Network Digital Twins: Towards a Future Proof Reference Architecture

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Abstract. With the evergrowing popularization of complex, distributed, and heterogeneous networks, how to architect and monitor networking environments is becoming a crucial open problem. In this context, digital twins can be used to mimic the structure and behavior of physical network. Albeit digital twin references architectures exist for other domains, to date, no comprehensive reference architecture for digital twins in the networking context was yet established. In this position paper, we discuss the current need for a reference network digital twin reference architecture, and describe the essential element in the road ahead to design it. We open the paper with the results of a preliminary survey we conducted to investigate the need for the reference architecture, the key information it should convey, and more practical insights on how to design it. Among other results, the survey corroborated that current standards are not best fitted to model network digital twin, and that a new reference architecture is needed. Following, we document our position on the need of a reference architecture for network digital twins. Our discussion is outlined as three main facets, namely (i) digital twins *of what*, *for what*, and *how to deploy them*. As conclusion, we outline our vision on the reference architecture, and the main research steps we plan to undertake to tackle the problem. As end goal, we intend to reach out to both networking and digital twin software architecture communities, towards the joint establishment of a future proof digital twin network architecture.

Keywords: Reference architecture · Digital twin · Networking.

1 Introduction

In recent years, Digital Twins (DTs) gained and increasing popularity, and year after year are becoming more adopted in different and new industrial contexts. A digital twin is a virtual representation of a system, facilitating bidirectional communication between the system and its digital representation [11]. Such virtual representation is used, among other goals, for designing, modeling, and monitoring physical asses [7]. DTs enable to mimic the structure, context, and behavior of a single or groups of physical assets, supporting both design and runtime decision making processes of the physical counterparts. By collecting and analyzing data from multiple sources, DTs can be used to digitally gain information on various attributes, such as performance and related inefficiencies, to identify and design solutions to improve their physical counterparts.

In networking environments, DTs are commonly used to represent physical networking assets such as routers, switches, controllers, and communication channels [17]. Network DTs (NDTs) usually include information regarding operational status, performance data, and environmental conditions of their physical twins. By exchanging network data and control messages with a network of DT instances through twin-physical interfaces, network engineers can rely on DT representations to design, test, assess security, and improve the maintenance of physical networks. This allows for efficient and intelligent management of networks, with the ultimate goal of supporting the improvement of network performance, reliability, and accelerate network innovation.

The concept of DT has been largely developed in the context of Cyber Physical Systems, much promoted by the agenda of Industry 4.0 where it was also addressed and formalized in standardization initiatives [8]. In the context of future generation networks, the growing level of softwarization demands architectural paradigms that can drive the organization of functional responsibilities, their connection with data collection and intelligent processing, and their deployment and composition across network computing, storage, and connectivity resources.

While various concepts can inherit results consolidated in contexts where the DT paradigm has already reached higher maturity and readiness, application in software driven networks raises several and hard new challenges, notably including: distribution across a large-scale network, with sustainable footprint on communication and storage resources; critical need for high levels of interoperability among heterogenous resources and services managed by multiple operators; autonomic orchestration capability supporting efficient and self-adaptive placement of network functions and applications across edge-to-cloud levels and localities. The relevance of these challenges, and their scientific and technological perception is clearly testified by the level of standardization initiatives and the growing number of scientific works.

In order to architect NDTs, comprehensively model their characteristics, and manage the high complexity such systems entail, a reference architecture, *i.e.,* a template solution for an architecture of a particular domain [2], could be used. Such solution was recently introduced for manufacturing environments, with the establishment of the ISO Standard 23247 [8] (which was also picked up in recent software architecture literature [6]). To the best of our knowledge, a reference architecture to model NDTs, covering both functional and non-functional aspects of NDT architectures, is still missing in the current body of knowledge.

As note, while reference architectures and standards might have similar properties, they convey different concepts. Specifically, a reference architecture is a template architectural solution for a particular domain and context. Software engineering standards instead are a set of guidelines for the process, quality, and documentation of software development and maintenance, usually developed by industry organizations or governing bodies, *e.g.,* IEEE and ISO. Therefore while a standard can document a reference architecture (*e.g.,* in the case of the ISO Standard 23247 [8]), the opposite is not always true.

