Network Digital Twin for Non-Public Networks

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***Abstract*— Digital Twin concept is one of the technologies that is being applied in different areas, especially for lifecycle product management in industry environments. Recently, Digital Twin became a trend in network planning, management, operation, and optimization as it demonstrated its value in managing complex systems, and for that reason it can be a disruptive technology for the future generations of communication networks. In this work we propose a Network Digital Twin to improve experimentation and verification frameworks, to reduce the lead time required for validating a new business use case using 6G technology. We describe a concrete use case, a Digital Twin of the private part of a Non-Public Network and how Digital Twin concepts helps to improve the deployment time and the observability of a new network segment, integrated with existing experimentation facilities.**

Keywords*— *digital twin, network digital twin, non-public networks, experimentation facilities, 5tonic.

I. Introduction

Digital Twin (DT) is a growing technology that promises to change the future of the Industry 4.0. Although the basic idea of DT was present since time ago, the first real use case of DT concept was introduced by M. Grieves, when he proposed to apply it to product lifecycle management in manufacturing [1]. Since then, the DT concept is being applied to the I4.0 digital transformations in several areas, enabled by the developments in Artificial Intelligence, security, cloud environments and low latency communications.

In parallel, the evolution of the mobile networks (5G and now Beyond 5G) promises better performance and for that, private wireless networks have been integrated in the communication processes of the industry, to provide mobility to the industry elements and/or to improve the deployment of the new components into the industry premises. Beyond the improvement in performance, the 5G networks introduces interesting new concepts that helps in the integration into Industry 4.0 communication. For example, using the Control/User Plane Split (CUPS), the Network Slicing and the local and central concurrent access to services [2], the private networks are evolving into 5G non-public networks, with different deployments options [3] and integrations with public networks. The addition of Network Slicing allows to create logical networks to serve to a specific business purpose.

From the convergence of both worlds, Digital Twin and 5G networks, we have the Network Digital Twin (NDT), where we apply DT concept to different use cases of mobile network: from R&D to network operation (management, deployment and site engineering)[4]. It is correct to say that most of the elements required to build a digital twin from network entities are already present in the Communication Service Providers (CSPs), as OSS systems that collects, analyze and modify information from the networks entities but it is also true that the DT concept introduce a unique framework that combines traditional OSS elements with the newest technology AI-based analysis and behavior models. Fig. 1 shows a proposal of high level architecture described in [4].

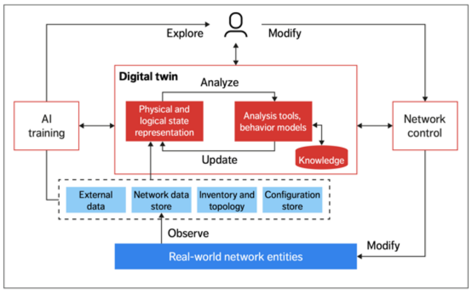

Fig. 1. A Network Digital Twin architecture(from [4])

In 5Tonic[5], an open research and innovation laboratory that focus on 5G technologies, we developed a portable non-public network (NPN) system following the deployment option of sharing the radio access network and the control plane[3] with the public network. The portable system, also known as *Carrito* (Fig. 2), includes all the elements for providing 5G SA NR radio access and the User Plane Function (UPF), including indoor and outdoor antennas. The portable system incorporates VPN capabilities that are used for the integration with the 5Tonic 5G Core Network, which acts as the public network of a CSP. This deployment has been demonstrated in different projects[6]–[8] and it is in continuous evolution for incorporating new technology (e.g. high bands).

In this work we propose to use the Digital Twin paradigm to create a Network Digital Twin of the private segment of a Non-Public Network, with the objective of improve an experimentation and verification facility to: (i) reduce the lead time of experimentation, by automatizing design, deployment, and integration of a new network segment into the existing facilities, (ii) improve the observability of the integrated network segments and (iii) prevent future network issues.

As described in [9], there are different definitions of what Digital Twin is. From all definitions of Digital Twin, we use in this work the following one: "(…) digital twins are software representations of assets and processes, which are enhanced with capabilities not present in the real-world entity." [10]. Using this approach, we present a novel application of the Network Digital Twin with the following contributions: (i) definition of the use cases of the NDT (Section IV), (ii) a proposal of architecture (Section V) that reuses existing standard interfaces for implementing the Digital Twin and (iii) experimentation results in 5Tonic laboratory.

