3GPP, '3GPP TR 23.700-80 V18.0.0; Study on 5G System Support for AI/ML-based Services (Release 18)', TR 23.700-80, Dec. 2022.
- [65] 3GPP, '3GPP TR 23.700-82 V0.4.0; Study on application layer support for AI/ML services; (Release 19)', TR 23.700-82, Apr. 2024.
- [66] 3GPP, '3GPP TR 28.908 V18.0. Study on Artificial Intelligence/Machine Learning (AI/ML) management (Release 18)', Sep. 2024.
- [67] 3GPP, 'AI/ML for NR Air Interface'. Accessed: May 22, 2024. [Online]. Available: <https://www.3gpp.org/technologies/ai-ml-nr>
- [68] 3GPP, 'AI/ML Management for 5G Systems'. Accessed: May 22, 2024. [Online]. Available: <https://www.3gpp.org/technologies/ai-ml-management>
- [69] X. Lin, L. Kundu, C. Dick, and S. Velayutham, 'Embracing AI in 5G-Advanced Towards 6G: A Joint 3GPP and O-RAN Perspective'. arXiv, Sep. 11, 2022. doi: 10.48550/arXiv.2209.04987.
- [70] P. H. Masur and J. H. Reed, 'Artificial Intelligence in Open Radio Access Network', *IEEE Aerosp. Electron. Syst. Mag.*, vol. 37, no. 9, pp. 6–15, Sep. 2022, doi: 10.1109/MAES.2022.3186966.
- [71] L. Bonati, M. Polese, S. D'Oro, S. Basagni, and T. Melodia, 'OpenRAN Gym: AI/ML Development, Data Collection, and Testing for O-RAN on PAWR Platforms', *Comput. Netw.*, vol. 220, p. 109502, Jan. 2023, doi: 10.1016/j.comnet.2022.109502.
- [72] B. Brik *et al.*, 'A Survey on Explainable AI for 6G O-RAN: Architecture, Use Cases, Challenges and Research Directions'. arXiv, Jul. 07, 2023. doi: 10.48550/arXiv.2307.00319.
- [73] C. Fiandrino, L. Bonati, S. D'Oro, M. Polese, T. Melodia, and J. Widmer, 'EXPLORA: AI/ML EXPLainability for the Open RAN'. arXiv, Oct. 20, 2023. doi: 10.48550/arXiv.2310.13667.
- [74] N. N. Sapavath, B. Kim, K. Chowdhury, and V. K. Shah, 'Experimental Study of Adversarial Attacks on ML-based xApps in O-RAN'. arXiv, Sep. 07, 2023. doi: 10.48550/arXiv.2309.03844.
- [75] N. Yungaicela-Naula, V. Sharma, and S. Scott-Hayward, 'Misconfiguration in O-RAN: Analysis of the impact of AI/ML', *Comput. Netw.*, vol. 247, p. 110455, Jun. 2024, doi: 10.1016/j.comnet.2024.110455.
- [76] M. Polese *et al.*, 'Colosseum: The Open RAN Digital Twin'. arXiv, Apr. 26, 2024. doi: 10.48550/arXiv.2404.17317.
- [77] Ericsson, 'AI standard for 5G RAN: what, why, and how', [ericsson.com](https://www.ericsson.com/en/blog/2023/11/ai-ml-5g-ran-3gpp). Accessed: May 22, 2024. [Online]. Available: <https://www.ericsson.com/en/blog/2023/11/ai-ml-5g-ran-3gpp>
- [78] Silicon Angle, 'Deutsche Telekom partners with Ericsson and Google to showcase next-gen cloud-native network', SiliconANGLE. Accessed: May 22, 2024. [Online]. Available: <https://siliconangle.com/2023/02/21/deutsche-telekom-partners-ericsson-google-showcase-next-gen-cloud-native-network/>
- [79] Nokia Bell Labs, 'Toward a 6G AI-Native Air Interface', Nokia Bell Labs. Accessed: May 22, 2024. [Online]. Available: <https://www.bell-labs.com/institute/white-papers/toward-6g-ai-native-air-interface/>
- [80] Nokia, 'Nokia, DOCOMO and NTT make two key 6G advances #MWC23 | Nokia'. Accessed: May 22, 2024. [Online]. Available: <https://www.nokia.com/about-us/news/releases/2023/02/15/nokia-docomo-and-ntt-make-two-key-6g-advances-mwc23/>
- [81] Nokia Bell Labs, 'dynamic-digital-twin', Nokia Bell Labs. Accessed: May 22, 2024. [Online]. Available: <https://www.bell-labs.com/research-innovation/projects-and-initiatives/dynamic-digital-twin/>
- [82] Y. Chen *et al.*, 'NetGPT: An AI-Native Network Architecture for Provisioning Beyond Personalized Generative Services', *IEEE Netw.*, pp. 1–1, 2024, doi: 10.1109/MNET.2024.3376419.
- [83] Huawei, 'Huawei Releases the Intelligent World 2030 Report to Explore Trends in the Next Decade', huawei. Accessed: May 22, 2024. [Online]. Available: <https://www.huawei.com/en/news/2021/9/huawei-releases-intelligent-world-report-2030>
- [84] L. E. Chatziefthერიou *et al.*, 'Orchestration Procedures for the Network Intelligence Stratum in 6G Networks', in *2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Gothenburg, Sweden: IEEE, Jun. 2023, pp. 347–352. doi: 10.1109/EuCNC/6GSummit58263.2023.10188297.