The NDTs architectures are foreseen to play a critical role in the RESTART Foundation (RESearch and innovation on future Telecommunications systems and networks, to make Italy more smART)[1], funded by the European Union (EU), under the Next Generation EU (NGEU) program.[2] The RESTART Foundation is a partnership between 25 Italian universities (*e.g.,* the Sant'Anna School and the University of Rome La Sapienza.), research centers (*e.g.,* the Italian National Research Council), and companies (*e.g.,* Vodafone and Ericsson). The goal of the RESTART project is to leverage DTs to provide a structural improvement of telecommunications research and development in Italy, supporting the digital transformation of industries, and growth of related research and professional communities. Within the RESTART Foundation, the COHERENT project *"Shaping a Digital Twins future proof network architecture"* focuses explicitly on integrating the outcomes of all RESTART research activities in a comprehensive network architecture considering both a technical and a business point of view. The research project, founded for a total of 116 million euros, aims to fill a current gap in networking, namely the lack of an extensible and evolvable NDT reference architecture. Current standards and documentation related to a NDTs reference architecture result to either be too generic to effortlessly incorporate the specifics of the networking domain, *e.g.,* consider the DT framework of Josifovska *et al.* [9] or the DT archetypes of van der Valk *et al.* [16], or result to be deeply grounded in current technologies, and are therefore inherently hard to evolve according to future emerging technologies. As documented by the funding body, realizing a future proof DT network architecture and documenting its related design rationale allows to establish a set of best-practices to fully harness the potential of the implementation of projects in the networking domain.

As part of COHERENT, in this position paper we outline how, in order to comprehensively consider and integrate the various facets of NDTs, a future proof *reference architecture for network digital twins* needs to be established.

The contributions of the paper are (i) an opening survey empirically investigating the need of a reference architecture for NDTs, (ii) a grounding problem statement outlining the need of such reference architecture, and (iii) our vision on a future proof reference architecture of NDTs.

2 Opening Survey

In order to gain introductory empirical insights into the need for a NDT reference architecture, independent of the statements and goal set by the RESEARCH funding body (see Section 1), we conducted a survey involving researchers and practitioners working in the field of networking. Participants were recruited *via* convenience sampling starting from the RESTART Foundation participant list and the personal network of the authors, followed by a subsequent snowballing

[1] `https://www.fondazione-restart.it/`. Accessed 18th June 2023.

[2] `https://next-generation-eu.europa.eu/index_en`. Accessed 2 August 2023.

sampling. Survey invitation target networking experts, belonging either to academic entities, renowned large scale industrial companies, or networking standardization entities. Under the human ethics guidelines governing this study, we cannot disclose affiliations of participants to preserve their anonymity.

In total, 16 participants took part in the survey.

The survey comprised a mix of close-ended 5-point Likert scale questions (CE) and free form open-ended questions (OE). Each CE was accompanied by a OE, where respondents could further clarify their answer.[3] The survey was composed of three main parts, namely:

1. Participant demographic questions: Current job position (OE), years of experience (OE), familiarity with networking and digital twins (CE);
2. On need of a NDT reference architecture: Degree to which the ISO 23247 can be used to represent NDTs (CE), degree to which the ISO 23247 needs to be modified to represent NDTs (CE), and perceived usefulness of a NDT reference architecture (CE);
3. Further advice to establish a NDT reference architecture: expected networking components modeled (OE), expected grouping of networking components (OE), degree to which elements of standardisation groups (*e.g.,* ETSI or IETF) should appear in the NDT reference architecture (CE).

To ensure respondents have enough knowledge on DT to answer the survey, a definition of DT is provided at the beginning of the survey. Similarly, an overview of the ISO 23247 standard provided by Bucaioni *et al.* [5] is provided in the survey. Participants who acknowledge not being familiar with networking and/or DT concepts are discarded from the respondents.

From the demographic answers, the vast majority of participants resulted to work in academia (11/16), possess an average of 10 years of experience, be highly familiar with networking concepts, and moderately familiar with DT.

Regarding the ISO 23247, most participants noted that it can be applied to networking concepts only to a moderate extent (6/16) or low extent (5/16). From the supporting OE answers, we note that this is primarily due to a perceived lack of generalizability of the ISO 23247 standard. By considering the extent to which the ISO 23247 standard needs to be modified in order to be used for NDTs, respondents primarily indicated a medium, or medium-high degree (13/16). Accompanying OE questions clarified that this is mostly due to the need to model concepts specific to NDTs, *e.g.,* details regarding network virtualization functions, and other networking-related attributes, which require new abstraction levels. All participants agreed on a medium-high, or high usefulness of a NDT reference architecture (15/16).