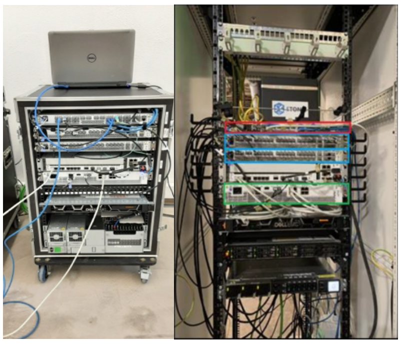

Fig. 2. *Carrito*, the NPN portable system, in different deployments

For driving the experimentation, we describe an example of NDT concepts applied to a real manufacturing use case, using the latest 5G technology in a non-public network integrated in an industrial environment and using existing experimentation facilities.

The rest of the paper is organized as follows. Section II contains the related work. In Section III we introduce an industrial use case that drive the NDT requirements. Section IV introduces the new Use Cases that our NDT supports. Section V propose an architecture for the NDT of the *Carrito*. Sections VI and VII describes the validation experiment performed using the NDT and finally we include in Section VIII our conclusions and future work.

II. Related work

For years, we have been involved in the development of experimentation facilities to help the experimentation and validation of business use cases using new mobile technology. In 5G EVE project, 5Tonic was integrated in a pan-European end-to-end facility for extensive trials [11][12], with fully automated workflows for experimentation [13] and successfully used for demonstrating industrial use cases [14]. Non-Public Network integration for industrial 4.0 use cases[15] has been explored[16] with satisfactory results. [3] describes different deployment options for Non-Public Networks.

Digital Twin paradigm applied to Network has been considered with potential to be the future of network planning, operation and management [17]. There are works that presents NDT for network planning [18], network management and optimization [19] . The relation of Digital Twin concept and 5G network is already discussed, for example in [20] and [21], where 5G and the edge-cloud continuum are explored, including their impact in the DT performance. Concrete services provided by 5G has also been explored, as for example Network Slicing provisioning for security [22].

III. Industrial Use case

For the research and developing of the Network Digital Twin we select industrial use cases, and we present in this work the Smart Manufacturing case.

Automation and control for industrial installations are based in programing blocks, which works as a sequence of commands and instructions that must be follow, to be able to carry out the automated actions and achieve the purpose of the machinery and at the same time ensure the safety in the installation. These programming blocks relay on inputs coming from different signals from the installation. To be able to execute the program without any error, these inputs must be received at the right moment (in-time flows) to active the subsequent sequences of the programs. This is the reason why determinism is critical to execute the program. All signals and commands needed to carry out the program must occur at the right moment, cannot be delayed, or lost, as if that would happen, this would create an error and the operation of the industrial installation would stop.

To be able to ensure this kind determinism, currently, industrial machinery leans, in one side in the industrial protocols, so signals and commands follow the correct order, and to wire input, (i.e., a sensor) to be able to ensure that the signals are transmitted at the right time, to the Program Line Controller (PLC). All this wire is a disadvantage to be able to have the need of flexibility and mobility required in a Smart Factory (i.e., as movement of assets or combination of machinery).

Therefore, to remove all the wires from an installation and have a wireless connection, the same level of determinism, reliability, and latency as when connected via wires is required and this is not possible with technologies that not implement time sensitives or determinism.

Added to this, industrial specific deterministic technologies are used, isolated from other networks to provide connectivity to the manufacturing process, including robots and conveyors. Among other problems, this isolated architecture forces the industries to rely on in-house network deployments and computing architectures, not been able to benefit from the latest innovations brought for example by 5G.

6G will be able to exploit the benefits of new technologies that will allow wireless access with deterministic characteristics to robots controlled in the cloud, using the innovations on disaggregated architectures.

This wireless access will enable concepts of flexibility, agility, and mobility for a manufacturing process, pillars for the Smart Factory. For this, it is needed to evolve the current concept of automated manufacturing installations.

Bearing in mind the possibilities that new technologies contribute to wireless connection, the PLC can be virtualized with a real-time connection in the cloud, using industrial protocols to ensure determinism. This architecture opens the possibility to re-think the design of industrial installations, so wires can be reduced/removed when needed, and to move the automation and control of the manufacturing line out of the installation, via wireless connectivity.

