An Architectural Framework for 6G Network Digital Twins System

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Future Network Services Project

Future Network Services (FNS) aims for a leading international position for the Netherlands in 6G, the next-generation communication networks.

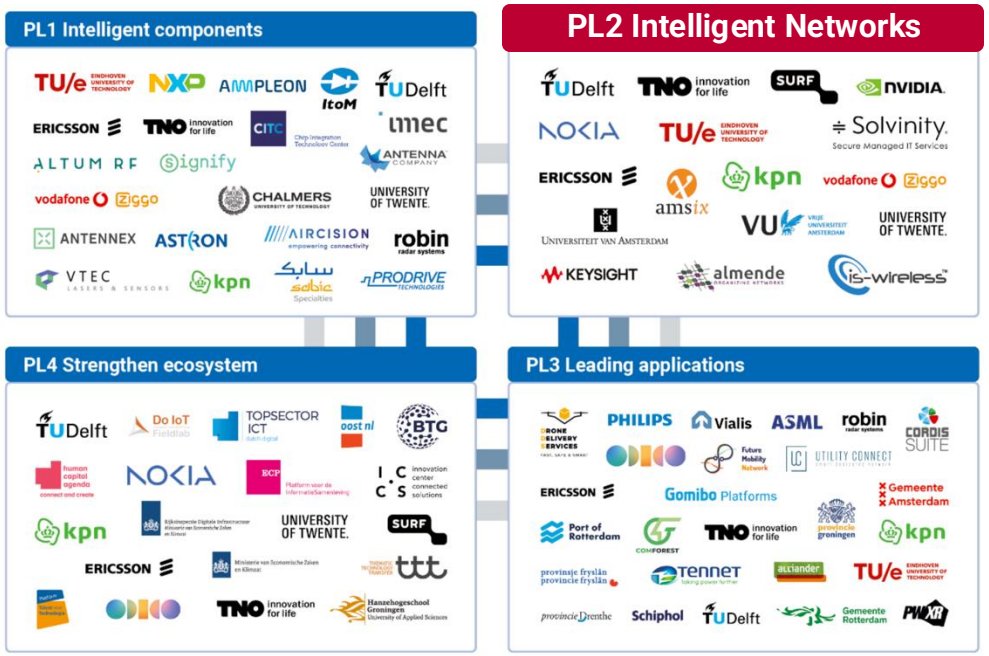


Figure 1: Consortium partners FNS

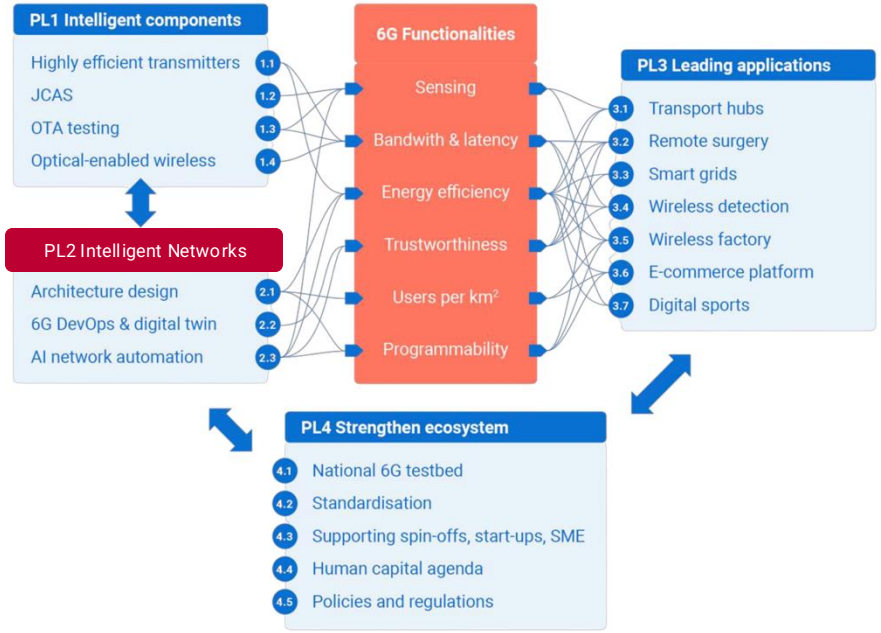


Figure 2: FNS Program lines and work packages

This work is funded by the Dutch 6G flagship project:

https://futurenetworkservices.nl/en/

Table of Content

What is a Digital Twin?