When considering the further advice provided by participants to establish a NDT reference architecture, respondents mostly indicated basic hardware networking components, *e.g.,* routers, switches, and hubs (8/16). In contrast, virtual elements, *e.g.,* virtual machines, VPNs, and firewalls, were mentioned far

[3] To support replicability and scrutiny, the survey and received answers are made available online at: `https://github.com/STLab-UniFI/twinarch-2023-reference-architecture-rep-pkg`

less frequently (3/16). Only seldom, communication-related elements, *e.g.,* physical channels, were mentioned (3/16). Only few respondents described the expected grouping of networking components, providing heterogeneous answers, *e.g.,* "physical layer; security; services; hardware; software; protocols" and "SDN control plane; 5G-oriented data plane". Finally, respondents indicated that networking elements of presented by standardisation groups (*e.g.,* the the European Telecommunications Standards Institute (ETSI).[4]) could be used between a medium and medium-high extent to model a NDT reference architecture (15/16).

Overall, as main takeaways of the opening survey conducted for this position paper, we can conclude that, based on the opinion of mostly academic researchers experienced in networking:

1. The ISO 23247 does not fit completely the networking context, and would need to be considerably modified;
2. A NDT reference architecture is perceived as highly useful;
3. Elements to be covered in the NDT reference architecture should primarily focus on hardware networking components, could use to a moderate extent elements of existing standards.

3 On the Need of a Reference Architecture for Network Digital Twins

Albeit extensive literature considered network DT [1, 12–14, 17], the topic has been primarily addressed from a purely networking point of view. As such, aspects related to a reference architecture NDTs, *i.e.,* a reusable metamodel that can applied to heterogeneous contexts, considering disciplines such as software engineering and software architecture, seem to have been almost completely neglected in current literature [4]. To address this point, in this position paper, we take a software engineering stance by reviewing the topic of NDTs reference architectures through the lens of software architects.

As emerges from recent reviews [1,7,17], when considering NDTs, three main aspects can be taken into account, namely *NDTs for what?*, *NDTs of what?*, and *how to deploy NDTs?*. In the following, we detail our position on these three aspects, building towards our vision on the main proprieties an NDT reference architecture needs to possess.

3.1 Network digital twins *for what?*

As one of the most consolidated aspects of NDTs, the related body of literature extensively describes the different application scenarios of NDT, *e.g.,* their use for network function virtualization, controlled orchestration, and reliability/security monitoring and assurance processes. For example, NDTs can be used to facilitate service placement, allowing for the efficient streaming of data from one point to another within a network [3].

[4] `https://www.etsi.org`. Accessed 18th June 2023.

Reference architectures for NDTs are available (*e.g.,* the NDTs architecture presented by the Telecommunication Standardization Sector of the International Telecommunication Union [15]). Nevertheless, such reference architectures considered primarily, if not exclusively, the functional nature of NDTs, *i.e.,* do not consider aspects related to the characteristics of the entities that have to be represented, or their concrete use / deployment (see also following sections).

Similarly, standards regarding functional aspects of DTs are widespread knowledge within the industry, as documented for example by the industry-driven effort in the Internet Engineering Research Force (IRTF) [19], as well as the evolution of standards relative to the network devices management planes (see for example the standards issued by the IETF NETCONF Working Group[5])

Overall, it appears as if the "*NDTs of what?*" field is a quite consolidated in the networking community. For example, the field of network function virtualization experienced a growing interest through the years, and can now be regarded as a mature, consolidated, and standardized area [18].

As more recent example of NDTs functional viewpoints, current research investigates the use of NDTs for AI model lifecycle management [10]. This topic, currently under investigation, opens for new challenges of functional NDT aspects, *e.g.,* controlling responsibilities, management of AI model lifecycle within NDTs, and consistency between models distributed *via* federated learning.

3.2 Network digital twins *of what?*

As less explored area, we note that often the literature on NDTs does not appear to predicate in detail and precision on the specific network elements that are required to be modeled in the NDT context. As a matter of fact, frequently the nature of network components which need to be modeled within NDT architectures seem to be reported at a rather high level, with auxiliary elements left implicit, or not regarded at all. This more often than not seem to cause the unsystematic documentation of incomplete or vague NDT reference architectures, that, due to their abstract and at times speculative nature, cannot be ported into practice without making considerable assumptions.

Even in the rare cases in which the most important elements of NDTs architectures are explicitly documented, their description often lacks basic details regarding property characteristics and attributes NDTs must posses. Therefore, theoretical or even simulation results are hardly portable into practice by implementing a concrete NDT architecture. In fact, the development process would imply a considerable upfront conceptual effort, which would require *per se* an independent study and verification prior the concrete development can take place.

As a possible solution to address this issue, the information to model NDTs could be derived from standard network architecture documentation, *e.g.,* the documentation provided by ETSI. Similarly, the necessary information could be identified by porting the modeling information of network simulators (*e.g.,* `ns-3`[6]

[5] `https://datatracker.ietf.org/wg/netconf`. Accessed 18th June 2023.
[6] `https://www.nsnam.org`. Accessed 18th June 2023.

and OMNET++[7]) to a NDT reference architecture, documenting *via* a metamodel the NDT elements, their attributes, and relations.