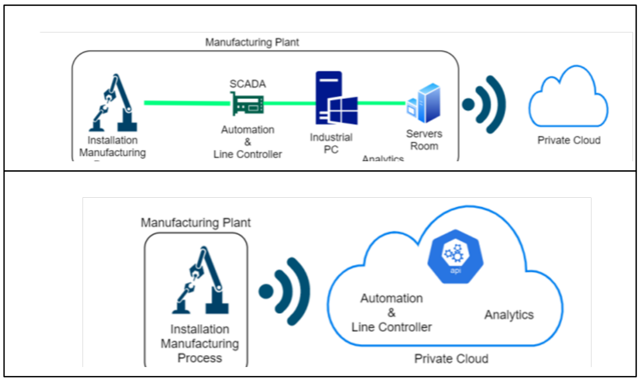

Fig. 3. Top picture shows the current network architecture in manufacturing plants. Bottom picture shows target Smart Manufacturing network architecture

IV. Network Digital Twin Use Cases

The potential of the NDT in mobile networks is broad and includes several areas of interest[10] and different applications. The main goal of the NDT of the *Carrito* is to minimize the lead times of experimentation cycles and to optimize the observability and predictability of the non-public network elements deployed abroad the main experimentation facility. Taking that in mind, we propose the following uses cases to be supported by the NDT: (i) intent-based configuration, (ii) performance checking, (iii) healthcheck using NDT and degradation forecast and (iv) edge (re)location.

In this work we present results related to the first use case, where we propose to use the NDT to process the end-user requirements for the use cases, expressed as intent-based and with that, and using its behavior models, express which are the best network configurations for supporting the experimentation of the use cases. As an add-on, we improve in the NDT the ability of configuring the *Carrito* with the best option for covering the requirements.

This solution proposed reduce the cost, in time and effort, of deploying new segments of non-public networks, as we will demonstrate in the results.

V. Network Digital Twin Framework

The Network Digital Twin presented in this work is a representation of the non-public part of a NPN network. Following, we describe the architecture and elements of the NDT.

A. Architecture

In the Fig. 4 we describe the architecture of the NDT used in this work.

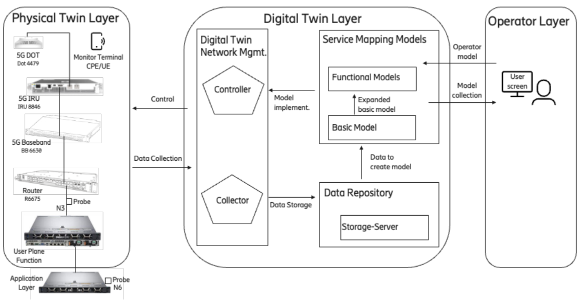

Fig. 4. Logical architecture for NDT of the *Carrito*

In the left side we have the Physical Layer, described in subsection B, and represents the segment of the NPN network replicated by the NDT. In the right side is the Operation Layer, which represents the user of NDT framework. The Digital twin Layer contains the standard interfaces towards the physical twin (Collectors and Controllers), the data repository with data and performance metrics, and the Models, which represents the different behaviors of the *Carrito.*

B. Physical Layer

The physical layer refers to the *Carrito*, which includes the radio access network components (passive and active radio elements, gNB or eNB, transport elements), the user plane of the network and the power supply. We have different flavors depending on the equipment used: legacy 5G NSA or 5G SA; low, mid or high band; indoor or outdoor coverage and UPF or Packet Data Network Gateway (PGW, legacy) for the user plane. These options are also modeled in the DT layer and a new *Carrito* is built according to the output of the DT layer. As add-on, single server for edge applications can be added.

The User Equipment (UE) is also included in the physical layer and modeled in the DT layer. The main reason is the fact that UE vendor and model selection have impact in the performance of the network, especially in latency and throughput. In addition, for the use case described in section III we also model in the DT basic Time-Sensitive Networking features and for that, Device-Side TSN Translator (DS-TT, [2]) is included in the Physical layer together with the UE.

C. Interfaces

The Physical layer offers two interfaces: Collection interface and Control interface. DT layer uses the collection interface for gathering the required information from physical layer in order to feed the DT model of the *Carrito*. This interface is built on top of standard interfaces provided by the network equipment: NETCONF and/or Ericsson CLI, both providing Ericsson Common Information Model (ECIM) or Yang models. A part of state replication, the *Carrito* provides metrics and performance indicators that are also collected using the Performance Management (PM) interfaces. Additionally, some software probes are deployed into the physical layer in order to collect per service flow metrics and Key Performance Indicators (KPIs).

DT uses Control interface for updating the *Carrito*'s configuration to implement a new service model. Control is also based in standard NETCONF/Ericsson CLI interfaces.

D. Digital Twin layer

The DT layer is an instance of the digital counterpart of the *Carrito*. Its interface towards the physical twin is built around OSS components such the Controller, which is a Network Controller with the ability of updating network elements configuration, and the Collector, which is in charge of collecting configuration and metrics from the physical twin. Collected data and models are stored in the Data Repository module, which provides a Time Series Database and an Unstructured Data Database.

