Definition Of Digital Twin Network Data Model in The Context of Edge-Cloud Continuum

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***Abstract*—The telecommunications sector is devoting an initial interest in the representation of complex networks as Digital Twins. The concept of a Digital Twin Network (DTN) is a research topic, but it promises to be an important step for harmonizing different models of the Edge-Cloud Continuum. The DTN software framework aims at helping network operations by providing updated and complete views on the network or parts of it, and it also introduces the possibility to simulate the network behavior or to learn from network events history (Machine Learning) without jeopardizing the actual operations of resources. In addition, thanks to the representation capabilities of the DT, its usage in the network promises to support different stakeholders' views on their virtualized and physical infrastructure. This work tries to consolidate a DTN data model representing the elements of the Edge-Cloud Continuum by providing a layered (horizontal) and segmented (vertical) view of the infrastructure to all the involved stakeholders. The DTN model is an ontology where the linked classes represent properties and relations of networked components. This work aims to design a flexible and extensible ontology that describes the Edge-Cloud continuum usable in the telecommunications as well in the Cloud (IT and web) industries creating a bridge between the two.**

***Index Terms*—Digital Twin Network,Edge-Cloud Continuum, Data Model, Ontology, Service User**

I. Introduction

The Digital Twin (DT) is a software representation of a physical object reflecting its properties, status, relationships, and behavior. Some major properties of this representation are: *reflection*, i.e., the capability of a DT of reflecting the major features of the physical object; *replication*, i.e., the ability to create several copies of the DT related to the same physical object; *entanglement*, i.e. the ability to quickly reflect the changes on the physical object; *responsiveness*, i.e., the ability of the DT to react to requests of the applications in due time; *function augmentation*, i.e., the ability to add new functionalities via software that can "augment" the DT capabilities with respect to the physical object; *composition/aggregation*, i.e., the ability to represent all the subsystems comprising a physical object as an integrated DT (and its composing DTs) [1]. Based on this vision of DT, a representation of a complex system and its components as cooperating Digital Twins is possible and, in fact, it is used in several different fields of engineering. Also the telecommunication sector is showing interest in representing the "network" by means of a Digital Twin. Some Digital Twin Network (DTN) definitions have been proposed [2] [3]. A DTN can represent and support the programming of network functions, components, resources, and communication events. The objectives of these propositions are the exploitation of the flexibility of the DT managing and configuring a complex network system. For instance, the DT network approach can be useful for "traditional" tasks of network management such as network troubleshooting, and fault handling (i.e., configurations error localization). It can also enable new capabilities such as simulation and experimentation on use case-based (What-if) scenarios without resource jeopardizing [2]. An IRTF group, Network Management Research Group (NMRG) [4] and International Telecommunication Union (ITU) [3] provide the DT definition in the context of networking. These definitions describe how the DTN could represent the virtual counterpart of a telecommunication network. In particular, they try to identify the key components that can help to develop, deploy, and use a DTN. Although the DT definition has been used in a complex environment (e.g., manufacturing or factory production systems), it is hard to create a full network representation by means of a DTN due to the specific complexities of the telecommunication environment. Recently, the network is entered into the process of increasing softwarization: this means that software platforms have more relevance over black-box systems and the network itself needs to transform into an integrated system of communication, processing, storage and intelligent management. In addition, there is an increasing diversity in consumers and end devices (e..g, smartphones, IoTs sensors, and micro-computing systems) that have an impact on how the telecommunication network should allocate its resources and capabilities. Also, the telecommunication industry competition and the request for stringent QoE support from Service Providers(SP) push for new management and dynamic configuration of large networks. These demands can be enablers for the introduction of the Digital Twin network in order to align the management part with the needs of the service user (customer, provider). A digital twin-based approach should not be disruptive with respect to the current situation, but it should help in creating a homogeneous view of network systems and subsystems with different degrees of granularity and should also support different perspectives on the infrastructure (the view of the user, of the SP, the application Providers, and the Operator). The Digital Twin could help create models of the important parts of the network and use them to identify/predict issues, simulate the effects of changes or events on the entire infrastructure, and help optimize the allocation of resources at the edge, core, and cloud segments [5]. The DT Network approach, then, must improve at least three features over the traditional telecommunication network models: 1) the ability to create, check and operate on network models of different granularity and abstraction capabilities; 2) the ability to operate on a rich information space with large massive well-formatted data that relevant Artificial Intelligence functions for predictive maintenance can readily exploit, optimize configuration and other functions; 3) the ability to forecast the effect of unexpected events or the impact that new use cases can have on the network infrastructure by simulating or "reasoning" on the expected behavior of the network.

