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Digital Twins: A Modeling and Deployment Approach for 5G Networks

Mrs. Pallavi N R, Assistant Professor,
Computer Science and Engineering,
BGS Institute of Technology,
Adhichunchanagiri University,
BG Nagara, Karnataka.

Bhargavi S H
Computer Science and Engineering,
BGS Institute of Technology,
Adhichunchanagiri University,
BG Nagara, Karnataka.

***Abstract*— The advent of Mobile Networks Digital Twins (MNDTs) heralds a paradigm shift in the management and optimization of mobile communication networks. MNDTs offer a virtual replica of the physical network, encompassing devices, communication links, environmental factors, and application behaviors. This paper introduces a comprehensive methodology for the automated creation and utilization of MNDTs, supported by a proposed architecture designed for implementation. Framed within the context of the B5GEMINI project, aimed at developing MNDTs tailored for 5G core environments and their evolution into 6G, this research focuses on leveraging MNDTs for advanced scenarios like cyber security and Industry 4.0. The methodology spans the entire lifecycle of an MNDT, starting from data acquisition and modeling to its utilization and establishing a bidirectional connection between physical and digital counterparts.**

By replicating diverse environments in laboratory settings and simulating multiple scenarios, MNDTs provide a cost-effective means to assess network performance, anticipate the impacts of network modifications, optimize network management strategies, and facilitate informed decision-making. This paper underscores the significance of MNDTs in addressing the complexities of modern mobile networks and outlines a roadmap for their effective deployment and integration into operational frameworks.

Keywords: Mobile Networks Digital Twin, MNDT, 5G, 6G, Network Management, Methodology, Architecture, B5GEMINI Project, Cyber security, Industry 4.0.

1.INTRODUCTION

In recent years, Digital Twin technology has emerged as a transformative paradigm, offering novel approaches to the design, deployment, and operation of next-generation networks. At its core, Digital Twin technology involves creating a digital replica of a physical network and establishing a bi-directional link between the two twins, enabling synchronous evolution throughout their lifecycle. This paradigm shift is not confined to a single domain; rather, it permeates various sectors such as Industry 4.0, cyber security, healthcare, aerospace,

intelligent systems, and notably, 5G and 6G networks.
This paper delves into the application of Digital Twin technology specifically within the realm of mobile networks, introducing the concept of Mobile Network Digital Twins (MNDT). MNDTs represent a significant advancement in network technology, harnessing the latest innovations in 5G, software-defined networks (SDN), and virtualized network functions (VNF). By integrating these technologies, MNDTs offer a comprehensive ecosystem poised to unlock the full potential of next-generation networks.

The benefits of MNDTs are multifaceted, promising advancements in cyber security, proactive network maintenance, quality of service control, network optimization, and self-configuration. However, amid these promises lie challenges, chief among them being the heterogeneity of equipment comprising modern operator networks. Addressing this challenge necessitates the development of methodologies tailored to specific data collection requirements and the creation of accurate semantic representations of network elements and behaviors.

Furthermore, establishing robust communication between the Digital Twin and its physical counterpart is paramount. This bidirectional interaction forms the cornerstone of the MNDT ecosystem, facilitating real-time data exchanges critical for preemptive network actions and quality of service configurations. Given the sensitivity of exchanged data, ensuring confidentiality, integrity, and authenticity (CIA) becomes imperative, necessitating the implementation of robust security mechanisms.

To address these challenges and capitalize on the potential of MNDTs in mobile networks, this paper proposes a methodology for the automatic creation of MNDTs. This methodology encompasses phases such as data acquisition, modeling, deployment, and interconnection between twins, aimed at standardizing the modeling and utilization of digital twins within the context of 5G mobile networks.

In subsequent sections, this paper provides a theoretical overview of technologies underpinning MNDT implementation, analyzes key works employing Digital Twin technology, and presents the proposed methodology and architecture. By offering insights into the application of Digital Twin technology in mobile networks and presenting a structured approach for MNDT creation, this paper contributes to advancing the state of the art in network management and optimization.

