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Abstract

With the support of artificial intelligence, the digital transformation through the lens of a Digital Twin has been emerged in many industries such as manufacturing, oil and gas, construction, bio-engineering, and automotive. However, concept of Digital Twins remains relatively unexploited for 5G/6G networks, despite the obvious potential in helping develop and deploy the complex 5G environment. These deliverable studies the current State-of-the-Art regarding Network Digital Twins and discusses the open challenges that will enable Digital Twin solution to be applied as tool to fulfil the potential of 5G networks and beyond.

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List of Acronyms

SoA: State of the Art

SDO: Standards Development Organization

DT: Digital Twin

ICT: Information and Communication Technology

5G: 5th Generation technology

IoT: Internet of Things

HW: Hardware

MEC: Multi-access Edge Computing

NPN: Non-Private Networks

AI: Artificial Intelligence

ML: Machine Learning

AAS: Asset Administration Shell

IEC: International Electrotechnical Commission

CU: Central Unit

DU: Distributed Unit

ACME: Automated Certificate Management Environment

CPO: Charging Point Operators

AR: Augmented Reality

VR: Virtual Reality

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Executive Summary

This document elaborates the existing State-of-the-Art regarding the applicability of Digital Twin concept for operator networks. The analyzed SoA is used to define existing challenges that 6G-EDGEDT-01 project will address. The results from this deliverable will be later on used to extend the initial architecture that is defined in 6G-EDGEDT-01-E5.

The main results described within the deliverable are:

- the definition of the main existing gaps in the State-of-the-Art,
- the definition of the possible contributions of the project with respect to the gaps in different SDOs,
- the description of the existing State-of-the-Art in Digital Twins for operator networks.

This subproject is oriented towards the adaptation of the Digital Twin concept in hyper distributed edge for operator networks. The architecture that is initially developed in 6G-EDGEDT-01 will be extended in this subproject to include the concept of Network Digital Twin.

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1. Introduction

The rapid advancements in Information and Communication Technology (ICT) are transforming telecom sector towards a full digitalization and integration concept. This transformation enhances telecommunication systems with the ability to make decentralized and autonomous decisions using Cyber-Physical Systems (CPSs) [1]. Consequently, operators can improve the preventive maintenance programs, next generation of business models and maximize the products sustainability and efficiency in the field. CPSs are the main linchpin for the operator's networks to move towards a fully automated infrastructure that relies on real-time capabilities, distributed control systems, virtualization, service orientation, and modularity [2].

Digital Twin is defined as *a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision-making* [3]. This concept truly embodies the cyber-physical integration helping to create comprehensive digital models of physical environments with full support for two-way communication between the digital model and the physical object to enable real-time engineering decisions. The digital operator network includes geometrical and virtual models of tools, network equipment, operatives, products, etc., as well as behaviours, rules, physics, and analytic models. The outputs of the Digital Twin processes are executed in the real operator network to improve the physical object performance [4].

The adaptation of Digital Twin in the operators network is inseparable from recent advances in ICT, such as 5G and supporting technologies. 5G networks are architected to simultaneously support different types of service profiles in the shared infrastructure, such as enhanced Mobile BroadBand (eMBB), massive Machine Type Communication (mMTC) and Ultra-Reliable Low Latency Communication (URLLC). Together with the Edge computing, they provide a communication link with low end-to-end (E2E) latency, low jitter, and localization awareness. In the next 10 years it is expected that operator networks will enable big global economic output and support more then 22 million jobs worldwide [5]. The manufacturing sector is expected to be largen beneficiary in this economic activity, while ICT is the second one. Despite all the promises, customers and investors still remain sceptical about the prohibitive complexities that come with the onsite operators' networks deployments especially in multi-vendor scenarios and with the diverse security risks. The security risks are essential in minimizing the risk for life-critical manufacturing or robot doctor applications. Some of the open questions that exist are:

1. How to provide dynamic and flexible testbed facilities with high availability?.
2. How to improve the deployment time of new ICT technologies?.

In this sense, the cyber space mirrored through Digital Twins arises as the perfect playground for to create virtual models that will replicate the complete operator network ecosystem and help address all the above-mentioned challenges to satisfy the end user needs. Using Digital Twins for networks has recently gained significant attention from the leading telcos (e.g., Ericsson [6] and Huawei [7]), being an emerging topic where sensor/network data, traffic data, data mining, data visualization, and

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data interpretation are integrated into one system to facilitate the live replica of a process or whole network. The Digital Twins has the potential to assess the performance, predict the impact of the environment change, and optimize the network processes and decision making accordingly. Consequently, this project presents a concept of cloud-native DT for operator networks, aiming to perform continuous assessment, monitoring, and proactive maintenance through the closed-loop feedback mechanisms. The control-loop starts with the physical network nodes sending information and its current state to the digital models, which then closes the control-loop by sending back optimization decisions in real-time into the living network. In doing so, the physical network become software-enhanced entity that incorporate self-management capabilities and respond quickly to changes. In this way, cyber-physical integration is achieved, providing a new set of tools to monitor, control and predict behaviours and to accurately optimize the network.

