

Exploiting a Network Digital Twin to optimize B5G networks management.

The OPTIMAIX approach

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Abstract—The rapid advancements in 5G and 6G networks call for novel solutions tackling network operation and management processes, which can effectively deal with the growing stringent requirements, as well as the remarkable service heterogeneity. In this context, Network Digital Twin (NDT) platforms are seen as a promising enabler for advanced network management solutions. In this work we introduce the NDT architecture that has been defined and developed within the OPTIMAIX project, as an element of the broader Optimize-as-a-Service framework. In addition, the work describes how this NDT approach can be exploited to address a particular problem of the Radio Access Network, such as the joint decision of RAN centralization and resource management in multi-slice scenarios.

Index Terms—NDT, 5G, 6G, centralization, slice, RRM

I. Introduction

One of the most relevant aspects of 5G (as well as 6G) networks is that they have been conceived to promote service-based architectures, and this has strongly increased the complexity of planning and management tasks. In this sense, both 5G and 6G networks need to provide connectivity solutions for a much wider range of services, each of them with distinct requirements, and belonging to rather different use cases and scenarios (i.e., smart cities, virtual reality, public safety, industry, etc.). In addition, traditional management tasks, based on Key Performance Indicators might become insufficient, as new cellular generations are starting to consider Key Value Indicators (KVIIs).

All of the above has caused an unprecedented surge of the complexity of the corresponding management procedures and mechanisms. This is already happening

with current 5G deployments, but it is also believed to become even more critical for forthcoming 6G networks, as discussed in [1].

Considering the described scenario, frameworks to handle this on a holistic way are deemed necessary. In this paper we focus on one of the potential tools to appropriately address these challenges: Network Digital Twin (NDT). It provides an updated virtual model of the real network, which brings the possibility to analyze, diagnose, emulate it in a zero-risk environment, as well as to send control decisions to tune its behavior [2]. In addition it needs to trade-off between accuracy and response time considering the continuous changes of real networks [3].

The OPTIMAIX project ¹ goes a step beyond, and proposes to house the NDT within a so-called Optimization as a Service (OaaS) platform, which provides a set of tools that support the automated planning, operation and optimization of 6G networks, targeting the efficient use of available network and compute assets and resources. The initial conception of the OaaS platform assumes a number of optimization algorithms, possibly exploiting Artificial Intelligence and Machine Learning (AI/ML) tools, tackling different planning or optimization problems. Based on certain inputs (for instance Service Level Agreement (SLA) requirements, the components of a network slice, the current load in different parts of the network, etc.) these algorithms will make decisions regarding the configuration of the network, which will be enforced through the corresponding management entities and interfaces.

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Furthermore, the NDT, which accurately mimics real networks, can be used to assess the performance of these configurations prior to their actual deployment.

This paper presents the NDT design conducted in the OPTIMAIX project, including its architecture, the information models that have been defined for the different entities, as well as the Application Programming Interface (API) established between the NDT and the OaaS platform. We illustrate the potential operation of the platform, by considering an illustrative problem, which considers functional division in Cloud Radio Access Network (CRAN), as well as resource slicing.

The document is organized as follows. Section II positions the OPTIMAIX NDT against existing approaches. Section III focuses on the architecture of the NDT, discussing it within the OaaS framework and depicting its components and operation. Then, in Section IV we discuss how the proposed OPTIMAIX NDT can be used as a means to address management of functional split and resource splitting. Finally, Section V concludes the paper, outlining some of our future lines of research.

II. Related literature

The definition and development of the NDT concept for 5G and Beyond 5G (B5G) networks is still in an early stage. A number of papers have provided initial visions of NDTs for B5G, [4] [2] [3] [5] [6] [7] [8], identifying the main challenges to be addressed, a number of potential technologies that could be used, as well as some initial use cases of NDTs that could be of interest.