2.BACKGROUND

Network Digital Twins (NDT) are a burgeoning concept poised to revolutionize various sectors, particularly in the realm of 5G mobile networks. Rooted in the Internet Engineering Task Force (IETF) draft on Digital Twin Networks, NDTs represent a real-time digital emulation of physical network entities, facilitating tasks such as monitoring, optimization, and risk management. They encapsulate historical and real-time data, employ models for emulation, and rely on standardized interfaces for interoperability. Mapping, essential for establishing relationships between physical and digital counterparts, is facilitated through gateways and messaging protocols like MQTT, ensuring secure communication. The proposed methodology integrates agents for data collection, data-based modeling techniques, and gateways for interconnection, addressing key challenges in NDT implementation.

5G technology heralds a paradigm shift in mobile networks, aiming to cater to diverse verticals with varying requirements. With features like SDN, NFV, and Network Slicing, 5G promises unprecedented scalability and reliability. Leveraging open-source implementations of standalone 5G core networks, NDT ecosystems can model dynamic elements like aggregation networks and static elements like 5G core functions (e.g., UPF, SMF). This integration enables the emulation and control of 5G networks throughout their lifecycle, aligning with the goals of NDTs and leveraging advancements in technology for comprehensive network modeling and optimization.

Network Function Virtualization (NFV) emerges as a cornerstone in modern network architecture, enabling the virtualization of network services for greater flexibility and efficiency. Led by ETSI, NFV standardization defines functional blocks and interfaces for managing virtualized network services. NFV infrastructure, composed of hardware and virtualization software, hosts Virtualized Network Functions (VNFs), while Management and Orchestration (MANO) frameworks facilitate resource management and lifecycle control. NFV's flexibility and scalability make it an ideal platform for deploying network elements modeled as digital twins, bridging the gap between physical infrastructure and virtual representations.

Templates play a pivotal role in NFV systems, defining instantiation parameters and operational behavior of VNFs and network services. VNFDs describe VNF topologies and lifecycle events, while NSDs specify network service composition. Technologies like OASIS TOSCA, Jinja2, and YANG provide robust frameworks for creating these templates, enabling efficient deployment and management of virtualized network services. These tools support the standardization efforts led by organizations like ETSI, ensuring interoperability and compatibility across diverse NFV environments.

3.RELATED WORK

In recent years, the research community has witnessed a surge of interest in Digital Twin (DT) technology, particularly in its application across various domains. While numerous works explore the foundational concepts of DT, a notable trend is the emergence of Network Digital Twins (NDTs), which extend DT technology to network environments. Authors have identified key technologies underpinning NDTs, encompassing communications, physical computing, DT modeling, and cloud and edge computing, with a specific emphasis on their relevance to advanced network generations such as 5G and 6G.

Several studies delve into the design, modeling, and implementation aspects of digital twins, addressing functional requirements like optimization, security, monitoring, and training. However, challenges persist, particularly in tailoring methodologies for specific use cases such as modeling 5G network behavior. While existing frameworks like Eclipse Ditto or FIWARE offer valuable resources, they may not fully align with the requirements of mobile network digital twins, necessitating further refinement and adaptation.

Moreover, the integration of NDTs within operator networks offers substantial advantages in fault location, network planning, anomaly detection, education, and training. Reference architectures proposed for NDTs emphasize the importance of telemetry data and standard formats for heterogeneous data capture, laying the groundwork for comprehensive network modeling and analysis.

In the context of 5G networks, the synergies between DT technology and artificial intelligence are highlighted, enabling proactive traffic modeling and accelerating the development of new services. Similarly, in the realm of 6G networks, proposals advocate for leveraging DT technology at the network edge to enable real-time monitoring and automated management through Multi-access Edge Computing (MEC) integration.

Addressing security concerns is paramount in the deployment of NDTs, necessitating robust measures such as synchronization security, communication latency optimization, access control, network isolation, and resilience. Proposals for secure DT design advocate for the adoption of post-quantum cryptography (PQC) to enhance the robustness of communication between physical and digital twins, ensuring the integrity and confidentiality of exchanged data.