- [85] M. Camelo *et al.*, 'DAEMON: A Network Intelligence Plane for 6G Networks', in *2022 IEEE Globecom Workshops (GC Wkshps)*, Rio de Janeiro, Brazil: IEEE, Dec. 2022, pp. 1341–1346. doi: 10.1109/GCWkshps56602.2022.10008662.
- [86] Y. Wang, C.-L. I, J. Sun, X. Sun, and S. Chen, 'End to End AI Architecture for Next Generation Network', *IEEE Wirel. Commun.*, vol. 31, no. 1, pp. 86–92, Feb. 2024, doi: 10.1109/MWC.013.2200269.
- [87] S. Zeb, M. A. Rathore, S. A. Hassan, S. Raza, K. Dev, and G. Fortino, 'Toward AI-Enabled NextG Networks with Edge Intelligence-Assisted Microservice Orchestration', *IEEE Wirel. Commun.*, vol. 30, no. 3, pp. 148–156, Jun. 2023, doi: 10.1109/MWC.015.2200461.
- [88] P. Li, Y. Xing, and W. Li, 'Distributed AI-native Architecture for 6G Networks', in *2022 International Conference on Information Processing and Network Provisioning (ICIPNP)*, Beijing, China: IEEE, Sep. 2022, pp. 57–62. doi: 10.1109/ICIPNP57450.2022.00019.
- [89] F. Brito *et al.*, 'A network architecture for scalable end-to-end management of reusable AI-based applications', in *2023 14th International Conference on Network of the Future (NoF)*, Izmir, Turkey: IEEE, Oct. 2023, pp. 98–102. doi: 10.1109/NoF58724.2023.10302791.
- [90] Y. Liu, Y. He, Y. Lin, and L. Tang, 'Toward Native Artificial Intelligence in 6G', in *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Bilbao, Spain: IEEE, Jun. 2022, pp. 1–6. doi: 10.1109/BMSB55706.2022.9828649.



- [91] M. A. Habibi *et al.*, 'Toward an Open, Intelligent, and End-to-End Architectural Framework for Network Slicing in 6G Communication Systems', *IEEE Open J. Commun. Soc.*, vol. 4, pp. 1615–1658, 2023, doi: 10.1109/OJCOMS.2023.3294445.
- [92] Q. Guo, F. Tang, T. K. Rodrigues, and N. Kato, 'Five Disruptive Technologies in 6G to Support Digital Twin Networks', *IEEE Wirel. Commun.*, vol. 31, no. 1, pp. 149–155, Feb. 2024, doi: 10.1109/MWC.013.2200296.
- [93] Y. Tao, J. Wu, X. Lin, and W. Yang, 'DRL-Driven Digital Twin Function Virtualization for Adaptive Service Response in 6G Networks', *IEEE Netw. Lett.*, vol. 5, no. 2, pp. 125–129, Jun. 2023, doi: 10.1109/LNET.2023.3269766.
- [94] DAEMON, 'Home - DAEMON: Network intelligence aDAptive sELf-Learning MOBILE Networks'. Accessed: Apr. 19, 2024. [Online]. Available: <https://h2020daemon.eu/>
- [95] 6G-SANDBOX, '6G-SANDBOX SNS HE PROJECT'. Accessed: Apr. 19, 2024. [Online]. Available: <https://6g-sandbox.eu/>
- [96] ORIGAMI, 'ORIGAMI | Home'. Accessed: Apr. 19, 2024. [Online]. Available: <https://sns-origami.eu/>
- [97] 6G-BRICKS, 'Home - 6G-BRICKS'. Accessed: Apr. 19, 2024. [Online]. Available: <https://6g-bricks.eu/>
- [98] 'BeGREEN', BeGREEN. Accessed: May 24, 2024. [Online]. Available: <https://www.sns-begreen.com/>
- [99] D. S. Buse, M. Schettler, N. Kothe, P. Reinold, C. Sommer, and F. Dressler, 'Bridging worlds: Integrating hardware-in-the-loop testing with large-scale VANET simulation', in *2018 14th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, Isola: IEEE, Feb. 2018, pp. 33–36. doi: 10.23919/WONS.2018.8311659.
- [100] D. S. Buse, C. Sommer, and F. Dressler, 'Demo abstract: Integrating a driving simulator with city-scale VANET simulation for the development of next generation ADAS systems', in *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, Honolulu, HI: IEEE, Apr. 2018, pp. 1–2. doi: 10.1109/INFOCOMW.2018.8406997.
- [101] D. S. Buse and F. Dressler, 'Towards Real-Time Interactive V2X Simulation', in *2019 IEEE Vehicular Networking Conference (VNC)*, Los Angeles, CA, USA: IEEE, Dec. 2019, pp. 1–8. doi: 10.1109/VNC48660.2019.9062812.
- [102] D. S. Buse, G. Echterling, and F. Dressler, 'Accelerating the Simulation of Wireless Communication Protocols using Asynchronous Parallelism', in *Proceedings of the 24th International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, Alicante Spain: ACM, Nov. 2021, pp. 57–66. doi: 10.1145/3479239.3485683.
- [103] M. M. G. Farag, H. A. Rakha, E. A. Mazied, and J. Rao, 'INTEGRATION Large-Scale Modeling Framework of Direct Cellular Vehicle-to-All (C-V2X) Applications', *Sensors*, vol. 21, no. 6, p. 2127, Mar. 2021, doi: 10.3390/s21062127.