Besides, standardization bodies have also started addressing the definition and integration of NDT in network architectures. In this regard, IETF is currently working on the definition of an NDT concept and its architecture in [9]. Similarly, the 3GPP opened a studio item on NDT for network management in [10], while ITU has identified the use of NDT as one of the key aspects for intent-based network management [11].

Aligned with the efforts from standardization bodies, some works in the literature have also proposed early NDT architectures. In this sense, a number of works [3] [5] [6] [7] [8] [4] have tackled the appropriate use of NDT for 5G network design and operation mechanisms, still from a high-level perspective, since they mostly identify the main subsystems. Among those papers, it is worth mentioning [4], being the only one that identified some specific components to be included in an NDT of the whole network.

On the other hand, other works provide more detailed guidelines towards the NDT realization. In this sense, the authors of [12] discuss potential use cases, introducing a reference architecture, particularly focused on their application to operator networks. Similarly, [13] identifies, and analyzes, 6G scenarios where

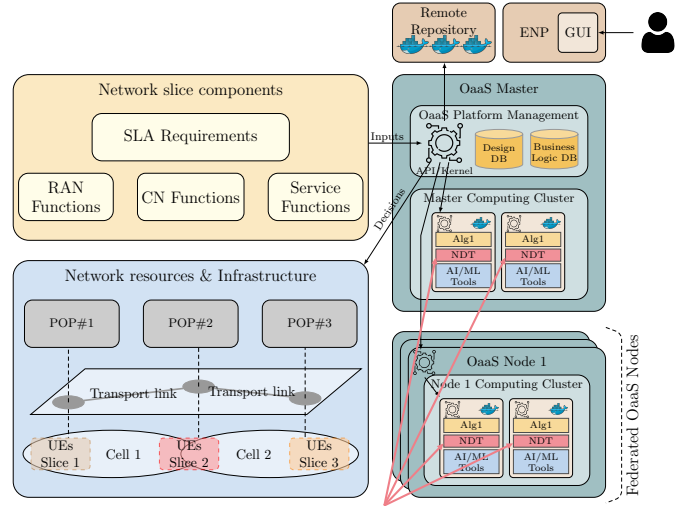


Fig. 1: OPTIMAIX OaaS system architecture

NDT can be applied, describing a general architecture where various component digital-twins are developed as data-driven models. The concept is then applied to control the Forward Error Correction (FEC) decoder of a 5G base station. Furthermore, Sanz Rodrigo *et al.* introduce in [14] a methodology for automatic implementation of NDT instances and a reference architecture, while Lombardo *et al.* [15] propose an NDT platform based on microservices.

While the previous works share similarities with our approach, regarding the realization and deployment of NDT instances, they do not aim to provide a general architecture, nor component and interface definitions are addressed whatsoever.

There are other works that focus on applying the NDT paradigm to specific networks segments or scenarios. For instance in [16] Vilalta *et al.* propose an NDT architecture that is focused on transport optical networks. The application to Internet of Things (IoT) scenarios is addressed in [17], which discusses a simulation framework. This idea of simulation-based NDT is also used in [18], where the authors propose extensions to *ns-3*, to be used as an NDT, or one of its components. In particular processing simulator models are proposed, which are not included in the default *ns-3*. Finally, it is worth noting that some works take a more fundamental approach; for instance, Böck *et al.* study in [19] the role of computing-hardware models to ensure trustworthiness of digital-twin models.

III. NDT design and architecture

This section introduces the OPTIMAIX NDT architecture [20]. It is conceived as the cornerstone of an OaaS framework for 5G and B5G networks, and it is depicted in Figure 1.