2. SoA analysis including related standards and existing challenges

This section provides detailed analysis of the existing SoA that contributes towards the definition of set of challenges that will be addressed to design the extension of the initial architecture covering the concept of Network Digital Twin. In this section we describe: i) Existing challenges based on the SoA that need to be addresses, ii) gaps and contributions of the project in related standards and iii) related works in Network Digital Twins.

2.1. SoA analysis and existing challenges

This project aims to realize an innovative, highly efficient, trustable network and computing ecosystem consisting of interconnected, computing communities (e.g., ad-hoc clouds) and supporting distributed services. By creating efficient mechanisms for leveraging locally generated data, along with the resources available across the IoT-Edge-Cloud continuum, this project will enable the development and seamless integration of network digital twin applications and services by third parties. Key challenges and advancements that this project will need to address are:

- *Challenge 1: Data-driven network as a service*

The orchestration of operator network operations and processes is a challenging step in the realization of the Network Digital Twin vision, involving the collection of semantically connected multi-source/-scale/-variant data across network. In addition, data analytics, multilevel simulation and process optimization techniques are required to allow operators to retain the control of the information flow and select appropriate actions that curb the impact of disruptions and maximize operational efficiency. For example, [8] proposes a SW controlling mechanism for data-driven service orchestration in future manufacturing environments and presents the main architectural elements that compose such a controller. [9] studies a data-driven optimization of manufacturing capabilities, processes, and services by adjusting manufacturing resources on the service call chain and improving the manufacturing capabilities of the resources. [10] outlines a data-driven service-orchestration

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approach as a foundation stone in the integration of different services that can deliver SW architectures for a smart manufacturing environment. However, these and other literature works address smart manufacturing and moreover they address they provide a single point of view, i.e., trying to chain and orchestrate existing services on the plant floor and in the back-end of manufacturing enterprises.

This project will instead enable a holistic view of the whole infrastructure, encompassing both the wireless connectivity and the production system. It will thus strive to realize a momentum shift from the deployment system defined by HW and logistics constraints, to one that is largely defined by SW. Through the virtuous cycle monitor-analysis-plan-execute, the operator network supported by the development provided in this project will converge to the optimum: it will autonomously monitor, tune, self-optimize and evolve to become more efficient, robust, intelligent, energy-saving and responsive. This project will strive to move from a reactive (multi-)feedback loop-based system to a more proactive – anticipating required tunings before they are actually required – approach of network digital twin service orchestration.

- *Challenge 2: Open and Secure Edge*

Secure, trustworthy networks and services are a fundamental prerequisite for the development and exploitation of the Edge [11][12][13][14] for building the Network Digital Twins. As highlighted in[15][16], distributed edge systems may be vulnerable to privacy leaks, denial of service attacks, function manipulation, and injection of malware, or false data. Passive mechanisms, like data encryption and isolation, cannot successfully address such vulnerabilities in distributed systems where data/services need to be shared between ad-hoc clouds and across the IoT-Edge-Cloud continuum [14]. It follows that in many cases it is not possible to use the emerging MEC security policies or traffic isolation and software-defined segmentation techniques, which aim at reducing the attack surface [17][18]. Current trust management approaches [13] still cannot scale to large quantities of connected nodes, while guaranteeing low latency or ensure interoperability across heterogeneous networks.

This project will realize a trustworthy meta-OS among actors in diverse application environments by leveraging open standards and - where applicable – open-source solutions. It will develop mechanisms for: i) attesting the identity and trustworthiness of the Edge nodes and devices, and the applications executed on top of them; ii) distributed user authentication, which is the foundation to enforce proper security policies and write meaningful traces (e.g., for audit or forensics analysis); iii) monitoring and verification of both software and node integrity in distributed virtualized environments; iv) container-based application protection, thus preventing unauthorized privilege escalation from container to host; v) protection against the aforementioned attacks to which IoT-based distributed systems are vulnerable, without significantly increasing latency or computational load.