- [104] T. Queck, B. Schünemann, I. Radusch, and C. Meinel, 'Realistic Simulation of V2X Communication Scenarios', in *2008 IEEE Asia-Pacific Services Computing Conference*, Yilan, Taiwan: IEEE, Dec. 2008, pp. 1623–1627. doi: 10.1109/APSCC.2008.23.
- [105] R. Protzmann, K. Mahler, K. Oltmann, and I. Radusch, 'Extending the V2X simulation environment VSimRTI with advanced communication models', in *2012 12th International Conference on ITS Telecommunications*, 2012, pp. 683–688. doi: 10.1109/ITST.2012.6425269.
- [106] N. Goebel, R. Bialon, M. Mauve, and K. Graffi, 'Coupled simulation of mobile cellular networks, road traffic and V2X applications using traces', in *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia: IEEE, May 2016, pp. 1–7. doi: 10.1109/ICC.2016.7511126.
- [107] D. Cui *et al.*, 'Extensible Co-Simulation Framework for Supporting Cooperative Driving Automation Research', *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2677, no. 3, pp. 1067–1079, Mar. 2023, doi: 10.1177/03611981221121263.
- [108] K. Schrab, R. Protzmann, and I. Radusch, 'A Large-Scale Traffic Scenario of Berlin for Evaluating Smart Mobility Applications', in *Smart Energy for Smart Transport*, E. G. Nathanail, N. Gavanis, and G. Adamos, Eds., in Lecture Notes in Intelligent Transportation and Infrastructure. , Cham: Springer Nature Switzerland, 2023, pp. 276–287. doi: 10.1007/978-3-031-23721-8_24.
- [109] T. Hades, D. Logan, T. H. Pritom, and C. Sommer, 'Towards an Open Source Fully Modular Multi Unmanned Aerial Vehicle Simulation Framework', in *2022 IEEE 42nd International Conference on Distributed Computing Systems Workshops (ICDCSW)*, Bologna, Italy: IEEE, Jul. 2022, pp. 284–289. doi: 10.1109/ICDCSW56584.2022.00060.
- [110] M. Yin, T. X. Tran, A. Sharma, M. Mezzavilla, and S. Rangan, 'Demo: SkyRoute, a Fast and Realistic UAV Cellular Simulation Framework', in *2021 IEEE 29th International Conference on Network Protocols (ICNP)*, Dallas, TX, USA: IEEE, Nov. 2021, pp. 1–2. doi: 10.1109/ICNP52444.2021.9651932.
- [111] A. Al-Mousa, B. H. Sababha, N. Al-Madi, A. Barghouthi, and R. Younis, 'UTSim: A framework and simulator for UAV air traffic integration, control, and communication', *Int. J. Adv. Robot. Syst.*, vol. 16, no. 5, p. 172988141987093, Sep. 2019, doi: 10.1177/1729881419870937.
- [112] G. Castellanos, M. Deruyck, L. Martens, and W. Joseph, 'Performance Evaluation of Direct-Link Backhaul for UAV-Aided Emergency Networks', *Sensors*, vol. 19, no. 15, p. 3342, Jan. 2019, doi: 10.3390/s19153342.
- [113] G. Castellanos, G. Vallerio, M. Deruyck, L. Martens, M. Meo, and W. Joseph, 'Evaluation of flying caching servers in UAV-BS based realistic environment', *Veh. Commun.*, vol. 32, p. 100390, Dec. 2021, doi: 10.1016/j.vehcom.2021.100390.
- [114] G. Castellanos *et al.*, 'Evaluation of Beamsteering performance in MultiuserMIMO Unmanned Aerial Base Stations networks', *IEEE Access*, pp. 1–1, 2022, doi: 10.1109/ACCESS.2022.3182120.
- [115] M. Kudelski, L. M. Gambardella, and G. A. Di Caro, 'RoboNetSim: An integrated framework for multi-robot and network simulation', *Robot. Auton. Syst.*, vol. 61, no. 5, pp. 483–496, May 2013, doi: 10.1016/j.robot.2013.01.003.
- [116] J. L. F. Pereira and R. J. F. Rossetti, 'An integrated architecture for autonomous vehicles simulation', in *Proceedings of the 27th Annual ACM Symposium on Applied Computing*, Trento Italy: ACM, Mar. 2012, pp. 286–292. doi: 10.1145/2245276.2245333.
- [117] F. A. Schiegg, J. Krost, S. Jesenski, and J. Frye, 'A Novel Simulation Framework for the Design and Testing of Advanced Driver Assistance Systems', in *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, Honolulu, HI, USA: IEEE, Sep. 2019, pp. 1–6. doi: 10.1109/VTCFall.2019.8891221.



- [118] A. Ibrahim, C. B. Math, D. Goswami, T. Basten, and H. Li, 'Co-simulation Framework for Control, Communication and Traffic for Vehicle Platoons', in *2018 21st Euromicro Conference on Digital System Design (DSD)*, Prague: IEEE, Aug. 2018, pp. 352–356. doi: 10.1109/DSD.2018.00068.
- [119] A. Choudhury, T. Maszczyk, C. B. Math, H. Li, and J. Dauwels, 'An Integrated Simulation Environment for Testing V2X Protocols and Applications', *Procedia Comput. Sci.*, vol. 80, pp. 2042–2052, 2016, doi: 10.1016/j.procs.2016.05.524.