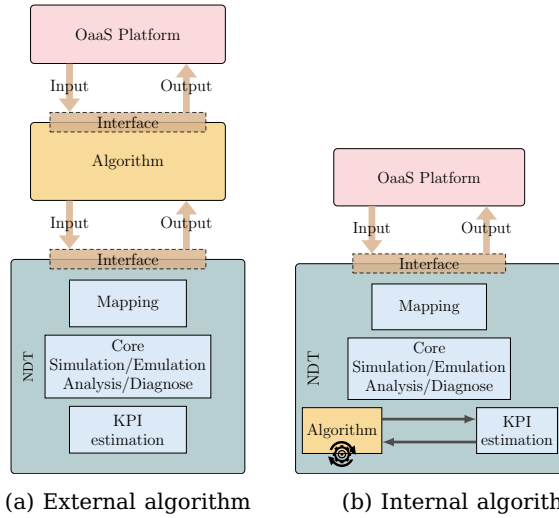


Fig. 2: NDT components and possible deployments

The NDT is a stateless model that replicates the behavior of real network components, considering certain configurations, and extract Key Performance Indicator (KPI) values. These models interact with algorithms, which aim to optimize the network operation. These techniques are tested in this virtual environment prior to their deployment in a real network. In this context, one or multiple NDTs can operate either isolated or in combination with other algorithms, all being deployed as Docker images. Once the image is instantiated and ready to receive requests, a testing process is performed to ensure that the NDT is operational, as well as integrated within the OaaS Platform.

A. Overall NDT architecture

The design of the NDT that we integrate in the OaaS framework is depicted in Figure 2. It follows a service oriented approach with three entities: the Mapping module, the Core module and the KPI estimation component. Firstly, the Mapping module extracts network design information, according to a specific network model. These network models are stored in a design database, which depends on the particular subsystem, and an illustrative example, for the Radio Access Network (RAN) segment, will be elaborated in Section III-C. Once the network configuration is defined, the NDT relies on the Core module to perform suitable network simulations or emulations. One of the objective of this module is to allow third-parties to develop their own NDTs models, according to their needs, and easily integrate them within the proposed framework, as Docker images. Finally, the KPIs values are extracted according to the configuration provided during the definition of the network context.

Figure 2 illustrates two possible NDT deployments, depending on whether algorithms are locally executable. In Figure 2a the NDT receives, as input, the results of the algorithm and it then estimates the corresponding KPI values. This option would lead to independent network realizations for each algorithm execution, and it would be therefore suitable for techniques seeking optimum network setups, for instance during planning phases. In contrast, in Figure 2b the algorithm is instantiated within the NDT, and it thus keeps interacting with the same instance. This would allow training algorithms where the corresponding input depends on previous outputs, as well as on varying network conditions. This second approach would be more appropriate for network management solutions.

B. RAN NDT Architecture

The RAN NDT architecture [21] is depicted in Figure 3 and it includes three main modules: the data repository, the service mapping models, and the digital twin management. The data repository module is responsible for collecting and storing data from the real RAN, allowing the NDT to have an accurate representation of such real network, as well as historical data to be exploited.

The service mapping models are defined to represent the various elements and functionalities of the RAN, and are divided into two main types: basic and functional models. The former ones refer to network elements and entities that define the network deployment (i.e. scenario topology, gNBs, UEs, etc.). On the other hand, the functional models cover different functionalities, and are grouped in three main categories:

- Emulation dynamics: this refers to the models that control the RAN environment dynamics in the NDT. This group entails, among other aspects, traffic generation, mobility and propagation models.
- RAN management and optimization: these models capture different management functionalities, such as Radio Resource management (RRM) policies and Self Organizing Networking (SON) functions, to allow the NDT to emulate the dynamic operation of the real RAN.
- Exploitation models: these models aim to cover the overall operation of the NDT. They include the monitoring model, the KPI reporting model, which generates metric reports (for instance, resource utilization or throughput), as well as the analysis and visualization models that allow processing the KPIs, providing a set of predefined graphs (NDT dashboard).