- *Challenge 3: Secure and reliable wireless and wired operator process communications*

The advent of 5G and ubiquitous wireless coverage has far-reaching implications on the possibility of replacing (at least part of) the existing operator facilities wired infrastructure with its wireless counterpart, while providing the same service level and guarantees. A common framework for wired operator process communications is thus needed, i.e., one that relies on a dense mesh of communication technologies that are integrated and cooperating into a smarter, more efficient whole, in connection with the wireless networks available. With more complex devices being connected there is a greater chance of possible vulnerabilities for a data or security breach. Since security and privacy have received little attention in wired manufacturing process communications, there are few strong data protection standards or protocols specifically developed for this purpose. Security and privacy concerns (e.g., data leakage) are thus major obstacles for the sharing of data in an Industrial Internet of Things (IIoT) wireless network. In [19] a protection method that satisfies differential privacy to protect location data privacy is proposed, without reducing much utility of data in IIoT. In [20], authors integrate blockchain into edge intelligence for resource allocation in IIoT. [21] formulates the data sharing problem into a ML problem by incorporating privacy-preserved federated learning, preserving the privacy of data by sharing the data model instead of revealing the actual data. They also integrate federated learning in the consensus process of blockchain.

This project will implement secure data distribution between data collection and processing points deployed at edge and cloud locations, aiming at developing and using standardized data and distributed computing mechanisms. For this purpose, it will leverage security gateways, zero-touch management of 5G NPN services deployed at the edge, thus delivering secure networks with IP convergence, and secure wireless/radio networks. These will have to be coupled with secure automation and control systems.

- *Challenge 4: Develop a scalable, open, flexible, and inter-operable DT leveraging AI/ML mechanisms for predictive quality, predictive maintenance, and operational performance*

Digital twinning is seen as a key mean in providing flexible testbed facilitating the deployment of new 5G technologies to carry out operational predictions and enforce optimized decisions into the living network and associated services. The quality of every physical network entity degrades over time, thus affecting its performance. Early detection of failures may promote on-time maintenance, fatigue avoidance, as well as time and cost savings. By combining DTs with AI/ML driven analytical efforts, operators can adopt advanced practices such as predictive maintenance and decision-making rooted on real-time and historical data. In Industry 4.0 [22] is such example taht proposes a manufacturing cell DT to optimize the dynamic scheduler for smart manufacturing. An intelligent scheduler agent, called digital engine, was developed, and trained for optimization using deep reinforcement learning algorithms. [23] performs a geometric optimization of centrifugal impeller (CI) by collecting features, such as meridional section, straight generatrix vectors, and set of streamlines, from both the physical and CAD-based digital model of the CI. However, with the improvement in machinability, the DT-based geometric optimization reduces the aerodynamic performance. Thus, the best model for the CI is selected by training the deep deterministic policy gradient reinforcement learning model [24]. [25] designs a deep learning and cyber-physical system-

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based DT (DTDL-CPS) architecture for smart manufacturing, that can be used in shop floor optimization, fault diagnosis, product design optimization, and predictive maintenance.

Through the integration of distributed AI/ML tools leveraging edge computing platform, this project will enrich the DTs explored in the proposed use cases by collecting data from heterogeneous sources in interoperable formats, thus reducing network traffic and latencies for ML tasks, by evaluating the degree of data reduction that can be achieved at the edge without a significant impact on the ML task accuracy. The DT will thus be able to detect, optimize, and take decisions dynamically based on physical network entity data and/or digital twin data. Additionally, simulation and prediction models will be organically developed. Data from all product lifecycle stages will be collaboratively managed and (if required) stored either in the on-premises edge, thus keeping the data always in the client network, or in cloud servers, possibly leveraging Federated Learning techniques.

Asset Administration Shell (AAS) is an enabler of DT, standardized within the scope of the International Electrotechnical Commission (IEC), and an organization called "Industrial Digital Twin Association" established by ZVEI and VDMA to drive the implementation of AAS. AAS is used to describe an asset (e.g., SW, HW, device, person) electronically in a standardized manner. Its purpose is to exchange related data among industrial assets, and between assets and production orchestration systems or engineering tools through a common standardized semantic. Therefore, AAS provides interoperability among I4.0-capable devices in a factory environment.

The implementation of the AAS can be based on OPC UA and include existing Companion Specifications and extended information models. Any device as well as the 5G network are equipped with an AAS that can communicate with each other. AAS includes a concept of sub-models, each of which characterizes an asset by describing its aspects in different domains such as identification, communication, engineering, safety, security, lifecycle status, energy efficiency, health status, etc. Each sub-model is described by several properties defined by a unique global identifier and a set of well-defined attributes.

This project will develop 5G Network AAS to enable interoperability and automation in management of 5G NPN and provide required 5G AAS submodels to existing 5G-capable devices to realize automated network adaptation for each device needs. The AAS instances will be integrated into the network, devices as well as the AI/ML tools so that they can provide vendor-agnostic interfaces.

2.2. Gaps and contributions in related standards

As of today, this project plans to contribute towards seven SDOs related gaps as described in the following:

3GPP

- **SA1:** Contribute with providing new distributed approaches for Smart Grid domain.