The initial definition:

*"a **virtual product model** capable of reflecting and simulating the real-time state of its physical counterpart [1]"*

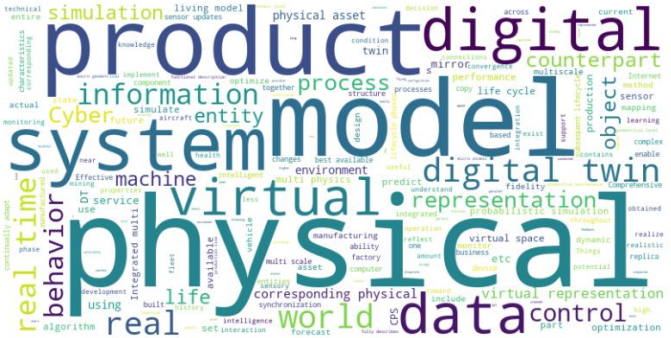


Figure 1: WordCloud from some existing definitions

Based on existing literature, we define Digital Twin as follows:

*A Digital Twin (DT) is a **virtual representation** that **maps** a physical object, system, process, or an intricate combination of these elements at certain levels.*

*It enables **bidirectional synchronization** between **the physical and digital realms**, allowing for seamless information exchange and simulation of physical behaviors.*

*It is developed to **achieve further objectives** by utilizing its functionalities (such as prediction, optimization, control, etc.).*

[1] Grieves, Michael. "Digital twin: manufacturing excellence through virtual factory replication." *White paper* 1.2014 (2014): 1-7.

What is a Network Digital Twin?

Network Digital Twin (NDT) builds on the concept of DTs to create a virtual representation of the physical objects of a telecommunications network.

Figure 1: An illustration of Network Digital Twin [1]

[1] Keysight, The Digital Twin Technology Applied to 5G/6G Communication - Evolution, Applications and Architectural Integration

DT Reference Architectures

Implementing an Network digital twin system is CHALLENGING.

A standardized framework should be:

- **Detailed and elaborate**
- **Tailored for next-generation network**
- **Scalable and extensible**
- **Practical**

Investigation of existing DT architecture is needed.

Existing Reference Architectures

Existing (Network) Digital Twin architectures vary in focus, key components, and applications.

For example:

- simulation and emulation aspects;
- life-cycle aspect;
- Layered framework based on key characteristics