It is worth mentioning that the architecture does not require using all models, but it defines those that

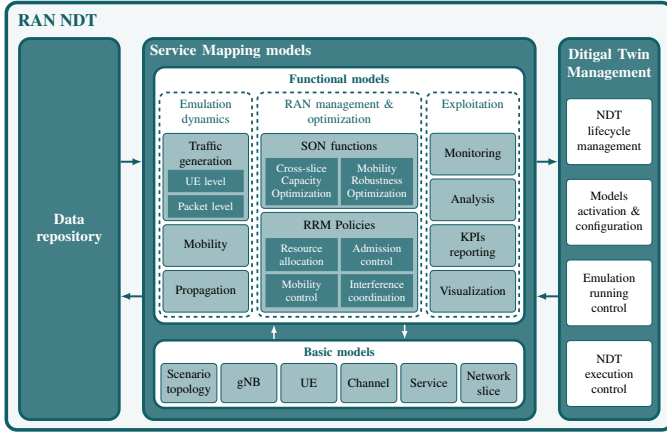


Fig. 3: RAN NDT architecture

are needed to ensure interoperability between NDT instances and the rest of the components. Finally, the NDT management module, represented in Figure 3, performs different functions related to the NDT operation. They include information exchange from and to the NDT instance, as well as its life-cycle management.

In the following we depict, with more detail, some illustrative relevant models that are used to implement the use-case presented in Section IV.

C. RAN NDT nodes models

Within the OPTIMAIX project, we have already specified models for, among other network elements, routers, 5G base stations (gNB) and User Equipment (UE). We focus herewith only on those that are used in Section IV: gNB and slices. The gNB model is based on the 3GPP Network Resource Management (NRM) [22] specification, which defines models for the Central Unit (CU) (both control and user plane), Distributed Unit (DU) and Radio Unit (RU) entities. The gNB models include the following parameters:

- Position and height: coordinates of the gNB radio unit in the geographical area.
- Operating frequency (MHz): it corresponds to attributes arfcnDL and arfcnUL of [22] for the downlink and uplink frequencies, respectively.
- Power related parameter: it includes the transmit power (configured MaxTxPower of [22]), as well as the noise figure of the UL receiver.
- Physical Resource Block (PRB) configuration: it includes the sub-carrier spacing according to the 5G NR numerologies, channel bandwidth, and number of PRBs in accordance with [23].
- Type of propagation environment: it corresponds to the environment that characterizes the propagation in the cell: for example, urban macrocell, urban microcell, indoor, etc.

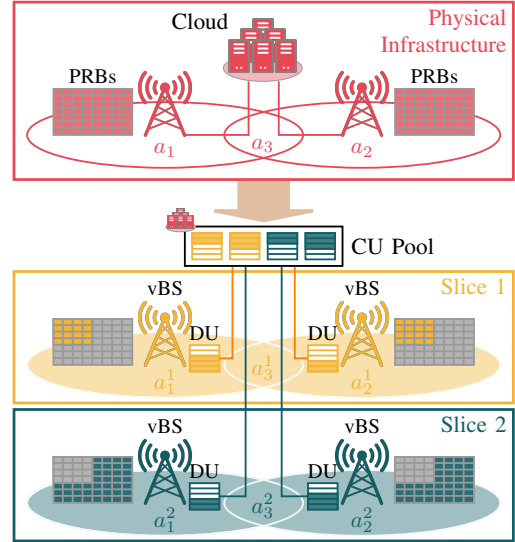


Fig. 4: Dynamic functional split and resource management scenario

The RAN slice model includes the following aspects:

- UE density: it is given by the fraction of overall UE density in the scenario associated with the slice.
- Service area: area of the scenario where the RAN slice should be accessible. By default, it would be the same service area considered by the RAN NDT. However, in a more general case, it could actually correspond to a certain part of this area.
- SLA terms: they are specified in terms of different attributes, such as the downlink and uplink required throughput, both for the whole slice and per UE.