- [120] D. Krajzewicz, L. Bieker, J. Härrä, and R. Blokpoel, 'Simulation of V2X Applications with the iTETRIS System', *Procedia - Soc. Behav. Sci.*, vol. 48, pp. 1482–1492, 2012, doi: 10.1016/j.sbspro.2012.06.1124.
- [121] S. Aoki, L. E. Jan, J. Zhao, A. Bhat, R. R. Rajkumar, and C.-F. Chang, 'Co-simulation Platform for Developing InfoRich Energy-Efficient Connected and Automated Vehicles', in *2020 IEEE Intelligent Vehicles Symposium (IV)*, Las Vegas, NV, USA: IEEE, Oct. 2020, pp. 1522–1529. doi: 10.1109/IV47402.2020.9304664.
- [122] H. Kim, T. Kim, S. Kang, C. Yoon, and J. Jung, 'Design of V2X runtime emulation framework for evaluation of vehicle safety applications', in *2014 4th IEEE International Conference on Network Infrastructure and Digital Content*, Beijing, China: IEEE, Sep. 2014, pp. 262–268. doi: 10.1109/ICNIDC.2014.7000306.
- [123] M. R. Cantas and L. Guvenc, 'Customized Co-Simulation Environment for Autonomous Driving Algorithm Development and Evaluation'. arXiv, May 31, 2023. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2306.00223>
- [124] D. Nalic, A. Eichberger, G. Hanzl, M. Fellendorf, and B. Rogic, 'Development of a Co-Simulation Framework for Systematic Generation of Scenarios for Testing and Validation of Automated Driving Systems', in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, Auckland, New Zealand: IEEE, Oct. 2019, pp. 1895–1901. doi: 10.1109/ITSC.2019.8916839.
- [125] C. Lei, E. M. Van Eenennaam, W. Klein Wolterink, J. Ploeg, G. Karagiannis, and G. Heijenk, 'Evaluation of CACC string stability using SUMO, Simulink, and OMNeT++', *EURASIP J. Wirel. Commun. Netw.*, vol. 2012, no. 1, p. 116, Dec. 2012, doi: 10.1186/1687-1499-2012-116.
- [126] A. Hegde and A. Festag, 'Artery-C: An OMNeT++ Based Discrete Event Simulation Framework for Cellular V2X', in *Proceedings of the 23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, Alicante Spain: ACM, Nov. 2020, pp. 47–51. doi: 10.1145/3416010.3423240.
- [127] D. Nalic, A. Pandurevic, A. Eichberger, and B. Rogic, 'Design and Implementation of a Co-Simulation Framework for Testing of Automated Driving Systems', *Sustainability*, vol. 12, no. 24, p. 10476, Dec. 2020, doi: 10.3390/su122410476.
- [128] B. McCarthy and A. O'Driscoll, 'OpenCV2X Mode 4: A Simulation Extension for Cellular Vehicular Communication Networks', in *2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Limassol, Cyprus: IEEE, Sep. 2019, pp. 1–6. doi: 10.1109/CAMAD.2019.8858436.
- [129] M. K. Müller *et al.*, 'Flexible multi-node simulation of cellular mobile communications: the Vienna 5G System Level Simulator', *EURASIP J. Wirel. Commun. Netw.*, vol. 2018, no. 1, p. 227, Dec. 2018, doi: 10.1186/s13638-018-1238-7.
- [130] Teeco, 'ASSET Suite'. 2022. Accessed: Nov. 24, 2022. [Online]. Available: <https://www.teeco.com/wp-content/uploads/2021/11/ASSET-Suite-Brochure-2021.2.pdf>
- [131] Forsk, 'Atoll 5G NR Planning Software \textbar Atoll 5G NR \textbar Forsk'. 2022. Accessed: Feb. 11, 2022. [Online]. Available: <https://www.forsk.com/atoll-5g-nr>
- [132] Capgemini Engineering, '5G Radio Access Network Planning and Optimization', *Capgemini Engineering Deutschland*. 2020. Accessed: Feb. 11, 2022. [Online]. Available: <https://capgemini-engineering.com/de/en/insight/5g-radio-access-network-planning-and-optimization/>
- [133] CelPlan, 'CellDesigner™ Software suite'. Feb. 2020. Accessed: Nov. 24, 2022. [Online]. Available: <https://www.celplan.com/products/celldesigner>
- [134] Hamina, 'Hamina Network Planner'. Oct. 2022. Accessed: Nov. 23, 2022. [Online]. Available: https://www.hamina.com/hubfs/PDF/Hamina_Data_Sheet.pdf
- [135] Huawei, 'Huawei 5G Wireless Network Planning Solution White Paper', Huawei, 2018. Accessed: Feb. 11, 2022. [Online]. Available: https://www-file.huawei.com/-/media/corporate/pdf/white%20paper/2018/5g_wireless_network_planning_solution_en_v2.pdf?la=en
- [136] iBwave, 'iBwave Design Enterprise to design indoor wireless networks', *iBwave Solutions*. 2022. Accessed: Aug. 02, 2022. [Online]. Available: <https://ibwave.com/ibwave-design-enterprise>
- [137] L. T. AG, 'Radio Network Planning CHIRplus_TC'. 2022. [Online]. Available: https://www.lstelcom.com/fileadmin/content/lst/marketing/brochures/LS_Brochure_CHIRplus_TC_EN.pdf
- [138] Tetcos, 'Tetcos: NetSim - Network Simulation Software, India'. 2022. Accessed: Nov. 25, 2022. [Online]. Available: <https://www.tetcos.com/index.html>
- [139] M. Platforms, 'Terragraph Runbook \textbar Terragraph'. 2022. Accessed: Aug. 02, 2022. [Online]. Available: <https://terragraph.com/docs/runbook>
- [140] M. Platforms, 'Terragraph Mesh Whitepaper', Meta Platforms, Jun. 2019. Accessed: Jul. 29, 2022. [Online]. Available: https://terragraph.com/assets/files/Terragraph_Mesh_Whitepaper-d906f1eb9c3ea7a8c1bbd8552b1f9f2d.pdf
- [141] 'Implementation of 5G Network Projects (Successfully)', *Network Simulation Tools*. Accessed: Nov. 28, 2022. [Online]. Available: <https://networksimulationtools.com/5g-network-projects/>
- [142] S. Martiradonna, A. Grassi, G. Piro, and G. Boggia, 'Understanding the 5G-air-simulator: A tutorial on design criteria, technical components, and reference use cases', *Comput. Netw.*, vol. 177, p. 107314, Aug. 2020, doi: 10.1016/j.comnet.2020.107314.