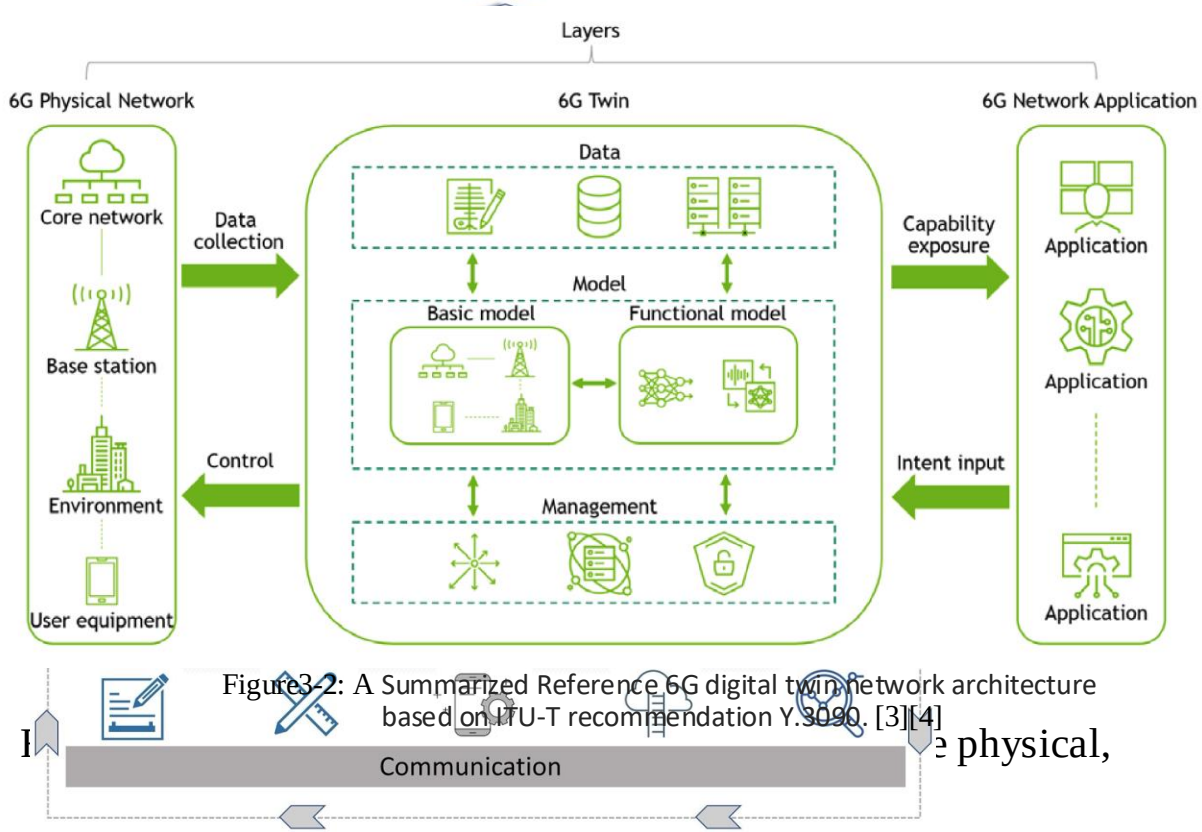


Figure 3-2: A Summarized Reference 6G digital twin network architecture based on ITU-T recommendation Y.3090. [3][4]

I[illegible]e physical,

LD focuses on the cyber [illegible]

Figure 2: A five-layer architecture in the DT as a service aspect and life-cycle aspect, where digital part is devided in three layers: communication, digital and cyber layer [2]

[1] da Silva Mendonça, Rafael, et al. "Digital twin applications: A survey of recent advances and challenges." Processes 10.4 (2022): 744.
[2] Aheleroff, Shohin, et al. "Digital twin as a service (DTaaS) in industry 4.0: an architecture reference model." Advanced Engineering Informatics 47 (2021): 101225.
[3] Xingqin Lin, Lopamudra Kundu, Chris Dick, Emeka Obiodu, Todd Mostak, and Mike Flaxman. 2023. 6G Digital Twin Networks: From Theory to Practice. Comm. Mag. 61, 11 (November 2023), 72–78.
[4] ITU-T, "Digital Twin Network – Requirements and Architecture," Recommendation ITU-T Y.3090, Feb. 2022.

Existing reference architectures:

Minus

- (-) Broad and general in scope
- (-) Weak link between theory and practical application
- (-) Limited focus on next-gen networks
- (+) Lacks detailed explanations

Plus

- (+) Basic layered design
- (+) Emphasize interaction and feedback
- (+) Service-oriented approach

Thus, we proposed an architectural framework to fill the gap.

Why Our Architecture?

6G NDTs System Architecture

Based on ITU-T recommendation Y.3090, Network Digital Twin should contain:

- **Interface**
- **Model**
- **Data**
- **Mapping**

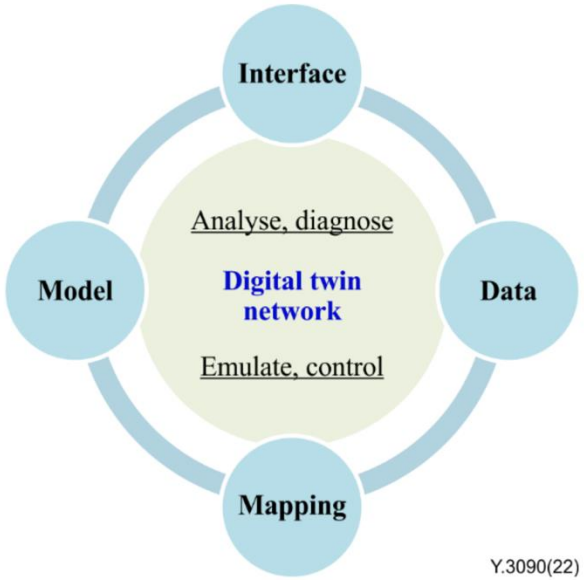


Figure3-1: Key characteristics of a network digital twin from ITU-T Y.3090

6G NDTs System Architecture

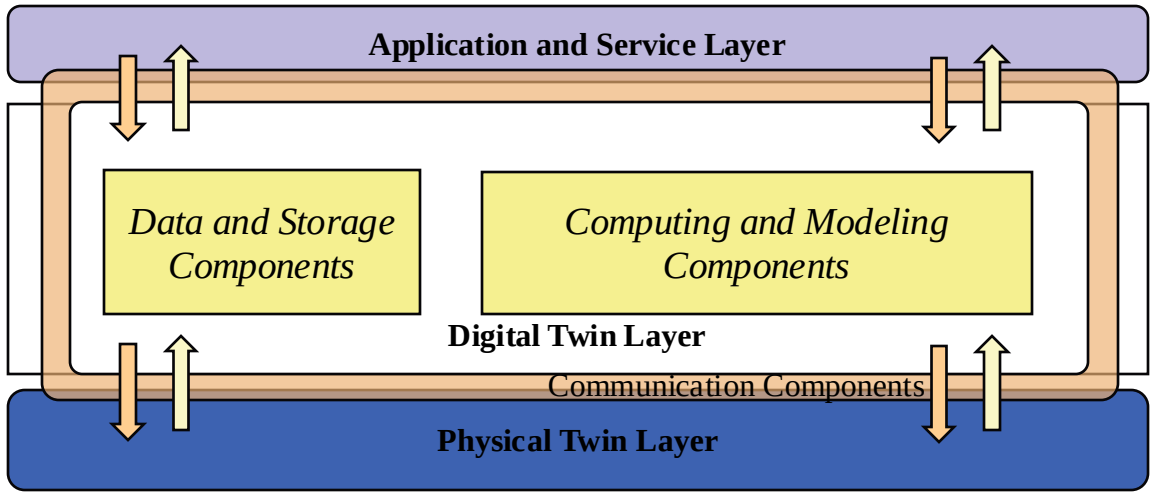


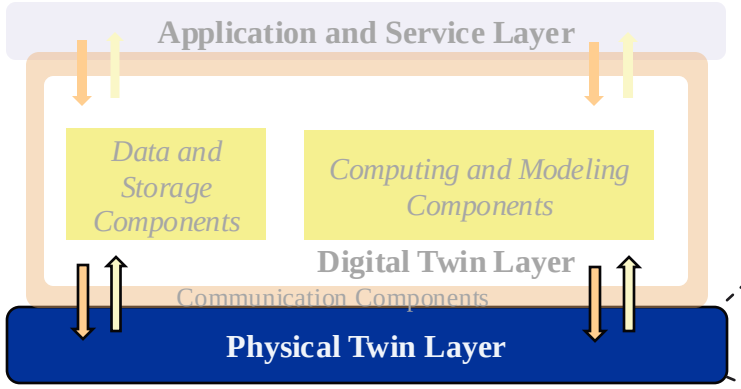
Figure: A three-layer high-level 6G NDTs system architecture, inlcuding Physical Twin, Digital Twin, and Application and Service Layer

Our Architecture:

- **Physical Twin Layer**
- **Digital Twin Layer**
- **Application and Service Layer**

