Managing and Optimizing 5G & Beyond Network Resources for Multi-Task Digital Twin Applications in Industry 4.0

Ziran Min*, Shuang Zhou*, Zhuangwei Kang*, Shashank Shekhar†, Charif Mahmoudi†,
Swapna Gokhale‡ Aniruddha Gokhale*
*Dept. of CS, Vanderbilt University, Nashville, TN, USA.
Email: {ziran.min, shuang.zhou, zhuangwei.kang, a.gokhale}@vanderbilt.edu
† Siemens Technology, Princeton, NJ 08540, USA. Email: {shashankshekhar, charif.mahmoudi}@siemens.com
‡Dept. of CSE, University of Connecticut, Storrs, CT, USA. Email: swapna.gokhale@uconn.edu

***Abstract*—Industry 4.0 is leading factories to undergo a significant transformation, where automation is achieved through the use of modern smart technologies, such as 5G & beyond (5G+) network and digital twins. Yet, many Industrial Internet of Things (IIoT) applications, including smart factories and robotic repair, present challenges in delivering dedicated and real-time network services between the physical world entities and their digital twins due to the different network requirements of each sub tasks of the applications. Although 5G+ networks can provide high-speed, low-latency, and reliable network services, managing and optimizing the network resources in real-time remains complex and time-consuming. To address these challenges, this paper proposes solutions to manage and optimize 5G+ network resources in real-time, and deliver dynamic and real-time network requirements of multi-task digital twin applications.**

***Index Terms*—Digital Twins, 5G and beyond, Industry 4.0, Industrial Internet of Things (IIoT), Software-defined Networking (SDN).**

I. Introduction

With the advent of Industry 4.0, the manufacturing industry is experiencing a significant transformation toward achieving automation through the adoption of advanced smart technologies. Digital twin, which is a virtual model that simulates the behaviors and responses of physical entities, is being adopted to monitor and optimize industrial processes and forecast future behavior [1] [2]. To ensure seamless real-time synchronization between the physical system and its digital twin, a communication network with high throughput and low latency is essential. In this context, the 5G and beyond (5G+) network technology has emerged as a promising solution to meet the quality of service (QoS) requirements. However, the detailed design of the network architecture remains an open research question that requires further investigation.

In real-world Industrial Internet of Things (IIoT) applications, such as industrial robots and automated production lines, as well as smart energy management systems, multiple dependent sub-tasks with various traffic patterns are prevalent. For instance, in smart energy management systems, tasks such as energy consumption forecasting, demand-side management, and energy trading have different traffic patterns and network requirements. Energy consumption forecasting may require periodic and real-time updates, whereas energy trading might have bursty traffic patterns linked to market demands. It is crucial to ensure real-time synchronization of these sub-tasks with different traffic patterns to maximize energy resource utilization and minimize energy waste. However, heavy network traffic generated by some sub-tasks can lead to congestion on both the network control and data plane, thereby adversely impacting QoS. Furthermore, the dependencies between sub-tasks can accumulate delays for succeeding sub-tasks. In this context, ensuring real-time synchronization across sub-tasks with differing traffic patterns is a crucial yet challenging task.

5G and beyond (5G+) network technology is able to to provide low-latency, high-throughput, prioritized, and tailored network services for communication between the physical world and its Digital Twin [3] [4]. Network Slicing (NS) technology, which a representative innovation in 5G+, enables network providers to dynamically create multiple customized and prioritized virtual networks on the same hardware infrastructure, thereby catering to the diverse and specific networking performance requirements of various applications. For instance, Ultra-Reliable Low Latency Communication (URLLC) [5] slice is specifically designed for industrial automation scenarios that demand high availability and ultra-low latency. Enhanced Mobile Broadband (eMBB) [6] slice offers a high data rate and improved network capacity, which are crucial for virtual reality applications. Massive Machine-Type Communication (mMTC) [7] slice is suitable for smart city and home applications that require high device density and low energy consumption. Therefore, a 5G-based digital twin has emerged as a promising solution.

In a production environment, however, it can be a challenging and time-consuming task to manage and optimize network resources continuously and proactively, as well as to maintain and monitor the network slice lifecycle. Moreover, constructing a 5G+-based digital twin presents challenges in terms of ensuring real-time synchronization, scalability, and addressing security and privacy concerns. To tackle the aforementioned challenges, a dynamic 5G+ network slice provisioning approach for digital twins is proposed in this paper. Additionally, a 5G+ network-slice digital twin architecture is presented to manage and optimize 5G+ network resources in the physical system. The rest of this paper is organized as follows: the technical challenges are discussed in Section II; Section III presents details of the proposed solutions to resolving the aforementioned challenges; and finally, Section IV offers concluding remarks alluding to future work.