- [143] J. Lee, M. Han, M. Rim, and C. G. Kang, '5G K-SimSys for Open/Modular/Flexible System-Level Simulation: Overview and its Application to Evaluation of 5G Massive MIMO', *IEEE Access*, vol. 9, pp. 94017–94032, 2021, doi: 10.1109/ACCESS.2021.3093460.
- [144] CGA, '5G NETWORK PLANNING TOOL \textbar Simulation'. 2022. Accessed: Aug. 05, 2022. [Online]. Available: <https://www.cgasimulation.com/network-planning-tool/>
- [145] OMNeT, 'SimuLTE - LTE User Plane Simulator for OMNeT++ and INET'. 2020. Accessed: Nov. 23, 2022. [Online]. Available: <https://simulte.com/index.html>



- [146] G. Nardini, D. Sabella, G. Stea, P. Thakkar, and A. Virdis, 'Simu5G—An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks', *IEEE Access*, vol. 8, pp. 181176–181191, 2020, doi: 10.1109/ACCESS.2020.3028550.
- [147] OPNET, 'Opnet Projects', *Opnet Projects*. 2022. Accessed: Feb. 11, 2022. [Online]. Available: <https://opnetprojects.com/>
- [148] nsnam, 'NS-3 Network Simulator', *ns-3*. 2022. Accessed: Feb. 11, 2022. [Online]. Available: <https://www.nsnam.org/>
- [149] F. Kaltenberger, '5G New Radio in OpenAirInterface', p. 18.
- [150] 'Vienna 5G Simulators – Telecommunications'. Accessed: Nov. 24, 2022. [Online]. Available: <https://www.tuwien.at/etit/tc/en/vienna-simulators/vienna-5g-simulators/>
- [151] 'What is OMNeT++?' Accessed: Jun. 20, 2024. [Online]. Available: <https://omnetpp.org/intro/>
- [152] P. A. Lopez *et al.*, 'Microscopic Traffic Simulation using SUMO', in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, Maui, HI: IEEE, Nov. 2018, pp. 2575–2582. doi: 10.1109/ITSC.2018.8569938.
- [153] A. Dosovitskiy, G. Ros, F. Codevilla, A. Lopez, and V. Koltun, 'CARLA: An Open Urban Driving Simulator', in *Proceedings of the 1st Annual Conference on Robot Learning*, 2017, pp. 1–16.
- [154] L. Codeca, R. Frank, S. Faye, and T. Engel, 'Luxembourg SUMO Traffic (LuST) Scenario: Traffic Demand Evaluation', *IEEE Intell. Transp. Syst. Mag.*, vol. 9, no. 2, pp. 52–63, 2017, doi: 10.1109/ITS.2017.2666585.
- [155] L. Codecá and J. Härrilä, 'Towards multimodal mobility simulation of C-ITS: The Monaco SUMO traffic scenario', in *2017 IEEE Vehicular Networking Conference (VNC)*, 2017, pp. 97–100. doi: 10.1109/VNC.2017.8275627.
- [156] C. Sommer, R. German, and F. Dressler, 'Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis', *IEEE Trans. Mob. Comput.*, vol. 10, no. 1, pp. 3–15, 2011, doi: 10.1109/TMC.2010.133.
- [157] T. Harges, I. Turcanu, and C. Sommer, 'Poster: A Case for Heterogenous Co-Simulation of Cooperative and Autonomous Driving', in *2023 IEEE Vehicular Networking Conference (VNC)*, 2023, pp. 151–152. doi: 10.1109/VNC57357.2023.10136319.
- [158] M. Franke and C. Sommer, 'Toward Space-Air-Ground Integrated Network Simulation with 4D Topologies', in *2024 19th Wireless On-Demand Network Systems and Services Conference (WONS)*, 2024, pp. 61–68. doi: 10.23919/WONS60642.2024.10449583.