6G NDTs System Architecture

- **Physical Twin Layer**



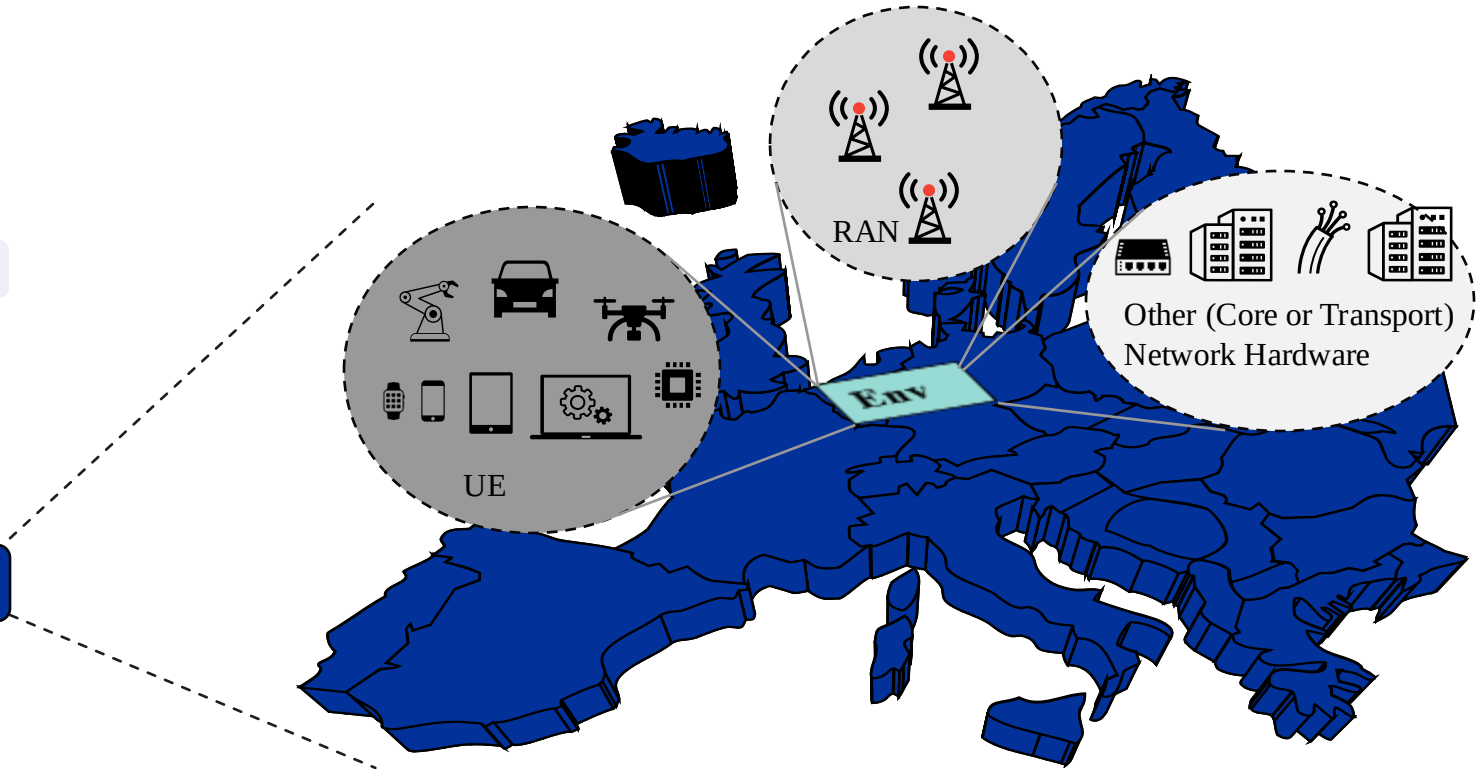


Figure: Physical Twin Layer,

including network devices and environment

6G NDTs System Architecture

- **Digital Twin Layer**

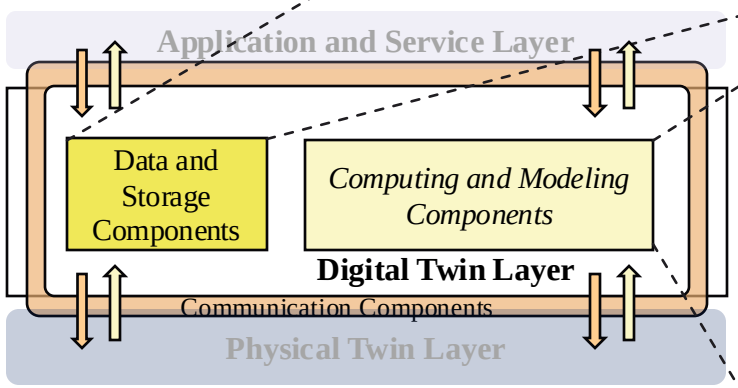
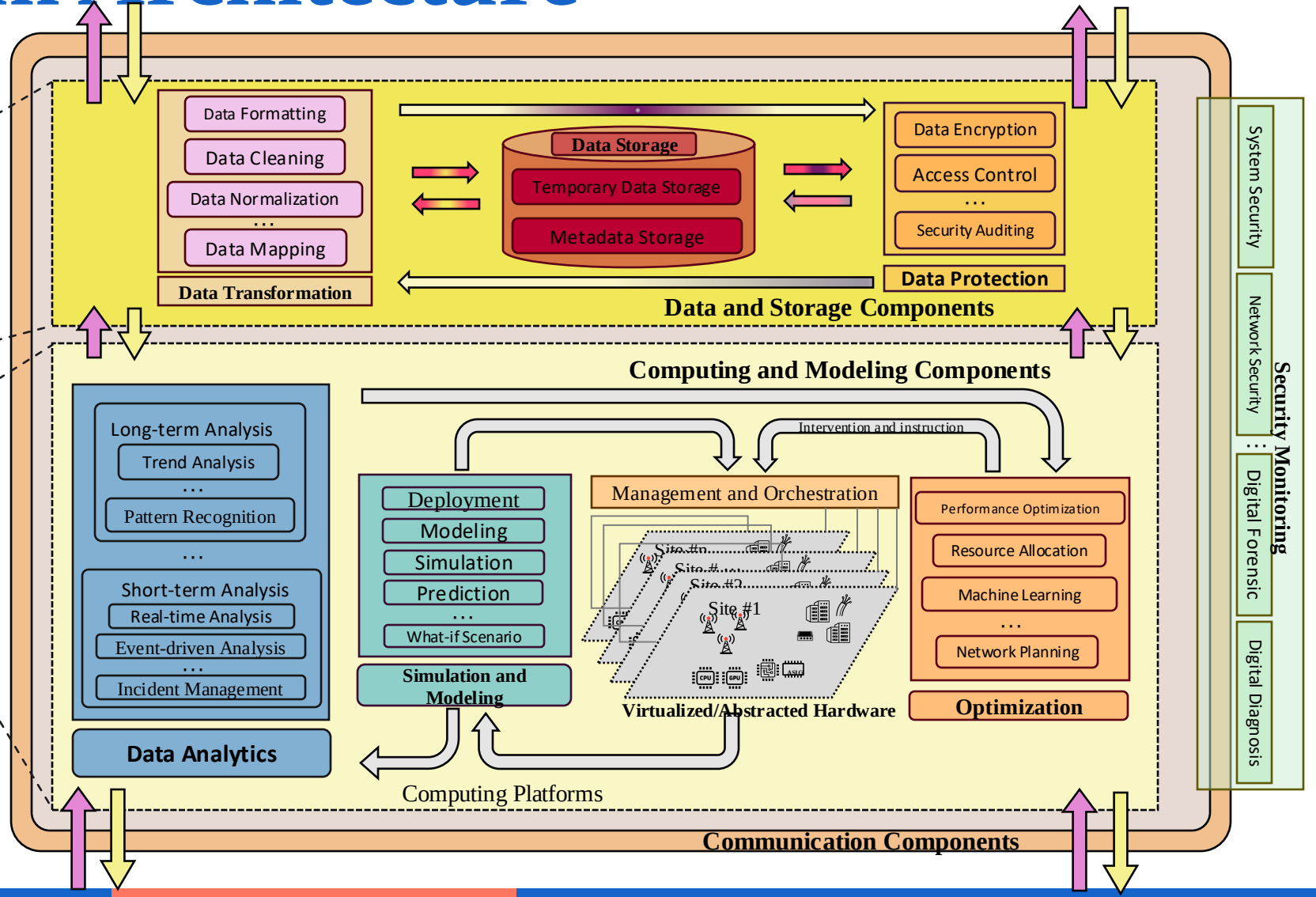