- **SA3:** Architectural considerations for sharing telemetry information to external entities, as well as architecture enhancements for tactile and multimodality communications services.
- **SA5:** Exposure of network and management capabilities through APIs in a controlled, secure, and auditable way.
- **RAN2:** Telemetry information gathering for radio resource control purposes for e.g., constraint devices (aka IoT-Edge-Cloud continuum).
- **RAN3:** Architectural considerations for CU/DUs enabling telemetry interfaces serving AI algorithms for traffic treatment.

ETSI

- **MEC:** Contributing to Edge architecture, platform federation and security. Contributing to new working item on MEC on constrained devices.
- **ZSM:** Contributions of Zero-touch service management, multi-domain, and closed-loop automation.
- **ENI:** Contributing to meta and context definitions for policies driving the closed-loop AI mechanisms.
- **SAI:** Security of AI. Contributing towards securing AI access to data.

IETF:

- **COINRG:** Contributions on how the hyper-distributed edge can be applied for computing in the network.
- **ACME:** Use of ACME standards for Automated certificate management. Contribution of new profiles for the IoT-Edge-Cloud continuum.

NGMN-Cloud Native: Contributing experiences, requirements, and visions about enabling the IoT-Edge-Cloud continuum by mobile telecommunication networks.

GSMA-OPG: Contributions towards the alignment of the continuum view with the ongoing telco-cloud platform initiatives.

EVRoaming – OCPI: Contributions of new approaches towards non-centralized solutions of eMSPs and CPOs.

IEC-TC57: Contributions of new distributed approaches to the management of power systems.

2.3. Network Digital Twin

The evolution of the operator networks towards realization of large capacity and small distance communications, go beyond best effort and high-precision communications and converged multitype communications [26]. Thus, the new operator networks may face additional challenges than the once introduced in the introduction that include security, spectral efficiency, intelligence, energy efficiency, and affordability. The implementation of Network Digital Twins has the possibility to overcome the above challenges. The Network Digital Twin can enable the new operator networks to finally execute innovative services, e.g., AR/VR, autonomous driving. The virtualized operator

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network will gather traffic information on the entire end-to-end network and use data analytics techniques to discover network traffic patterns and detect abnormal traffic behaviour. The physical operator network uses the information fed back from the virtualized network to prepare in advance to improve network security. In addition, by collecting and analysing the communication data in the network, the rules of communication can be discovered to automate demand and provide services on demand. Since the communication demand can be predicted in advance, it can feed back to the operator network to reserve resources, such as spectrum resources.

The appearance of Network Digital Twin brings the opportunities in overcoming the security, spectral efficiency, intelligence, energy efficiency, and customization in the operator network, while reshaping and accelerating the development of the network. There have been studies combining Network Digital Twin and networks. For instance, to increase the higher capacity wireless communication links in the network, the authors propose Network Digital Twin for meta surface reflector management in Terahertz communications [27]. DT is used to model, predict, and control the signal propagation characteristics of an indoor space to maximizes THz signal-to-noise ratio (SNR) in the system. In [28] the DTWN was introduced that incorporates DTs into wireless networks to migrate real-time data processing and computation to the edge plane. DTWN uses DT to mitigate the unreliable and long-distance communication between end users and edge servers in the operator network. The integration of DT and operator networks bridges the physical system with digital space and enables robust wireless connectivity. In addition to building a virtual model of the operator network, DT can be used in the effective management of mobile cell towers, particularly for those in remote locations and hard to maintained [29]. Remote sensors can collect a range of data, on aspects, such as proximity, temperature, motion, and position with tower. According to these data a virtual tower can be set up, which can then be analysed using data processing algorithms to management the tower.

3. Extension of the general system architecture

The studied SoA and defined challenges in this deliverable will help us in extending the initial architecture that was designed in 6G-EDGEDT-01-E5. However, due to the delayed start of the work with the subcontracting companies (at the time of writing of this deliverable only ONB has signed the contract with UC3M and it was signed in November 2022) we didn't get the opportunity to properly design the extension of the initial architecture that will be compliant with the rest of the partners in the project. For this reason, we scoped this deliverable around the State-of-the-Art study and the definition of the existing challenges that need to be addressed while designing the architecture extension. In the next deliverable (6G-EDGEDT-03-E6), we will provide the initial and refined design of the architecture extension.

4. Summary and Conclusions

This deliverable provides study of the existing SoA that needs to be considered when defining the extension of the overall system architecture proposed in the 6G-EDGEDT-01 that is under the scope

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of this project. First, the deliverable specifies the exiting gaps in the SoA from system point of view, defining a set of challenges that this project will address. Next, this deliverable specifies the identified gaps and possible contributions with respect to seven related SDOs of the project. Finally, this deliverable provides the related works with respect to the Network Digital Twins that are available up to this date.

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