In order to achieve these objectives, the DT Network should be supported by flexible Data Model. This model should be built starting from the existing specification with changes and addition needed to support the increasing ability to host processing at the edge and the core of the network; the creation of large data sets on top of which to operate AI tools; and simulation and reasoning capabilities for understanding the impact of an event or changes to parts of the infrastructure on the entire system.

II. State of the Art

There is an increasing interest in adopting a Digital Twin based approach for modeling, managing, and orchestrating resources of different networks [6], [7]. There are two major trends emerging from the newer DTN approaches: on one side, the enrichment of the DTN functionalities by integrating AI and optimization algorithms (i.e., Hidden Markov Chain, Markov Decision Process, Graph Neural Network, Federated learning, Reinforcement Learning), e.g., [8]. These learning models try to maximize the networking environment performance by correlation with specified Keep Performance Indicators (KPIs) belonging to service quality. On the other side, there is an attempt to develop DT network solutions that encompass, take care of, and exploit Edge-Cloud Continuum [9].

In order to satisfy these two needs, there is a need to define an extensive and flexible data model representing the capabilities of an Edge-Cloud Continuum system. A relevant input to this endeavor is the work presented in [10]. In this paper, a high-level conceptual view of cloud infrastructure is described in terms of a flexible ontology. By taking into account the resources and features of the trending edge segment, this work can be extended and employed as a foundation for the design of a Digital Twin Network Model.

III. Requirements on a DT Network Data Model

In order to be useful, a Data Model needs to represent usable properties to all the stakeholders of the model. In addition, the model should be flexible enough to allow coordinated extensions and improvement for capturing different requirements and need. For this reason, different stakeholders and their specific views on the Digital Twin Network should be considered and represented. As an initial step, two major stakeholders have been identified: the Edge-Cloud Platform Provider (PP) and the Customer. The PP can be considered as a sort of federation/aggregation of resources and platforms pertaining to different stakeholders such as Communication Service Providers (CSP) providing edge and core computing and networking capabilities in conjunction with cloud providers that focus their offering on well established and world-wide present cloud infrastructures. Some stakeholders (e.g., Amazon) could have a different perspective on what edge is (e.g., at the level of Internet Exchange Points).

Edge-Cloud Platform Provider View The PP has the core role to support the availability and continuity of the services in all the networking infrastructure. Thus it needs to have a global view and insights into the customer usage of part of the infrastructure, the status, occupancy, and usage of virtual resources of the network, and how the customer applications are "mapped" into the continuum in terms of allocated/used resources. In addition, the PP may need to manage and understand the virtual view of the actual physical network that is providing services to the customers. Under this perspective, there is the need to consider how the slicing concept can be integrated into the Digital Twin Network model [11]. The PP needs to control how to allocate resources pertaining about a network slice that meets the need of customer applications, and how this allocation can be supported by the underlying physical capabilities. The needed views for the PP are very different and complementary: from a very granular view of particular parts of the network and its resources to a global view of the network. The integration of granular and global views is a major challenge to the composition and aggregation capability of the Digital Twin.

Customers View The Customer view refers to the perspective that the customer has on the entire Edge-Cloud Continuum infrastructure that is made available for running its applications. Depending on the needs and skills of the customer, different abstract views (i.e., allocated resources in edge-cloud continuum) should be offered in order to allow the users to focus on the specific level with which they are familiar.