IV. Dynamic functional split use case

The applications of a RAN NDT embrace different resource management phases, including network planning and operation, as well as the application of optimization techniques [10]. For instance, NDTs can be used to assess different RAN deployment topologies and their configuration before facing the real deployment. Furthermore, they can contribute to real-time monitoring and anomaly detection, and they can also be used to train Machine Learning (ML) solutions [24]. In this section we describe an illustrative use of the OPTIMAIX RAN NDT to a particular use-case, where joint resource allocation and functional-split configuration are jointly tackled.

Figure 4 shows the use-case scenario. We consider that services are provided by means of network slices deployed in a given area. In particular, we focus on the RAN slicing, where physical radio resources are scheduled for each slice, leading to different instances of virtual gNBs at each physical base station. On top of

it, we also assume that different centralization levels can be configured for each virtual base station, by tuning their functional split.

In this sense, the centralization level would enable the use of different configuration techniques [25], bringing improvements on the Signal to Interference plus Noise Ratio (SINR). In turn, this would require the re-allocation of physical radio resources (PRBs) between the virtual base stations instantiated for each slice. Finally, access elements with the same centralization level, covering an overlapping area can be coordinated, thus having a positive impact on the SINR.

Using this scenario, the goal is to develop algorithms that adapt to wireless conditions by jointly re-configuring the centralization level and reallocating the PRBs. The reader may refer to [26] for an elaborated definition of the underlying problem formulation. In what follows, we discuss how we can leverage the OPTIMAIX NDT in this use case, how it can be instantiated to test such algorithms.

A. Involved network models

The NDT would be fed with a scenario definition, which involves a number of different models. Besides those described in Section III-C, the RAN scenario topology model provides information about the service area and the UE density. The former corresponds to the overall geographical area where the RAN is deployed, while the latter parameter establishes the user density.

Then, each slice would be defined, according to the RAN slice model described in Section III-C, which entails the following pieces of information: the particular area (or areas) where the slice provides service, the percentage of UEs served by that slice and the performance requirements fixed in the corresponding SLA. Finally, the 5G gNB and UE models would detail the characteristics of the corresponding elements.

B. Execution flow

According to the scenario description, it seems sensible to address the problem in two stages, as it is the case in [26]: at a first step, we tackle the functional split configuration, and then the proposed solution would seek an optimum allocation of the corresponding resources for the given centralization level.

Figure 5 showcases the realization of such approach as a RAN NDT, which would have the following steps:

- 1) The NDT Core and algorithms are deployed. The network scenario would be defined by the OaaS, triggering the deployment of the NDT Core, as well as the corresponding algorithms, which will be included as Docker images.
- 2) Then, the *Mapping* instance would pass the scenario configuration to the *Core*, which would

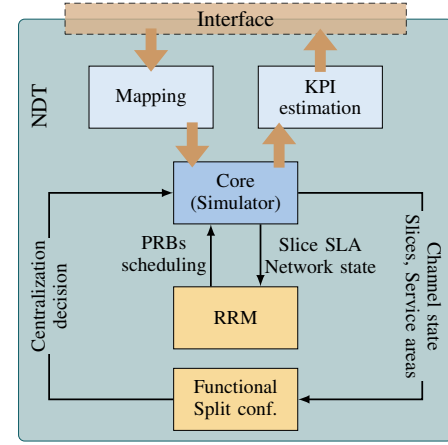


Fig. 5: Execution flow of joint functional-split and resource allocation

replicate the network. In the case of the problem discussed in [26], this is carried out by means of a proprietary simulation tool.

- 3) Then, the optimization process would proceed in an iterative way as follows: First, the *Core* calls the algorithm in charge of the functional split decision, by passing information about slice service areas, and area-wide channel conditions. Then, the algorithm responds with a new centralization configuration for all the virtual base stations, considering as well the overlapping areas. The *Core* then calls the *RRM* algorithm, passing, as arguments, the slices' SLA and the corresponding functional split configuration. Finally, the *RRM* algorithm establishes a new distribution of PRB among the corresponding slices, to satisfy the required Quality of Service (QoS).