- [159] 'INET Framework - INET Framework'. Accessed: Jun. 20, 2024. [Online]. Available: <https://inet.omnetpp.org/>
- [160] 'inet-framework/inet-gpl'. INET Framework for OMNeT++, Mar. 17, 2022. Accessed: Jun. 20, 2024. [Online]. Available: <https://github.com/inet-framework/inet-gpl>
- [161] 'The most powerful real-time 3D creation tool', Unreal Engine. Accessed: Jun. 20, 2024. [Online]. Available: <https://www.unrealengine.com/en-US/home>
- [162] 'Docker: Accelerated Container Application Development'. Accessed: Jun. 20, 2024. [Online]. Available: <https://www.docker.com/>
- [163] 'Podman Desktop - Containers and Kubernetes | Podman Desktop'. Accessed: Jun. 20, 2024. [Online]. Available: <https://podman-desktop.io/>
- [164] 'Oracle VM VirtualBox'. Accessed: Jun. 20, 2024. [Online]. Available: <https://www.virtualbox.org/>
- [165] J. Mirzaei, I. Abualhaol, and G. Poitau, 'Network Digital Twin for Open RAN: The Key Enablers, Standardization, and Use Cases'. arXiv, Aug. 04, 2023. doi: 10.48550/arXiv.2308.02644.
- [166] A. Alkhateeb, S. Jiang, and G. Charan, 'Real-Time Digital Twins: Vision and Research Directions for 6G and Beyond', *IEEE Commun. Mag.*, vol. 61, no. 11, pp. 128–134, Nov. 2023, doi: 10.1109/MCOM.001.2200866.
- [167] H. Ahmadi, A. Nag, Z. Khar, K. Sayrafian, and S. Rahardja, 'Networked Twins and Twins of Networks: An Overview on the Relationship Between Digital Twins and 6G', *IEEE Commun. Stand. Mag.*, vol. 5, no. 4, pp. 154–160, Dec. 2021, doi: 10.1109/MCOMSTD.0001.2000041.
- [168] G. Baldoni, J. Quevedo, C. Guimarães, A. De La Oliva, and A. Corsaro, 'Data-Centric Service-Based Architecture for Edge-Native 6G Network', *IEEE Commun. Mag.*, vol. 62, no. 4, pp. 32–38, Apr. 2024, doi: 10.1109/MCOM.001.2300178.
- [169] UN, 'The UN Sustainable Development Goals – UN Environment Management Group'. Accessed: May 24, 2024. [Online]. Available: <https://unemg.org/our-work/supporting-the-sdgs/the-un-sustainable-development-goals/>
- [170] 'Verticals Cartography | 6G SNS Tracker'. Accessed: Jun. 25, 2024. [Online]. Available: <https://sns-trackers.sns-ju.eu/vertical-engagement-tracker/vertical-cartography>
- [171] A. Hadziaganovic, 'Deterministic6G - HOME', Deterministic6G. Accessed: May 31, 2024. [Online]. Available: <https://deterministic6g.eu/>
- [172] DETERMINISTIC6G, 'DETERMINISTIC6G - D1.1: Use Cases and Architecture Principles', Jun. 2023.
- [173] Hexa-X-II, 'HEXA-X-II - Deliverable D2.2: Foundation of overall 6G system design and preliminary evaluation results', Dec. 2023. [Online]. Available: https://hexa-x-ii.eu/wp-content/uploads/2024/01/Hexa-X-II_D2.2_FINAL.pdf
- [174] 'Homepage | Fidal - Field Trials Beyond 5G'. Accessed: May 31, 2024. [Online]. Available: <https://fidal-he.eu/>
- [175] Fidal, 'FIDAL - D2.1: Requirements, Architecture and Methodologies', Jun. 2023. [Online]. Available: https://fidal-he.eu/sites/default/files/pd/file/2023-07/D2.1_FIDAL.pdf
- [176] S. N. S. TrialsNet, 'TrialsNet', TrialsNet. Accessed: May 31, 2024. [Online]. Available: <https://trialsnet.eu/>
- [177] O. M. Gardin *et al.*, 'Use Cases definition for Infrastructure, Transportation and Security & Safety (ITSS) domain', May 2023, doi: 10.5281/ZENODO.7944484.
- [178] A. Basso *et al.*, 'Use Cases definition for Culture, Tourism, and Entertainment (CTE) domain', May 2023, doi: 10.5281/ZENODO.7944731.
- [179] D. Tsakanika *et al.*, 'Use Cases definition for eHealth and Emergency (eHE) domain', May 2023, doi: 10.5281/ZENODO.7944691.
- [180] P. Agddam, '6GTandem KPI/KVI', presented at the Stream B/D Joint Workshop on KPIs and KVIs, May 16, 2023. [Online]. Available: <https://smart-networks.europa.eu/wp-content/uploads/2024/05/6gtandem-stream-b-kpi-kvi-presentation.pdf>



- [181] C. Navarro, A. Torrealba, and G. Darzanos, 'IMAGINE-B5G: Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe.', presented at the Stream B/D Joint Workshop on KPIs and KVIs, May 16, 2024. [Online]. Available: https://smart-networks.europa.eu/wp-content/uploads/2024/05/imagine-b5g_streambd_kpikvi_workshop.pdf
- [182] I. Mesogiti, I. Patsouras, and M. Dieudonne, 'Introduction to TMV WG KPIs-related activities. - Test, Measurement, and KPIs Validation (TMV) WG - 6GSNS', presented at the Stream B/D Joint Workshop on KPIs and KVIs, May 16, 2024. [Online]. Available: https://smart-networks.europa.eu/wp-content/uploads/2024/05/trialnet_ws_tmv-kpis-prez_16_5_kviv_3.pdf
- [183] 5GAA, 'C-V2X Use Cases Volume II: Examples and Service Level Requirements', München, Germany, Oct. 2020. [Online]. Available: https://5gaa.org/content/uploads/2020/10/5GAA_White-Paper_C-V2X-Use-Cases-Volume-II.pdf
- [184] M. Emara, M. C. Filippou, and D. Sabella, 'MEC-Assisted End-to-End Latency Evaluations for C-V2X Communications', in *2018 European Conference on Networks and Communications (EuCNC)*, Ljubljana, Slovenia: IEEE, Jun. 2018, pp. 1–9. doi: 10.1109/EuCNC.2018.8442825.