II. Techniques Challenges

In this section we discuss the challenges associated with providing real-time and dynamic network services for multi-task digital twin applications, as well as the difficulties in effectively managing and optimizing 5G+ network resources to address these challenges.

A. Challenge 1: Dynamic and real-time network requirements of multi-task digital twin applications

1) Real-time state synchronization: Digital twin technology has been developed to create virtual models of physical entities that are aimed at enhancing the monitoring, analysis, and maintenance of physical systems. However, managing and maintaining digital twins requires extensive data transmission, which can lead to delays, congestion, and other network-related issues. In the fields of automation and robotics, even slight delays or latency can cause major production efficiency reductions or safety hazards. For instance, in an automated assembly line, a robotic arm that experiences a delay in movement could result in misalignment during the assembly process leading to defective products or equipment damage. While 5G and beyond (5G+) network technologies are recognized for their capability to deliver low-latency and high-throughput network services, designing a dedicated 5G+ network slicing for an IIoT system that integrates digital twin technology remains an underexplored research topic.

2) Reconstruction of task topology: Despite the advantages of 5G network, real-world digital twin applications often present challenges for real-time synchronization due to the presence of multiple sub-tasks. For example, a digital twin used for robotic repair may include workpiece scanning, defect detection, tool path generation, workpiece milling, and milling monitoring as its sub-tasks. As an application's topology in a physical system may involve multiple sub-tasks, synchronizing the state of each sub-task independently from the physical system to the digital twin may result in an inconsistent representation of the physical world's pipeline in the digital twin due to network fluctuations and variations in the data transfer rates of each sub-task. Therefore, real-time state synchronization and data transfer are critical to ensure a coordinated representation of the topology in the digital twin. Additionally, heavy network traffic generated by the sub-tasks can lead to queue backlog on both the network's control and data planes. Previous studies have shown that high queuing delays within a 5G network lead to rate variability [8] that negatively affect the QoS [9].

B. Challenge 2: Managing and optimizing 5G+ network resources in a proactive, dynamic, and continuous manner

In a practical IIoT system, the communication needs of various applications or sub-tasks can vary thus leading to diverse demands on network resources. This poses challenges for managing network resources dynamically, proactively, and continuously. To tackle this challenge, 5G+ networks utilize Network Slicing (NS) technology that enable network providers to create multiple customized and prioritized virtual networks on the same hardware infrastructure. However, evaluating various network slicing and configuration options to achieve optimal network performance can be challenging and impractical in a real-world production setting. Inspired by the success of creating digital twins for physical objects, building a 5G+ network digital twin is a promising solution to address these challenges. This digital twin provides a virtual representation of the real 5G+ network through real-time traffic synchronization. Moreover, scalability is crucial for a 5G digital twin to be compatible with the increasing complexity and size of the 5G network topology, requiring significant computational resources and advanced modeling techniques. Lastly, security and privacy concerns arise due to the sensitive data collection and storage in the digital twin.

III. Proposed Solutions

In this section, we present our proposed solutions to address the aforementioned challenges.

A. Resolving Challenge 1: A dynamic network slicing provisioning approach for digital twin

To meet the real-time requirements of multi-task digital twin applications, we propose leveraging our prior work on the Dynamic and Autonomous Network Slice Management (DANSM) middleware [10] as a 5G network slicing approach for communication between the physical world and digital twin, which is shown in Figure1. To highlight the idea, we use a robotic repair as an example of an IIoT use case, which requires real-time synchronization between the physical system and its digital twin. As depicted in Figure 1, a 5G+ network comprises User Equipment (UE), Radio Access Network (RAN), and Core Network (CN). The UE, which includes 5G-enabled mobile devices, establishes wireless connections with the RAN, which provides wireless connectivity between the UE and CN. In the robotic repair example, the UE can comprise a 5G-enabled cameras and a 5G-enabled robotic arm, where each UE is responsible for a specific sub-task with its own network requirements. To ensure real-time synchronization, we employ Multi-access Edge Computing (MEC) in close proximity to the RAN, enabling the real-time defect detection sub-task within the robotic repair.