As can be seen in Figure 5, after the optimization process has been completed, the *Core* entity would report the corresponding *KPI* estimation, including the resulting configuration.

V. Conclusion and future works

We have described the main features of the NDT architecture that has been defined within the OPTIMAIX project. The NDT is a key component of the broader OaaS platform, which provides a common framework for tackling automated processes, such as planning, operation and optimization of 5G/6G networks.

We have first described the main design aspects of the NDT architecture, as well as its interaction with the OaaS platform. Then, we have focused on a RAN NDT, identifying the models that have been adopted to replicate components of this network segment. We have also presented a use case that tackles the joint optimization of RAN centralization and RRM. The deployment of

the algorithms that were developed to address such particular problem, as well as their interaction, are described according to the OPTIMAIX NDT design.

Currently, the OPTIMAIX project is prototyping the OaaS platform, where the NDT plays a central role, to test different use cases. In our future work we plan to exploit this platform, not only to optimize the operation of particular network segments, but also as a means to foster an improved management of real systems.

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References

- [1] A. Yazar, S. Doğan-Tusha, and H. Arslan, "6g vision: An ultra-flexible perspective," *ITU Journal on Future and Evolving Technologies*, vol. 1, no. 1, pp. 121–140, 2020.
- [2] X. Shen, J. Gao, W. Wu, M. Li, C. Zhou, and W. Zhuang, "Holistic network virtualization and pervasive network intelligence for 6g," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, pp. 1–30, 2022.
- [3] L. Hui, M. Wang, L. Zhang, L. Lu, and Y. Cui, "Digital twin for networking: A data-driven performance modeling perspective," *IEEE Network*, vol. 37, no. 3, pp. 202–209, 2023.
- [4] H. X. Nguyen, R. Trestian, D. To, and M. Tatipamula, "Digital twin for 5g and beyond," *IEEE Communications Magazine*, vol. 59, no. 2, pp. 10–15, 2021.
- [5] Y. Wu, K. Zhang, and Y. Zhang, "Digital twin networks: A survey," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 13 789–13 804, 2021.
- [6] 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 Communications Standards Magazine*, vol. 5, no. 4, pp. 154–160, 2021.
- [7] S. Mihai, M. Yaqoob, D. V. Hung, W. Davis, P. Towakel, M. Raza, M. Karamanoglu, B. Barn, D. Shetve, R. V. Prasad, H. Venkataraman, R. Trestian, and H. X. Nguyen, "Digital twins: A survey on enabling technologies, challenges, trends and future prospects," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 2255–2291, 2022.
- [8] P. Almasan, M. Ferriol-Galmés, J. Paillisse, J. Suárez-Varela, D. Perino, D. López, A. A. P. Perales, P. Harvey, L. Ciavaglia, L. Wong, V. Ram, S. Xiao, X. Shi, X. Cheng, A. Cabellos-Aparicio, and P. Barlet-Ros, "Network digital twin: Context, enabling technologies, and opportunities," *IEEE Communications Magazine*, vol. 60, no. 11, pp. 22–27, 2022.
- [9] C. Zhou, H. Yang, X. Duan, D. Lopez, A. Pastor, Q. Wu, M. Boucadair, and C. Jacquenet, "Network Digital Twin: Concepts and Reference Architecture," Internet Engineering Task Force, Internet-Draft draft-irtf-nmrg-network-digital-twin-arch-05, Mar. 2024, work in Progress. [Online]. Available: <https://datatracker.ietf.org/doc/draft-irtf-nmrg-network-digital-twin-arch/05/>