4.PROPOSED ARCHITECTURE

The proposed architecture for the Mobile Networks Digital Twin (MNDT) system applied to 5G networks is characterized by its modularity and scalability, offering an automated approach to create comprehensive MNDT models. This architecture aligns with the methodology presented earlier, aiming to model each element within a 5G network as a Digital Twin to accurately emulate network behavior in specific use cases or studies, leveraging technologies such as artificial intelligence for various tasks. Figure 8 illustrates the conceptual design of the overall system, with subsequent sections elaborating on the individual modules comprising the MNDT architecture.

The MNDT System Input module serves as the initial step, incorporating information gathered and processed from preceding phases of the proposed methodology. Utilizing software agents deployed in the physical architecture, this module collects essential data through protocols like ALTO, ICMP, SNMP, and Iperf3, facilitating the creation of a semantic representation of the network. Once stable network conditions are ensured, this module initiates the process of modeling and adapting the physical network topology to prepare for MNDT deployment within an NFV architecture.

Following data collection and processing, the NFV Deployment Module, based on OpenMANO and OpenStack technologies, orchestrates the deployment of the virtual infrastructure hosting the MNDT in Virtual Network Function (VNF) format. Leveraging slicing capabilities inherent in 5G networks, this module allows for the creation of isolated MNDT deployments, enhancing scalability and resource utilization. Deployed VNFs, including those representing the 5G core network, can either adopt a monolithic architecture or a distributed approach to enable communication among different VNFs.

Communication and Interconnection between Twins module facilitates bidirectional communication between the virtual MNDT and its physical counterpart, establishing V2V and P2V pipelines to mirror communication behaviors and ensure continuous coevolution and cooperation capability. Leveraging existing data acquisition elements, communication gateways facilitate secure data exchange between twins, demultiplexing communication flows using messaging protocols like MQTT or Kafka.

The Monitoring Module oversees the overall operation of information exchange within the MNDT, activating port mirroring functions to generate data sets for emulation. Additionally, the Traffic Injection Module enables the injection of traffic based on different 5G models, facilitating validation and analysis of network performance without the need for real radio access networks and 5G hardware. This module acts as a signaling NAS traffic generator, emulating UE operation and facilitating session management, registration, and data transmission within the virtualized infrastructure.

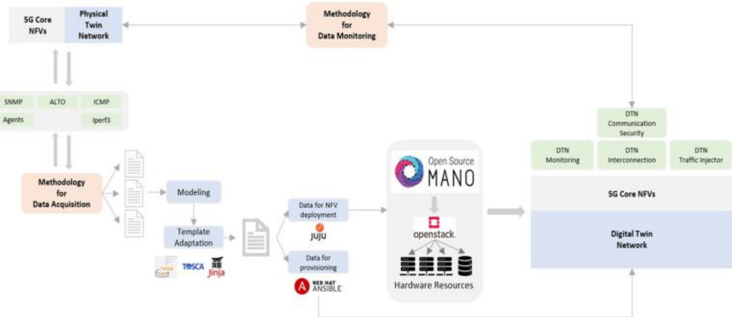

Fig1. Design for automatically deploying digital twins on networks

5. METHODOLOGY

Phase 1: Data Acquisition

The initial phase of the methodology focuses on automating the collection of topological information, hardware resources, routing tables, bandwidth measurements, and other pertinent parameters of the 5G network. Utilizing agents deployed in the network infrastructure, data collection is facilitated through protocols such as ALTO, SNMP, ICMP, and Iperf3. This collected information is then centralized and processed to construct a comprehensive data model that semantically represents the network's characteristics. The communication between agents and the central management entity can be either decentralized or centralized, depending on the specific deployment strategy. It is essential to ensure network stability at the start of this phase to facilitate effective data acquisition within a finite period.

Phase 2: Modeling

Following data acquisition, an in-depth analysis of the collected information is performed to develop a simplified yet comprehensive model of the 5G network. Correlation and data inference techniques are applied to construct a semantic representation of the network topology, hardware, and software elements. The aim is to avoid complete replication of the physical network while ensuring the model captures essential characteristics accurately. This phase aims to create a model that effectively emulates the behavior of the physical network without unnecessary complexity.

Phase 3: Adaptation

After modeling the Digital Twin, an adaptation phase ensues to map the data model to the template format compatible with NFV deployment. This phase involves extracting relevant parameters necessary for deploying virtual resources in the NFV architecture, such as hardware resources, network interfaces, and software configurations. The data model is adapted to ensure compatibility with NFV deployment standards, facilitating seamless integration into the virtualized environment.