In order to correctly support these general views (Provider and Customer), a matrix view of the network is proposed

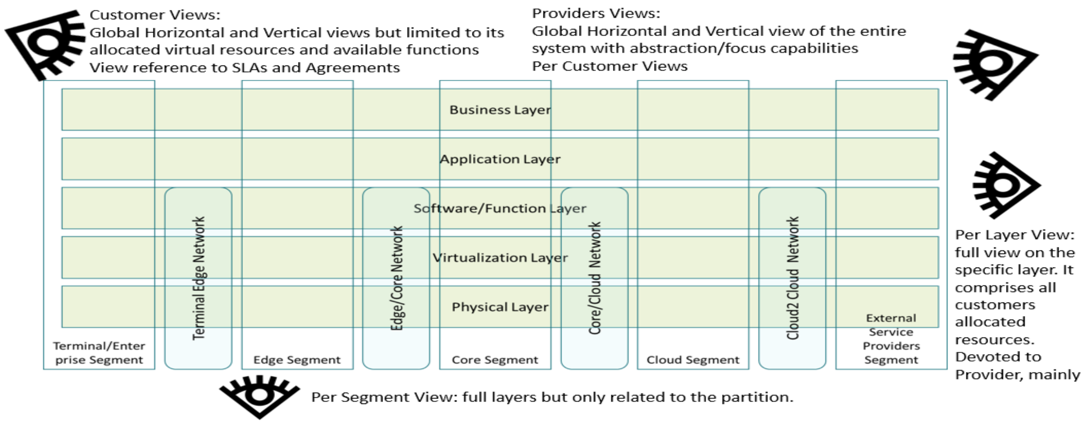

Fig. 1. Edge-cloud Continuum DT data model offering different views to Service Users

(Figure 1). It considers a traditional layered view (from the physical layer to a business layer) together with a segmented view that takes into consideration the different segments of the network (from the Terminal/End-user segment to the Cloud Segment considering also the needed interconnection network capabilities to support the segment communication).

Layer View The initial layered view comprises:

- A Physical Layer that provides a view of physical resources according to the needs of the different stakeholders (where the DTN should give a very specific view on what is the status of any possible physical resources by using the information and data collected by the appropriate repository of the Operational Support System, OSS);
- A Virtual Layer that provides a view of the virtual resources allocated to this virtualized infrastructure. At this level, the concept of slicing should be integrated in order to characterize the type of service being provided to the customer. Also in this case, the DTN should collect and represent through the Data Model the status of the layer by accessing and modeling the OSS information and data;
- A Software/ Function Layer comprising different functionalities and software tools that the PP makes available to the customers. This layer should provide a clear view of who and how is using the different resources, what the status of usage is, and what additional availability is still possible. This layer should also provide insights on how to improve the usage of the resources for satisfying the requirements of the user (e.g., by replicating or migrating functionalities in different parts of the network depending on specific requirements such as latency or bandwidth optimization);
- Application Layer represents the resources of the Customers deployed and running for supporting the specific applications of the Customer with respect to its users. Here the DTN should consider the different interactions between the Customer components (e.g., packages of microservices) and suggest optimization with respect to Service Level Agreements [12] or specific constraints posed by Business Processes;
- Business Layer represents the constraints and the goals posed by the PP and the Customers regarding the usage and the intended behavior of the entire infrastructure for satisfying the processing/communications requirements, for optimizing the costs and resources usage.

  Additional levels or integration of these functions in a layer are still possible. The Data Model should be flexible enough to support extensions and integration needed to support the real requirements of the different stakeholders.

  Segment View The Segment view has, so far, identified these segments:

- Terminal/Enterprise Segment represents the capabilities and the functions allocated in the user domain. Typically they are not exposed to the PP and they are not integrated into the management capabilities of the Edge-Cloud Continuum, however, it is a possibility to be considered.
- The Edge Segment represents the processing and storage resources and functionalities allocated at the edge of the PP network. They are allocated to different Customers either statically or dynamically. This segment should provide a clear view (layer by layer) of the status, usage, and additional capabilities.
- The Core Segment represents the processing and storage resources and functionalities made available at the Core of the network by the PP.
- The Cloud Segment represents the resources and the functionalities available in the Cloud (under the supervision of the PP).
- The external Service Provider Segment represents the capabilities and the resources made available by external providers, these capabilities may or may not coordinate within the infrastructure provided by the PP depending on the specific agreements with external SP.