- [10] TSG-SA5 (Telecom Management), "Study on digital twin for network management," 3GPP, Study Item, 8 2021.
- [11] FG-NET2030, Focus Group on Technologies for Network 2030, "Network 2030 architecture framework," ITU-T, TS, 6 2020.
- [12] X. Lin, L. Kundu, C. Dick, E. Obiodu, T. Mostak, and M. Flaxman, "6g digital twin networks: From theory to practice," *IEEE Communications Magazine*, vol. 61, no. 11, pp. 72–78, 2023.
- [13] N. Apostolakis, L. E. Chatziefletheriou, D. Bega, M. Gramaglia, and A. Banchs, "Digital twins for next-generation mobile networks: Applications and solutions," *IEEE Communications Magazine*, vol. 61, no. 11, pp. 80–86, 2023.
- [14] M. Sanz Rodrigo, D. Rivera, J. I. Moreno, M. Álvarez Campana, and D. R. López, "Digital twins for 5g networks: A modeling and deployment methodology," *IEEE Access*, vol. 11, pp. 38 112–38 126, 2023.
- [15] A. Lombardo, G. Morabito, S. Quattropiani, and C. Ricci, "Design, implementation, and testing of a microservices-based digital twins framework for network management and control," in *2022 IEEE 23rd International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2022, pp. 590–595.
- [16] R. Vilalta, L. Gifre, R. Casellas, R. Muñoz, R. Martínez, A. Mozo, A. Pastor, D. López, and J. P. Fernández-Palacios, "Applying digital twins to optical networks with cloud-native sdn controllers," *IEEE Communications Magazine*, vol. 61, no. 12, pp. 128–134, 2023.
- [17] S. Geißler, F. Wamser, W. Bauer, S. Gebert, S. Kounev, and T. Hoßfeld, "Mvnocoresim: A digital twin for virtualized iot-centric mobile core networks," *IEEE Internet of Things Journal*, vol. 10, no. 15, pp. 13 974–13 987, 2023.
- [18] K. Chang, Y. Du, M. Liu, J. Shi, Y. Zhou, and Y. Li, "Os packet processing mechanism simulation architecture for enabling digital twins of networks in ns-3," in *2023 IEEE International Performance, Computing, and Communications Conference (IPCCC)*, 2023, pp. 186–193.
- [19] Y. N. Böck, H. Boche, R. F. Schaefer, F. H. Fitzek, and H. V. Poor, "Virtual-twin technologies in networking," *IEEE Communications Magazine*, vol. 61, no. 11, pp. 136–141, 2023.
- [20] J. Pérez-Romero et al., "OPTIMAIX NDT: Development of a network digital twin to support advanced service planning in 5G/6G services," OPTIMAIX Project, TR, 10 2023. [Online]. Available: https://drive.google.com/file/d/1_G7EQnzNQne-mlw7LTGNxibi7qvNj2Uw/view
- [21] 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, 2023. [Online]. Available: <https://www.mdpi.com/1424-8220/23/3/1197>
- [22] O. SA WG5 (Management and Charging), "Ts 28.541 management and orchestration; 5g network resource model (nrm); stage 2 and stage 3 (release 18)," 3GPP, TS, 9 2022.
- [23] RAN4 (Radio Performance and Protocol Aspects), "TS 38.104 NR; Base Station (BS) radio transmission and reception (Release 18)," 3GPP, TS, 3 2023.
- [24] J. Deng, Q. Zheng, G. Liu, J. Bai, K. Tian, C. Sun, Y. Yan, and Y. Liu, "A digital twin approach for self-optimization of mobile networks," in *2021 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2021, pp. 1–6.
- [25] A. M. Alba, S. Janardhanan, and W. Kellerer, "Enabling Dynamically Centralized RAN Architectures in 5G and Beyond," *IEEE Transactions on Network and Service Management*, vol. 18, no. 3, pp. 3509–3526, 2021.
- [26] N. Villegas, S. Pérez, L. Diez, and R. Agüero, "Joint and dynamic optimization of functional split selection and slice configuration in vRAN," *IEEE Wireless Communications and Networking Conference (WCNC)*, 2024.