Phase 4: NFV Deployment

Once the data model is adapted, the deployment phase within the NFV architecture commences. Using the NFV architecture proposed by ETSI and Open Source MANO (OSM), Virtual Deployment Units (VDUs) representing the Digital Twin's physical elements are deployed. OpenStack technology serves as the base technology for the Virtual Infrastructure Manager (VIM), with support for multi-VIM configurations accommodating container-based virtualization technologies like Docker Swarm or Kubernetes. The setup includes provisions for the fixed elements of the 5G network core dedicated to signaling traffic.

Phase 5: Provisioning

In this phase, specific features of the real network operation are completed and adapted to the Digital Twin. Using deployment automation tools like ANSIBLE, playbooks are executed to finalize the characterization of the Digital Twin based on the adapted data model. This phase ensures that the Digital Twin operates congruently with its physical counterpart within the NFV architecture.

Phase 6: Interconnection

The interconnection phase focuses on establishing bidirectional communication between the physical and Digital Twins, a fundamental requirement of

Digital Twin technology. This phase addresses challenges related to communication security and management between the twins. Communication gateways are employed to ensure secure communication, while messaging-based flow management tools like MQTT, RabbitMQ, or Apache Kafka facilitate real-time data exchange between the twins.

Phase 7: Feedback

The final phase activates a feedback loop between the physical and Digital Twins, enabling real-time information exchange and higher-level tasks such as topology optimization and preventive actions in network management. This phase completes the transition from state 0, associated with the automatic creation of the network's Digital Twins, to state 1, where the twins engage in ongoing monitoring and information exchange tasks.

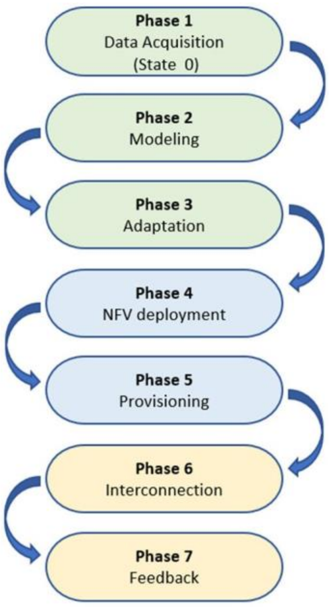

Fig 2. Techniques for Digital Twin Networks

6.CONCLUSION

In this paper, we have presented a comprehensive methodology for the development and implementation of Mobile Network Digital Twin (MNDT) platforms, specifically tailored to 5G networks and aligned with the Network Function Virtualization (NFV) architecture proposed by ETSI. Our methodology addresses the key features of the Digital Twin paradigm, emphasizing data acquisition, modeling, and interconnection between physical and digital twins. The main contributions of our work include the design of a lifecycle methodology for digital twin-based development, deployment of smart agents for data collection, structuring of data for NFV deployment, and establishment of a technological framework for digital twin deployment.

We have identified and addressed technical needs associated with digital twin technology, particularly focusing on the interconnection phase to enable seamless communication between digital twins and their physical counterparts. Additionally, we have proposed an initial security model, emphasizing the importance of securing communications between twins and exploring the use of post-quantum cryptography for enhanced security measures.
While our methodology has shown promising results in facilitating the modeling tasks of mobile networks and providing a method for semantic representation of network topology, there are areas for improvement. Future work should focus on characterizing SDN-based networks using protocols like OpenFlow, validating the interconnection of digital twins with messaging protocols supporting post-quantum cryptography, and enabling dynamic reconfiguration of the MNDT based on optimization decisions.

Overall, our approach holds significant potential in advancing the development and evolution of digital twin-based systems, particularly in the context of next-generation networks. By aligning with the work of organizations like the IETF and leveraging technologies suitable for MNDT deployment platforms, we aim to contribute to the ongoing innovation in digital twin technology and its application in the telecommunications domain. Through continued refinement and expansion of our methodology, we envision further advancements in network emulation, optimization, and management in the era of 5G and beyond.

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