Each of these segments is connected with the next one by a specific network infrastructure that has to be modeled accordingly to properties, resources, and parameters representing its capabilities and possibilities. The following interconnection segments have been defined: Terminal / Edge Network (i.e., typically the access network); the Edge /Core network (i.e., the network collecting all the traffic from the periphery and injecting it into the robust infrastructure of the CSP); the Core / Cloud Network used to quickly forward traffic from the CSP network towards the infrastructure of the Cloud Provider; the Cloud to Cloud Network used to interexchange information flows between different Cloud Providers.

The segment components should represent (at the different layers of abstraction discussed before) the relevant resources and their characteristics so that a DTN can provide a clear view of the status of the Segment as a whole or at a specific layer under consideration.

Figure 2 represents a high-level model highlighting some of the topics discussed so far. The Customer of the DTN services may have different levels of interest corresponding to their business goals and the related expected QoE. This goal and the need to monitor the QoE level may span across the continuum of Edge, Core, and Cloud infrastructure and the related networking capabilities.

It is important to highlight that the layer and segment views should be built and supported by the DTN accordingly to the stakeholder needs. A segment or layer view for a PP is comprising all the resources in that segment serving all the Customers.

IV. Proposed Data Model

The proposed data model for a DT network extends the work presented in [10] by introducing the description of edge resources and their communications capabilities integrated into an Edge-Cloud Continuum infrastructure; and the possibility to create different stakeholder views. This work is justified by the fact that the current network management can be empowered by the definition of a flexible ontology that represents the linked data of network software, hardware, and the increasing set of components. It proposes an ontology that is flexible to extend and represents the relationships between different components and resources. The representation of network components in terms of data, properties, and their relationships allows investigation of how a possible cause of an error can propagate its effects from the fault components to the other resources generating general problems (in a bottom-up fashion, from the granular component to the global infrastructure) or the other way around, from the identification of a general infrastructural problem down to the elements that have caused it (a top-down approach). The proposed ontology consists of the description and modeling of multiple subsystems i.e., partition and segmentation of resources, organizational structure of resources and its relationship to one or more organizations, business products built on the infrastructure by the composition of resources and functions, and processing, storage, and communication capabilities (e.g., data centers) which are identified during the specification phase of a networked service. In this sense, we have identified three major partitions of the systems: Edge, Core, and Cloud, as well as a Terminal Network. Each of these subsystems represents a set of resources and in some cases how the resources group can be mapped or associated with another group (for instance, the components of a service in a data center). The number of partitions could change according to the needs of the representation. For example, the Cloud partition can be subdivided into geographical Clouds or private Clouds depending on the needs of the Providers. This ”vertical” partitioning is complemented by a horizontal segmentation aiming at describing the resources, functions, and properties of the entire system considering different layers of functionalities.

The ontology in [10] has been extended, notably by introducing some major enhancements to the original model: **Partitioning of Resources**, i.e., the identification of resources accordingly to different partitions of the edge-cloud continuum: terminal domain, edge, core, cloud, and external cloud; **Segmentation of Layers**, i.e., the identification of ”views and perspective on the resources that are operating at the same (logical) level, such as Physical, Virtualisation, Software and Functional, Applications, and Business Layers. In addition, the Edge resources and their communications needs and properties are introduced and represented by: **Edge Nodes**, i.e., the representation of resources that are explicitly referring to the edge capabilities and are operating at the edge. **Segment Links**, i.e., communications capabilities capable of supporting the communications needs between adjacent segments.

The extended ontology definition (i.e., the proposed DT Network data model) tries to be as much as possible flexible, but it offers the possibility to map components and properties to existing standards such as ETSI MANO definition. Models and organization structures of existing Cloud and Edge systems can be expressed and described by the ontology. For instance, orchestration description can reuse existing models and promote the extension and interoperation of orchestration capabilities from the Cloud Segment up to the Core, Edge, and possibly to the Terminal/Enterprise and External Cloud Segments. Under this perspective, different orchestration models can be represented, from MANO to Kubernetes and possibly future ones.