Figure: Digital Twin Layer, with Communication, Computing and Modeling, and Data and Storage Components (the composition is omitted in the figure)



6G NDTs System Architecture

- **Application and Service Layer**

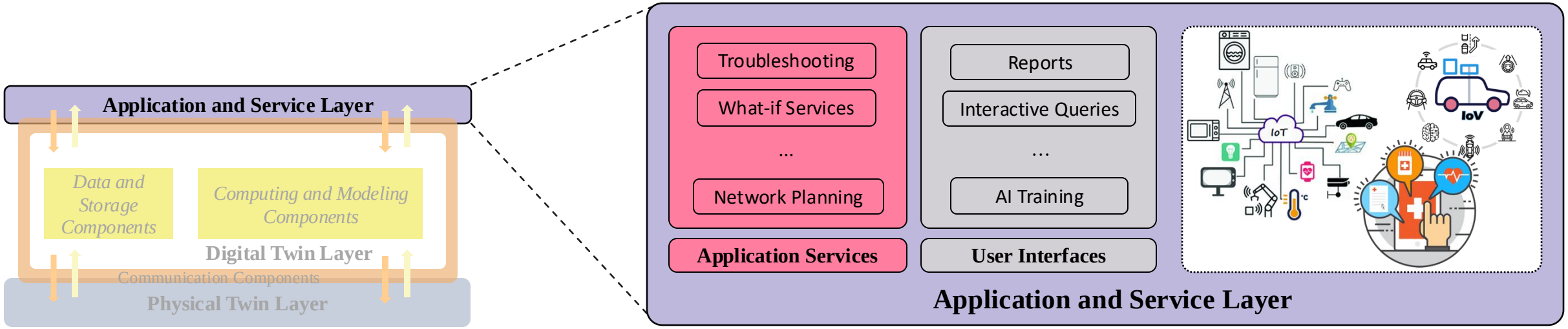


Figure: Application and Service Layer

1. Network Design and Planning
2. Network Optimization
3. Energy Optimization
4. Network Automation
5. AI training
…

Benchmarking Some Existing Simulation Tools

Why the benchmarking is necessary?

Experimental Setup

Key insights from Benchmarking?

Why the Benchmarking is Necessary?

- The Digital Twin Layer is the core of the NDTs system architecture
- Simulation can contribute to Key functions (e.g., optimization, prediction)
- Lower resource consumption allows complex analyses and more data generation
- Scalable, extensible tools adapt to future changes

Experimental Setup

- **Objective**: Measure resource usage and scalability of simulation/emulation tools;
- **Test Scenarios**: Each nodes exchange UDP datagrams for traffic and communication;
- **Network Configuration**: Dynamic setups with different complexity levels;
- **Test Environment**: Containerized environment ensuring consistency and isolation across all experiments;
- **Metrics**: Virtual Memory Resident Set Size (VMRSS) and CPU usage