Service Mapping Models contains the DT implementation of the Physical Twin model, processes, simulations, and decision algorithms, with the basic model (exact copy of the physical twin) and the functional models (contains the simulations of the physical twin).

E. Operator Layer

The operation layer reflects the interfaces used by the end-user for any of the use cases described in section IV. For the intent-based configuration use case, the DT layer receives the description of the services that the physical layer must support, expressing the requirements in expected Key Performance Indicators (KPIs), such as end-to-end latency, experienced data rate, jitter and resilience. Also, the end-user can define the traffic model of the required services.

In the NDT process the input, based on the functional models it has, is able to forecast the behavior of the physical layer, tailored to the traffic model expressed by the end-user. As output, the NDT can provide the set of recommended configurations, as well as the possibility of implementing the best one automatically.

VI. NETWORK DIGITAL TWIN FOR SMART MANUFACTURING

We present as practical application of the NDT the initial deployment of a non-public network for doing initial experimentation of the Smart Manufacturing use case. The following table contains the schematic of the required KPIs for the service. The rationale behind those requirements is related to the kind of traffic of the service: the most important flow is the commands sequence that the smart controller sends towards the manufacturing elements, which imposes an almost zero packet loss requirement and certain predictability of the delivery time, expressed in terms of jitter. Also, a basic traffic modeling of the command flow is introduced in the NDT: “the smart controller generates a packet with the command, of size $\leq MTU$, every $10\ ms$”.

TABLE I. SMART MANUFACTURING REQUIRED KPI

KPI	Target
Jitter	1 ms
Latency	10 ms
Packet loss	10^{-6} packet lost

In addition to the end-user requirements, we implement a default extra KPI, which impose the requirement of offering a configuration with at least 60% of energy consumption saving. The energy consumption of each proposed configuration is compared with the NDT baseline, which assumes a deployment of a 5G NSA *Carrito*, using mid-band spectrum and outdoor antennas. This model also receives the input of the site planning, which considers the coverage requirements of the deployment (this process is out of scope of this work, as it uses a different NDT for the site planning).

Taking all the input into account, the NDT proposes a base configuration that fits all the input requirement. The output includes the physical network elements (NE) configuration, with the quantity and model. The best configuration for our use case is to replace the baseline solution with another one based on small cells for indoor coverage. Although the number of NE are increased with the proposal, the solution meets the requirements specified, especially the energy efficiency, as we show in the TABLE III. .

TABLE II. NETWORK ELEMENTS

NE	Legacy NSA Baseline solution	5G SA Small Cells solution
Antenna(s)	AIR 6488[1] (3)	Indoor (5): DOT 4479[2] Outdoor (1): 4408/6524
gNodeB	BB 6630 (1)	BB 6630 (1)
Indoor NE	-	IRU 8846 (1)
Transmission	Ericsson router 6K	Ericsson router 6K
User Plane	Dell r640 (network configuration)	Dell r640 (network configuration)
User Equipment	Askey	Askey

In addition to the hardware information, the NDT also generates the recommended configuration of the whole system, including Radio Access Network (RAN) configuration, transport, and user plane. The configuration includes the selected band (mid-band, n78), multiplexing schema (TDD), TDD pattern (default) and the internal features required for the NE. An important required feature is the TSN basic scheduling, which performs a (very) basic de-jittering of the traffic. Also, it activates the support for PDU sessions of type Ethernet in the system.

TABLE III. ENERGY OPTIMIZATIONS

KPI	Legacy NSA Baseline solution	5G SA Small Cells solution
Power consumption (average)	2096 W	499 W
CO_2 Emissions	5030 Kg CO_2e/year	1197 Kg CO_2e/year

NDT can also indicate configuration for advanced features like MIMO, Network Slicing and Application location, but they are not used in this work as we are using a dedicated equipment for the use case.

VII. DEPLOYMENT AND TESTING

For testing the output of the NDT, we use a deployment in the 5Tonic laboratory. Hardware network elements are updated in the flight-rack according to the NDT recommendation and the recommended configuration is deployed in the network elements. The *Carrito* system is integrated with the 5Tonic 5G Core using the network transmission elements (Ericsson router 6675). For the first integration we are simulating the manufacturing elements using a client (Data Network side) and server (User Equipment side) which are directly integrated with TSN translators (DS-TT and NW-TT) deployed behind the UE and in N6 interface respectively [2]. Fig. 5 shows an schematic for the experimental setup.