The DTN is complex and comprises many different elements that describe the resources and capabilities of an entire distributed system and its communications capabilities. Its main components are abstractly represented in Figure 2: The extended DT network model specifies the components, their properties, and relations to support the detailed representation, factual monitoring, and visualization capabilities to all the stakeholders of the infrastructure. Some of the important components/classes of models, presented in extended ontology, which is in progress, are presented in Figure 3.

The Digital Twin Network: it is the originating class that gives the overall representation of the network as a digital twin reflecting all the changes in the status of its components. **Service User**: An important class in this proposed ontology is the services user. It is intended to represent the stakeholders of the DT Network, their possible ”views” on their infrastructure, and some characteristics of the Service Level Agreement,

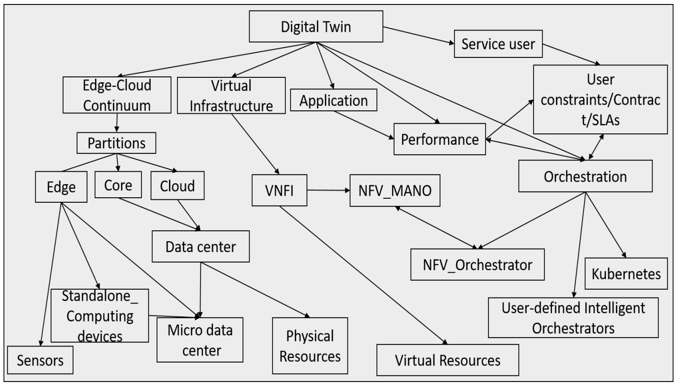

Fig. 2. High level representation of the DTN

SLA. It refers, for each stakeholder, to the resources and software components associated with the stakeholder infrastructure, their mapping into partitions and layers as well as a set of properties that characterize the level of service to be achieved in terms of KPI. The Infrastructure Provider will have a complete view of the entire network, all its resources, and software components as well as all the associated users of the platform.

Edge-Cloud Continuum: This class represents the physical and the virtualized infrastructure as well as the partitions and the different layers. It is the aggregation of data center classes (edge, core, cloud, and external SP data center capabilities) and their connectivity. The model can represent clusters of distributed processing capabilities as regional, local infrastructure, or even at the level of rooms and racks. In order to offer fine-grained visibility for performance and service customer SLA validation, this data center segmentation is aiming at alignment with the data center infrastructure management systems (DCIM) [13]. Node capabilities (i.e., processing, storage, and ability to host software components like microservices) are described in detail in order to represent the status of servers in a specific rack or the status of a single edge node (e.g., an IoT micro-controller) and its battery status. The representation is very heterogeneous and ranges from single edge nodes to micro edge data center up to the large cloud data center infrastructures.

Applications: This class represents the set of applications that can be deployed on the infrastructure (in any partition) and that can interact with infrastructural services components (Network Function Virtualization services). These applications can be monolithic with a well-defined interface or API and being deployed and executed as a single entity, or they may be designed into many well-formed small software functions, termed Microservices. In case of an application deployed and executed into a continuum of nodes (from edge to core up to the cloud), a user-specific Service Functions Chain (SFC) describing the intended interaction of the application's components are represented by the ontology and used to keep track of the deployment options. The SFC could also be associated with components of elements of the Services_User components in order to reflect the user's requirements and related KPI for the execution of the application.

Network Function Virtualization Infrastructure(NFVI): Some Infrastructure/Service providers are adopting an ETSI MANO approach. Hence they typically require to fully describe the NFVI elements and their organization and relations. In the DTN Model, as dictated by the set of standards defined by ETSI for the Management and Network Orchestration (MANO), the Network Function Virtualization Infrastructure, the NFVI may be represented. This class, in fact, describes the basic NFVI components that are needed in order to determine how the running services are behaving and which resources/capabilities they are using.

Orchestration: This class is provided to help you choose the most appropriate set of policies for managing containerized components(i.e., microservices) and orchestrating infrastructure resources that are SLA and performance aware. Different orchestration models, for example, NFV Orchestrator, Kubernetes, and User-Defined are possible to use and can be selected based on business goals.

Performance: This class includes the parameters required to calibrate the virtual resources and service status. The performance metrics are a concern of the SP and customer. This class tries to represent the relationships between the (physical and virtualized) components that can have an impact on the global execution of services and applications.