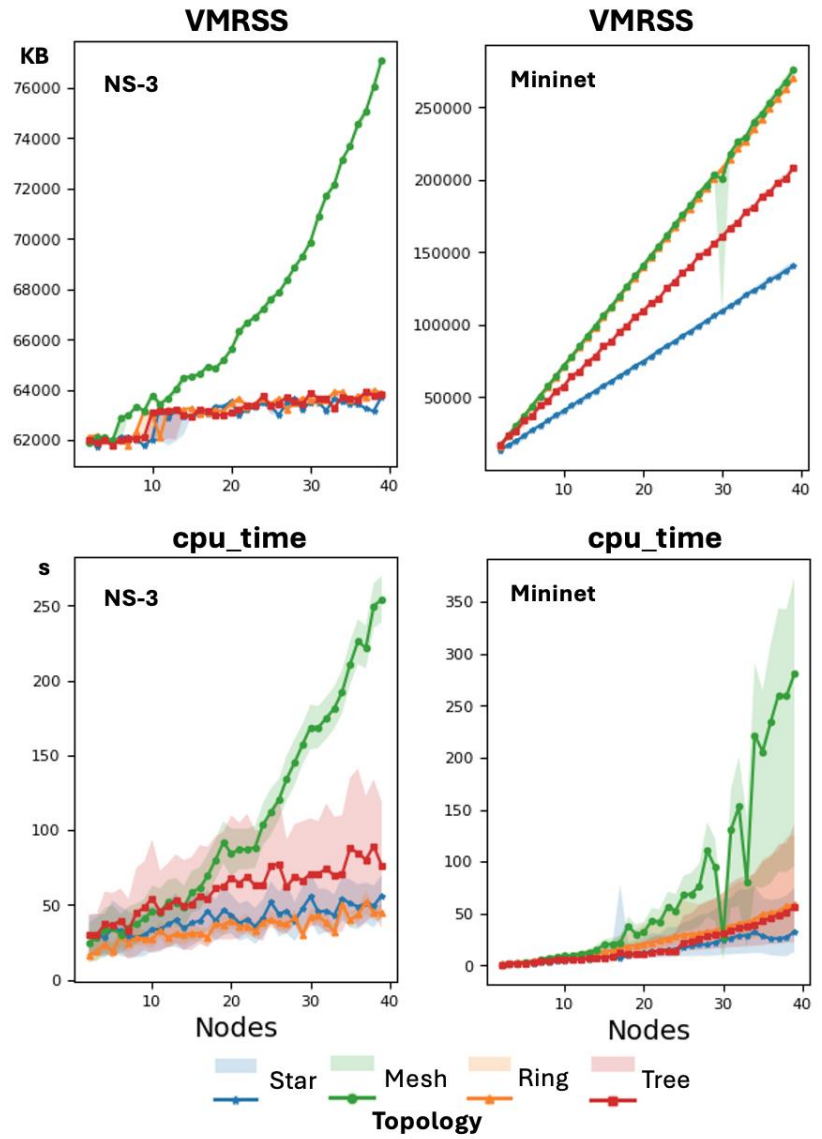
Experimental Result

Complex network structure:

- Simulators and emulators need more CPU and memory for complex data and behavior.
- Additional resources are needed for extra nodes and connections.

Increased network scale:

- More nodes and connections increase CPU and memory usage.
- Larger networks require handling more data flow and interactions.



Experimental Result

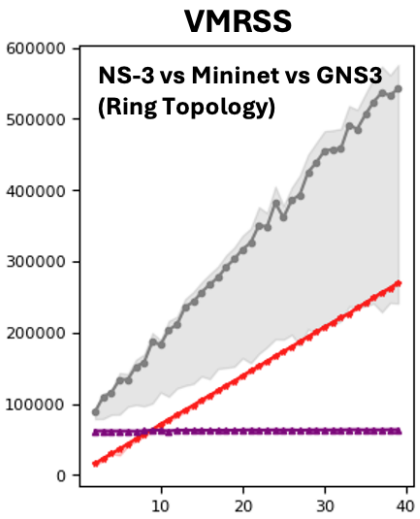
Simulators:

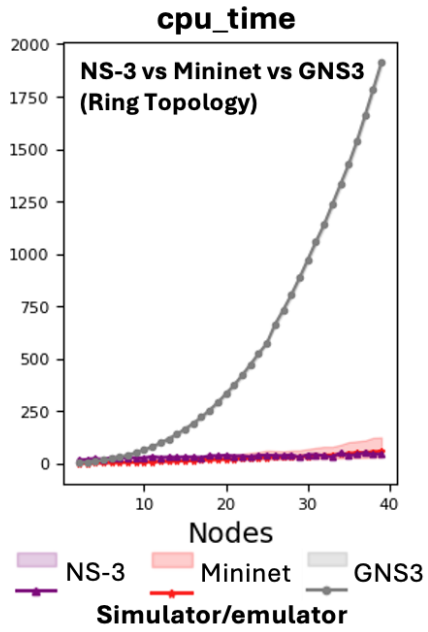
- Resource-efficient with **lower CPU/memory use**, **ideal for large, scalable systems**
- **Higher memory demand** as network size grows