[1] https://www.ericsson.com/en/ran/massive-mimo

[2] https://www.ericsson.com/en/small-cells/indoor-coverage

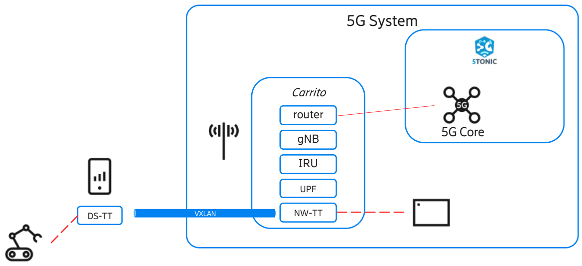

Fig. 5. Schematics of the experimental deployment

As in the time of writing this work there is not commercially available UE equipment that supports natively PDU sessions of type Ethernet, the layer 2 integration of the 5G System uses a small feature present in the TSN Translators that extends the L2 network between UE and DN side by using a VXLAN tunnel. As we can see in the result, although it is not the optimal solution, the fast data-path implementation of the TSN translators allows to encapsulate the traffic without impacting in the final performance of the service.

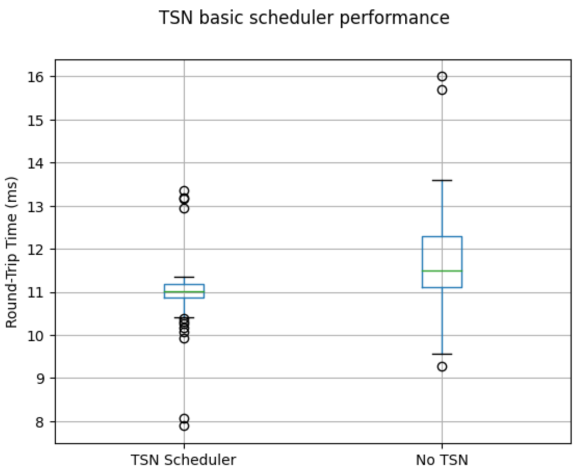

Fig. 6. Round-Trip Time distribution with and without TSN basic scheduling

The measurements we take from the experimentation setup demonstrates that the deployment of the NPN segment accomplishes the requirements expressed in input to the Network Digital Twin. In the Table III we compare the average consumption of the baseline solution with the proposed by the DT, with a benefit of 76% in the power consumption. We have a similar figure in the improvement of the CO_2 emissions. In Fig. 6 we show the results regarding Round-Trip Time of the service traffic. As we can see, the proposed TSN basic scheduler is enough to guarantee the required stability of the latency in a 5G network. Finally, regarding the deployment time, we improve it from the usual time for designing and configuring a new solution, which is measured in days, to the NDT process time, which varies depending on the complexity but has an order of magnitude of minutes.

VIII. CONCLUSIONS

In this work we presented a new experimentation framework, based on Network Digital Twin, that improves the lead time for experimentation cycles. As we described, DT concept is a powerful tool for automatizing and industrializing network management, offering to end-user the possibility of tailor the future 6G network based on their requirements for their business. We demonstrated how NDT helps to an industrial use case to accelerate the configuration and deployment of a private network segment. This approach is very helpful and applied to experimentation facilities, increases the possibilities of extension by not only reducing deployment time, but also by reducing the effort of creating new dedicated network segments. This opens the possibility of creating on-the-fly network segments for experimentation and validation even for a short time (e.g., a one-time event) currently is not take into account due to the effort that requires.

IX. FUTURE WORK

This work shows the first practical results of the Network Digital Twin we are creating at 5Tonic in the scope of the projects that use 5Tonic as experimentation facilities. The immediate future work includes the development of the rest of uses cases, that are more focused in improving the observability of the *Carrito* and network issues prevention.

One of the areas we need to improve is the gathering of measurements in real time. One example is the energy optimization: we presented results based on average consumption of the equipment. We plan to improve that with the incorporation of a new probe to measure the instant consumption of the network elements, allowing to the Network Digital Twin to learn and react from consumption fluctuations. We also want to explore how the different configurations impacts on the consumption, to create an optimizer that can take into account the real status of the network segment.

We also plan to incorporate more features for the industrial scenario. For that, we will add more Time-Sensitive Networking features like for example the path redundancy in the user plane design (radio access and UPF) to the NDT, to produce hardware design that meets the reliability and packet loss usual KPIs.

One of the stopers that prevents to fully automatize the deployment of a new network segment is the fact that some design decisions imply the use of different hardware, which requires manual installation. With the future incorporation of the Cloud RAN we believe that we can present an almost fully automatize Network Digital Twin with the ability of deploying different RAN designs over the same standard *Carrito*, reducing the manual installation to deploy a standard cloud environment and the physical antennas elements.

ACKNOWLEDGMENT

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