- [185] M. T. Ribeiro, S. Singh, and C. Guestrin, "'Why Should I Trust You?': Explaining the Predictions of Any Classifier'. arXiv, Aug. 09, 2016. Accessed: Jun. 25, 2024. [Online]. Available: <http://arxiv.org/abs/1602.04938>
- [186] P. Soto *et al.*, 'Towards Autonomous VNF Auto-scaling using Deep Reinforcement Learning', in *2021 Eighth International Conference on Software Defined Systems (SDS)*, Gandia, Spain: IEEE, Dec. 2021, pp. 01–08. doi: 10.1109/SDS54264.2021.9731854.
- [187] E. Aycan Beyazit, B. Özbek, and D. Le Ruyet, 'Deep learning based adaptive bit allocation for heterogeneous interference channels', *Phys. Commun.*, vol. 47, p. 101364, Aug. 2021, doi: 10.1016/j.phycom.2021.101364.
- [188] D. Bega, M. Gramaglia, M. Fiore, A. Banchs, and X. Costa-Perez, 'AZTEC: Anticipatory Capacity Allocation for Zero-Touch Network Slicing', in *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*, Toronto, ON, Canada: IEEE, Jul. 2020, pp. 794–803. doi: 10.1109/INFOCOM41043.2020.9155299.
- [189] J. Jimenez Agudelo *et al.*, 'Resource Allocation of Multi-user Workloads in Cloud and Edge Data-Centers Using Reinforcement Learning'. Zenodo, Oct. 16, 2023. doi: 10.5281/ZENODO.10007880.
- [190] A. Rezaei, A. Khalili, J. Jalali, H. Shafiei, and Q. Wu, 'Energy-Efficient Resource Allocation and Antenna Selection for IRS-Assisted Multicell Downlink Networks', *IEEE Wirel. Commun. Lett.*, vol. 11, no. 6, pp. 1229–1233, 2022, doi: 10.1109/LWC.2022.3161410.
- [191] ETSI, 'ETSI ES 202 336-12 V1.1.1: Environmental Engineering (EE); Monitoring and control interface for infrastructure equipment (power, cooling and building environment systems used in telecommunication networks); Part 12: ICT equipment power, energy and environmental parameters monitoring information model', Sophia Antipolis Cedex - FRANCE, ETSI ES 202 336-12, Jun. 2015.
- [192] Ion Turcanu *et al.*, 'Integrating Network Digital Twinning into Future AI-Based 6G Systems: The 6G-TWIN Vision', in *2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Antwerpen, Belgium, Jun. 2024.
- [193] Sebastien Faye *et al.*, 'Integrating Network Digital Twinning into Future AI-Based 6G Systems: The 6G-TWIN Vision', in *2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Antwerpen, Belgium, Jun. 2024.
- [194] 6G-TWIN, '6G-TWIN - D2.1 Data governance, privacy, and harmonization.', Jun. 2024.
- [195] Q. Zhou, A. J. G. Gray, and S. McLaughlin, 'ToCo: An Ontology for Representing Hybrid Telecommunication Networks', in *The Semantic Web*, vol. 11503, P. Hitzler, M. Fernández, K. Janowicz, A. Zaveri, A. J. G. Gray, V. Lopez, A. Haller, and K. Hammar, Eds., in *Lecture Notes in Computer Science*, vol. 11503., Cham: Springer International Publishing, 2019, pp. 507–522. doi: 10.1007/978-3-030-21348-0_33.
- [196] Smart data Models, 'Smart Data Models', Smart Data Models. Accessed: Apr. 19, 2024. [Online]. Available: <https://smartdatamodels.org/>
- [197] C. Szegedy *et al.*, 'Intriguing properties of neural networks'. arXiv, Feb. 19, 2014. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/1312.6199>
- [198] Ö. F. Tuna, F. E. Kadan, and L. Karaçay, 'Practical Adversarial Attacks Against AI-Driven Power Allocation in a Distributed MIMO Network'. arXiv, Jan. 23, 2023. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2301.09305>
- [199] W. Zhao, S. Alwidian, and Q. H. Mahmoud, 'Adversarial Training Methods for Deep Learning: A Systematic Review', *Algorithms*, vol. 15, no. 8, p. 283, Aug. 2022, doi: 10.3390/a15080283.
- [200] Y. Siriwardhana, P. Poramage, M. Liyanage, and M. Ylianttila, 'AI and 6G Security: Opportunities and Challenges', in *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Porto, Portugal: IEEE, Jun. 2021, pp. 616–621. doi: 10.1109/EuCNC/6GSummit51104.2021.9482503.