Communication Link: The Communications Link class includes the sub-classes which represent the connection of (virtual and real) resources across the continuum of micro and macro data centers, between the different computing and storage capabilities and the external entities (e.g., the user terminals). These links among the computational nodes in the continuum have important parameters(e.g., latency, bandwidth, jitter).

The DTN data model has been imported and extended in an open-source ontology editor, Protege [14]. This is a tool capable to design complex interactions also as linked data and can represent the ontology in form of JavaScript Object Notation for Linked Data (JSON-LD). These capabilities can be useful for promoting a shared and open development of a Digital Twin Network Data Model that could eventually be mapped to different representations (e.g., the NGSI-LD notation and smart data model promoted by FIWARE, to make it available for the research community).

Many activities are related to the creation of a Digital Twin Network, for instance, IETF group document [4], the definition of FIWARE's Data Models and the native support for DT representation, and some other activities in standardization. They all aim at the definition of a DTN. On the industrial side, there is a need to renew the current management systems by introducing Artificial Intelligence, Machine Learning capabilities, as well as decision-support mechanisms, and simulation tools. The definition and consolidation of a robust and flexible Digital Twin Network model are seen as a means to support new applications and approaches to network and business management without the need to dismiss the existing systems.

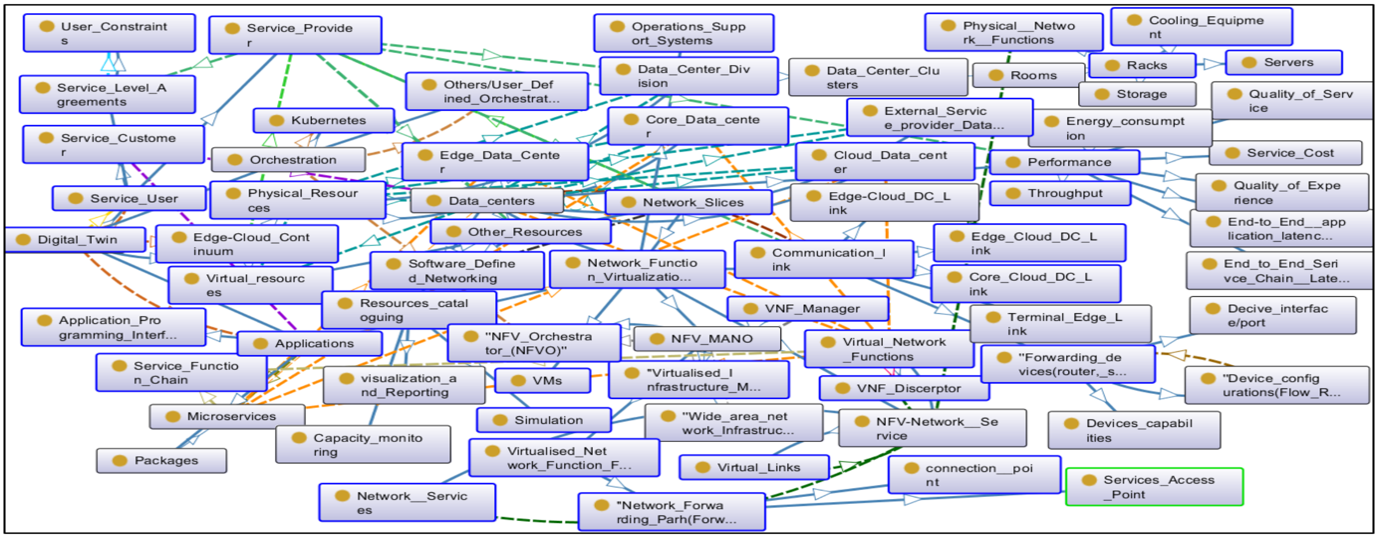

Fig. 3. An ontology (classes) representation of the DTN data model

In fact, the DTN is based on data modeling and the integration of different sources of information (data lakes).