Emulators:

- **Higher fidelity** but require **more computational resources**
- **Stable resource usage** in dynamic networks
- Virtualization-based emulators (e.g., QEMU, VirtualBox) need significantly more CPU/memory for detailed OS and hardware replication

		CPU	Memory	CPU Stability	Memory Stability	Scalability
Simulators	NS-3	Low	Low	Low	High	High
Emulators	Mininet	Medium	Medium	Medium	Medium	Medium
	GNS3	High	High	Medium	Low	High





Take Away Points

1. Digital Twins are essential for network optimization
2. Multi-layer architectures are fundamental
3. Composibility and scalability are critical
4. Tool evaluation highlights the need of resource efficiency
5. AI and automation are the future focus

Our Future Work & FNS innovations

AI/ML-Driven Optimization and Control:

- Apply AI/ML techniques to optimize digital twin performance.
- Develop control systems to manage digital twins in 6G contexts dynamically.
- Leverage Generative AI to synthesize network patterns and insights.

Framework and Mechanism Development:

- Define the structure and key components for Digital Network Twinning.
- Develop mechanisms to integrate with 6G-specific applications.

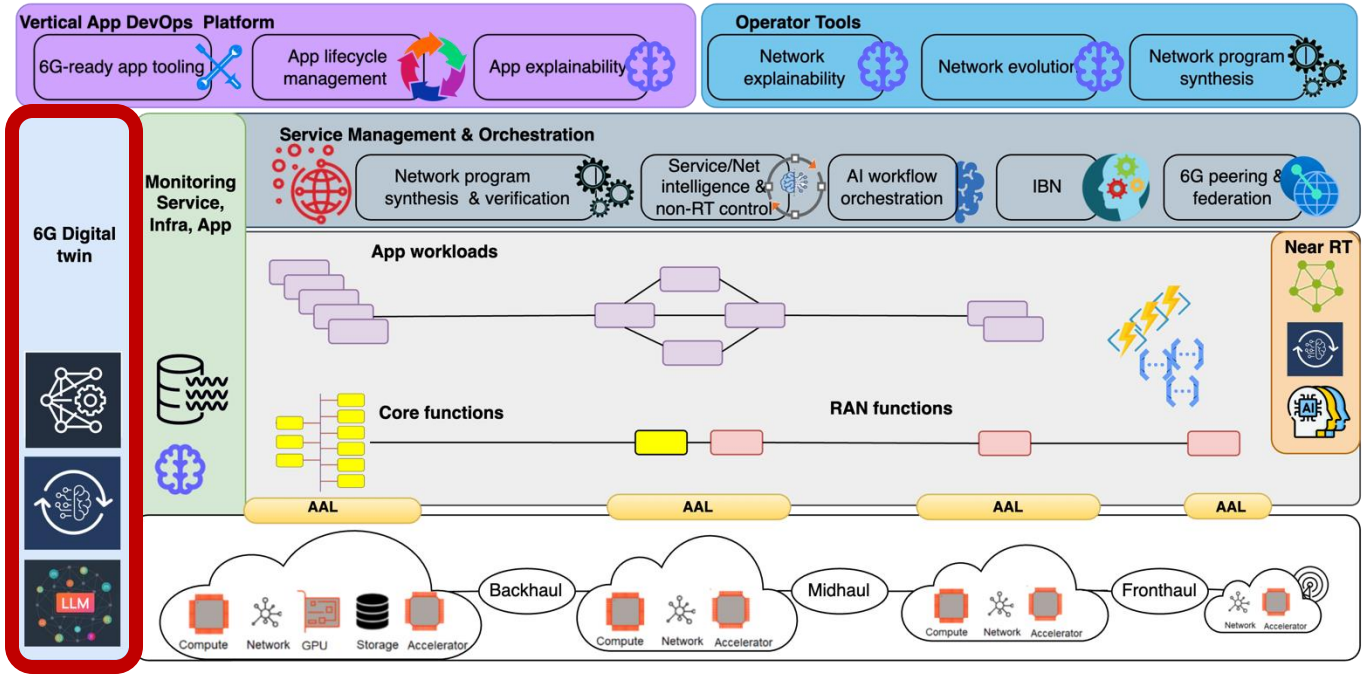


Figure 1: FNS innovations and our position [1]