3.3 *How to deploy* network digital twins?

Another area that appears to be only marginally considered from a practical standpoint is the concrete deployment of NDTs over a network.

As for DT in general, one of the challenges in the use of NDTs within a network is the distributed deployment of these virtual representations. To date, standards do not appear to provide a clear guidance on how NDTs should be deployed, distributed, and relocated. From an architectural standpoint, one approach could be to consider network elements, such as Media Access Control (MAC) addresses, as monolithic entities. Nevertheless, given the growing functional complexity of NDTs, this approach might be considered as too simplistic. As alternative, network elements could be factored into bounded contexts. This strategy would lead to the production of microservices, allowing, albeit their potential complexity increase, to take advantage of the benefits of the microservice architecture style, *e.g.,* fault tolerance and fault isolation.

By considering the adoption of a microservice architecture in the context of NDTs however, there is a special emphasis on enabling deployment and placement at different levels of the edge-to-cloud continuum at different localities.

As a double-edged sword, on one hand NDTs are responsible for resolving placement problems through their state and associated computational power (or by delegating the task at hand to other NDTs to obtain states and/or delegate the processing). However, NDTs also rise novel issues associated to how to place these responsibilities on physical and virtual resources within a network. Therefore, while DTs can resolve placement problems, they also open up new challenges in terms of the placement of NDT themselves. The challenges associated to the deployment of NDTs must be carefully managed, in order to optimize the performance of DTs within a network environment. To date, this problem appears to be marginally addressed in the literature, lacking to provide concrete guidance and reference on how NDTs should be deployed.

4 Conclusions, Our Vision, and Future Work

Despite the growing adoption and complexity of network digital twins, a reference architecture for this context, which considers both functional and non-functional aspects, appears to date to be missing in the literature. From the preliminary motivating survey conducted for this position paper, we noted that (i) such reference could be highly helpful, (ii) existing standards do not totally fit the networking context, and would need to be considerably modified, and (iii) elements to be considered would be primarily of hardware nature, and could to a certain extent be modeled by leveraging existing network standards and tools.

[7] https://omnetpp.org. Accessed 18th June 2023.

We documented our position on the current state of the art, and what is needed to move towards a future proof reference architecture for NDTs. By considering current trends and advancements, we reasoned on the key aspects of architecting NDTs, which we formulated in terms of *NDTs for what*, *NDTs of what*, and *How to deploy NDTs*. Based on these three facets, we note that research and development endeavors primarily focused on the functional "*for what*" aspects of NDTs. As such, albeit crucial, which elements to be represent with NDT, and how / where to deploy NDTs, are aspects that are only marginally considered in the current state of the art.

To move towards a standardized modeling of NDTs architectures, we posit that all three aspects, digital twins *of what*, *for what*, and how to *deploy them*, need to be considered. To do so, a reference architecture covering all three of these aspects needs to be established. Providing a standardized framework for NDTs would allow the community to move with a unified effort towards consolidated new abstractions of networking attributes, supporting the design and development of the next-generation wireless networks.

As future work, we plan to proactively build upon the position outlined in this document, by working towards the establishment of a future proof reference architecture for network digital twins. As first research step, we plan to conduct (i) a comprehensive qualitative empirical research involving network researchers and practitioners, and (ii) a systematic literature review on network digital twins. With this first step, we aim at gaining a deep and systematic understanding of the state of the art and practice of NDTs. In a second phase, we plan to design a reference architecture that comprehensively covers aspects related to NDTs *of what*, *for what*, and *how to deploy them*. Data and inspiration could be drawn from existing concrete artifacts to model networks, *e.g.,* the elements and attributes used by widespread simulation tools such as `NS3` and `OMNET++`. Finally, we plan to evaluate and refine the established NDT reference architecture in a design science fashion, by gathering feedback from researchers and practitioners in the field *via* qualitative assessments and concrete case studies.

The task of establishing a NDT reference architecture is ambitious, and requires by definition interdisciplinary knowledge coming from the areas of software architecture, digital twin modeling, and networking. For this reason, we more than welcome feedback, insights, and collaboration with researchers and practitioners of any of these areas who are interested in jointly progress towards a holistic, standardized reference architecture for NDT.

With this position paper, we aim to reach out to both the networking and digital twin software architecture research and practitioners communities, in order to jointly progress towards the end goal of the RESTART mission, namely the establishment of a future proof digital twin network architecture.

Acknowledgments

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (PE0000001 - program "RESTART").

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