V. Future work

This work aims at the integration and consolidation of Edge-Cloud continuum models adopting the concept of Digital Twin Modelling. As such, it should be considered a work in progress because there is a dual need: **Extending and consolidating the ontology**: there are several activities going on in this respect. For instance, the FIWARE initiative has defined a set of Data Models [15] that could be interestingly integrated into a DTN ontology. There is a need to coalesce efforts and activities into a joint definition covering the most urgent requirements of the SP and supporting a practical usage of the model. **Testing and using the ontology**: the proposed ontology should be used in practical cases in order to prove that it is relevant, implementable, and actually offers advantages to the envisaged stakeholders. Along this line of development, the ontology will be implemented as a use case within the French National Project CLOUD CONTINUUM SOUVERAIN ET JUMEAUX NUMÉRIQUES (C2JN) with the help of companies and businesses operating in the Cloud Computing market.

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References

[1] R. Minerva, G. M. Lee, N. Crespi, Digital twin in the iot context: a survey on technical features, scenarios, and architectural models, Proceedings of the IEEE 108 (10) (2020) 1785–1824.

[2] P. Almasan, M. Ferriol-Galmés, J. Paillisse, J. Suárez-Varela, D. Perino, D. López, A. A. P. Perales, P. Harvey, L. Ciavaglia, L. Wong, et al., Network digital twin: Context, enabling technologies and opportunities, arXiv preprint arXiv:2205.14206 (2022).

[3] Y. S. . Y.3090, Digital twin network - requirements and architecturedigital twin network - requirements and architecture, https://www.itu.int/rec/T-REC-Y.3090, year2022.

[4] C. Zhou, H. Yang, X. Duan, D. Lopez, A. Pastor, Q. Wu, M. Boucadair, C. Jacquenet, Digital twin network: Concepts and reference architecture, Internet Engineering Task Force, Internet-Draft draft-zhou-nmrg-digitaltwin-network-concepts-06 (2021).

[5] K. Oztoprak, Y. K. Tuncel, I. Butun, Technological transformation of telco operators towards seamless iot edge-cloud continuum, Sensors 23 (2) (2023) 1004.

[6] Y. Wu, K. Zhang, Y. Zhang, Digital twin networks: A survey, IEEE Internet of Things Journal 8 (18) (2021) 13789–13804.

[7] H. X. Nguyen, R. Trestian, D. To, M. Tatipamula, Digital twin for 5g and beyond, IEEE Communications Magazine 59 (2) (2021) 10–15.

[8] M. Ferriol-Galmés, J. Suárez-Varela, J. Paillissé, X. Shi, S. Xiao, X. Cheng, P. Barlet-Ros, A. Cabellos-Aparicio, Building a digital twin for network optimization using graph neural networks, Computer Networks (2022) 109329.

[9] Y. Lu, S. Maharjan, Y. Zhang, Adaptive edge association for wireless digital twin networks in 6g, IEEE Internet of Things Journal 8 (22) (2021) 16219–16230.

[10] O. Corcho, D. Chaves-Fraga, J. Toledo, J. Arenas-Guerrero, C. Badenes-Olmedo, M. Wang, H. Peng, N. Burrett, J. Mora, P. Zhang, A high-level ontology network for ict infrastructures, in: International Semantic Web Conference, Springer, 2021, pp. 446–462.

[11] J. Ordonez-Lucena, P. Ameigeiras, L. M. Contreras, J. Folgueira, D. R. López, On the rollout of network slicing in carrier networks: A technology radar, Sensors 21 (23) (2021) 8094.

[12] M. B. Monir, T. Abdelkader, E.-S. M. Ei-Horbaty, Trust evaluation of service level agreement for service providers in mobile edge computing, in: 2019 Ninth International Conference on Intelligent Computing and Information Systems (ICICIS), IEEE, 2019, pp. 362–369.

[13] D. Huang, Data center infrastructure management, Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center (2021) 627–644.

[14] T. Tudorache, J. Vendetti, N. F. Noy, Web-protege: A lightweight owl ontology editor for the web., in: OWLED, Vol. 432, 2008, p. 2009.

[15] F. Cirillo, G. Solmaz, E. L. Berz, M. Bauer, B. Cheng, E. Kovacs, A standard-based open source iot platform: Fiware, IEEE Internet of Things Magazine 2 (3) (2019) 12–18.