- [201] F. Klement *et al.*, 'Open or not open: Are conventional radio access networks more secure and trustworthy than Open-RAN?' arXiv, Jun. 22, 2022. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2204.12227>
- [202] Ericsson, 'Explainable AI: How humans can trust Artificial Intelligence'. Accessed: Apr. 19, 2024. [Online]. Available: <https://www.ericsson.com/en/reports-and-papers/white-papers/explainable-ai-how-humans-can-trust-ai>
- [203] Q. Liu *et al.*, 'Operationalizing AI in Future Networks: A Bird's Eye View from the System Perspective'. arXiv, Feb. 14, 2024. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2303.04073>
- [204] Z. Chen, K. He, J. Li, and Y. Geng, 'Seq2Img: A sequence-to-image based approach towards IP traffic classification using convolutional neural networks', in *2017 IEEE International Conference on Big Data (Big Data)*, Boston, MA: IEEE, Dec. 2017, pp. 1271–1276. doi: 10.1109/BigData.2017.8258054.
- [205] M. Camelo, P. Soto, and S. Latre, 'A General Approach for Traffic Classification in Wireless Networks Using Deep Learning', *IEEE Trans. Netw. Serv. Manag.*, vol. 19, no. 4, pp. 5044–5063, Dec. 2022, doi: 10.1109/TNSM.2021.3130382.
- [206] S. Ackerman, E. Farchi, O. Raz, M. Zalmanovici, and P. Dube, 'Detection of data drift and outliers affecting machine learning model performance over time'. arXiv, Sep. 06, 2022. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2012.09258>
- [207] W. Wang, V. W. Zheng, H. Yu, and C. Miao, 'A Survey of Zero-Shot Learning: Settings, Methods, and Applications', *ACM Trans. Intell. Syst. Technol.*, vol. 10, no. 2, pp. 1–37, Mar. 2019, doi: 10.1145/3293318.



- [208] M. Hutsebaut-Buysse, K. Mets, and S. Latré, 'Hierarchical Reinforcement Learning: A Survey and Open Research Challenges', *Mach. Learn. Knowl. Extr.*, vol. 4, no. 1, pp. 172–221, Feb. 2022, doi: 10.3390/make4010009.
- [209] F. Bayram, B. S. Ahmed, and A. Kessler, 'From Concept Drift to Model Degradation: An Overview on Performance-Aware Drift Detectors', 2022, doi: 10.48550/ARXIV.2203.11070.
- [210] D. M. Manias, A. Chouman, and A. Shami, 'Model Drift in Dynamic Networks', *IEEE Commun. Mag.*, vol. 61, no. 10, pp. 78–84, Oct. 2023, doi: 10.1109/MCOM.003.2200306.
- [211] P. M. Mammen, 'Federated Learning: Opportunities and Challenges'. arXiv, Jan. 13, 2021. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/2101.05428>
- [212] H. H. Zhuo, W. Feng, Y. Lin, Q. Xu, and Q. Yang, 'Federated Deep Reinforcement Learning'. arXiv, Feb. 09, 2020. Accessed: Apr. 19, 2024. [Online]. Available: <http://arxiv.org/abs/1901.08277>



ANNEX 1: 6G-TWIN SPECIFIC OBJECTIVES AND KPI MAPPING

6G-TWIN Specific Objectives	KPI Number	KPIs and targets
SO1: 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 (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.
	KPI1.2	Achieve the improvements proposed to the KPIs associated with the use-cases (see use case description, including at least 30% end-to-end improvement in energy efficiency) compared to a 5G Service Based Architecture and baseline techniques from state-of-the-art research.
	KPI1.3	Provide at least three AI-based NF/NS for data analytics or/and decision-making to optimise network performance per use case.
	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.
	KPI1.5	Have regular links with at least two open network community working groups (WGs) (e.g., O-RAN, ETSI-ENI) to support the definition of an OCCA for 6G.
	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.
SO2: 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 (WP2)	KPI2.1	Provide an NDT that supports the representation and operation of a real network.
	KPI2.2	Ensure the completeness of the basic model representing the identified use case
	KPI2.3	Ensure the completeness of the functional models, covering at least all the necessary functions to emulate use case physical system behaviour.
	KPI2.4	Be involved in the standard description of network elements for DT and the FiWare Smart data schema.
	KPI2.5	Support the following three operations
SO3: To implement an accurate, reliable, open and secured modelling and simulation framework to represent a networked environment and test the functionalities of the proposed 6G architecture (WP3)	KPI3.1	Design a platform-independent solution that allows the integration of new frameworks by implementing an abstract interface.
	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.
SO4: To test, validate and facilitate the transferability of the solutions developed in 6G-TWIN through the development of two demonstrators supporting highly dynamic use cases, with two key focus areas: teledriving and energy efficiency (WP4)	KPI4.1	Build two different demonstrators (energy-saving and teledriving) to trigger the solution developed within the project (DUT): 1) Set up the teledriving testbed to provide full E2E connectivity for the successful transmission of control signalling and user traffic from the remote driving apps. 2) Set up the energy-saving testbed to provide connectivity and successful communication via O1, E2 and A1 to the third-party RIC (Accelleran). 3) Set up three environments a) City Skyscraper, b) City Market Hall and c) City Main Shopping Street.
	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.
SO5: To support the standardisation of the	KPI5.1	Develop at least two position papers containing business-driven feedback and recommendations for the 6G initiative and EU bodies.



6G-TWIN operation system to ensure the interoperability, platform openness and operation harmonisation of future 6G-TWIN Solutions (WP5)	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.
SO6: To provide industry with insights on innovative business models based on 6G-TWIN solutions and visions (WP6)	KPI6.1	Obtain feedback from industry experts involved in DEC activities (min. three round tables)
	KPI6.2	Provide a clear and consensual business case for each exploitable result (i.e. commonly developed and accepted by its co-owners).