By bringing computing resources closer to the RAN, the latency in transmitting data between the physical network and the digital twin is reduced thus resulting in a more accurate emulation and testing of the network. This is critical for real-time synchronization in the digital twin leading to faster decision-making and improved efficiency and overall

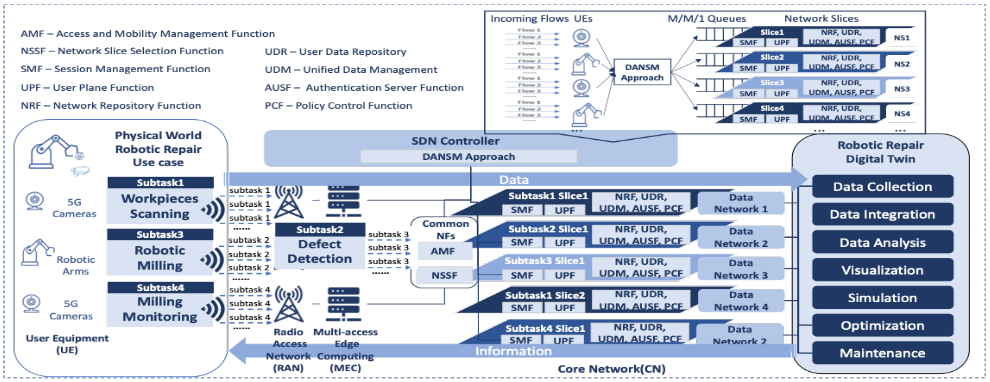

Fig. 1: A dynamic network slicing provisioning approach

performance of the robotic repair. This approach differs from the traditional 5G architecture, where MEC is usually placed in the CN, away from the RAN. Then the network flow processed by RAN and MEC will be forwarded to the CN, which manages and orchestrates a number of network functions from both the control plane and the data plane. The service-based 5G core network allows us to deploy a number of independent network slices to satisfy various network requirements from UE and its applications.

To that end, we create a specific type of network slice for every sub-task within the robotic repair based on its network requirements. In our CN architecture, every independent network slice has its own dedicated control plane functions, which are responsible for managing the network resources within the slice. This independent slice design reduces the risk of misconfiguration and potential security vulnerabilities. Moreover, the dedicated control plane functions enable each slice to scale up and down its own data plane functions based on the real-time traffic pattern. To improve network scalability and resource utilization, we deployed the DANSM in a Software-defined Networking (SDN) [11] controller to perform the following tasks: 1) computing the sub-task priority for determining the dynamic and autonomous assignment/release of network resources within each network slice; 2) utilizing multiple M/M/1 queuing model to balance the load and minimize the queuing latency among every network slice; and (3) propose a heuristic algorithm to schedule the sub-tasks and dynamically manage the network resources based on the sub-task priority.

In conclusion, the MEC-based multiple network slicing approach helps minimize the end-to-end latency between physical world devices and their digital twin. Furthermore, the use of DANSM improves resource utilization and minimizes queuing latency, resulting in further reduction of end-to-end latency and enhanced performance of the digital twin.

B. Resolving Challenge 2: A 5G+ network slicing digital twin

To address the challenges of managing and optimizing 5G+ network resources in a proactive, dynamic, and continuous manner, we propose a 5G+ digital twin architecture as shown in Figure 2. Our 5G+ network slicing digital twin consists of 5 modules. 1) **Data Repository** module is responsible for collecting, storing, and processing data from the physical 5G+ network. It serves as a logically centralized location for all the data needed for the digital twin, allowing for efficient access and analysis by other modules while ensuring sensitive data is securely stored and processed to address security and privacy concerns. 2) **Traffic Emulator and Monitoring** is responsible for current network behavior emulation and monitoring in the virtual environment. This module addresses the need for real-time synchronization with the physical network by creating virtual network traffic based on data obtained from the Data Repository by UE and RAN emulator, routing and forwarding the virtual traffic by Service-Based 5G Core Network. Moreover, this module allows for the monitoring of all virtual traffic by the SDN controller and includes tools for measuring and analyzing network performance metrics, as well as identifying potential bottlenecks for improvement. 3) **Data Analysis and Optimization** module analyzes the data collected by the Data Repository module to optimize network performance, resource allocation, and QoS based on analysis results. Using advanced analytics and machine learning algorithms, this module identifies and predicts network traffic patterns and trends, and makes recommendations for network optimization, which can be tested in the Traffic Simulator module. In addition, the module provides real-time feedback to network operators through the Digital Twin Manager on network performance. 4) **Traffic Simulator** module is responsible for simulating and testing different network slicing scenarios and configurations in a controlled environment. It works in conjunction with the Traffic Emulator and Monitoring module to generate virtual network traffic and assess the network's performance under different scenarios. This module allows network operators to evaluate and optimize the network's performance before implementing any changes in the physical network, thus addressing the challenge of scalability and reducing the risk of disruptions or downtime. It also serves as a platform for testing new network applications and services before they are deployed. 5) **Digital Twin Manager** module is responsible for managing and coordinating all the modules of the 5G+ network slicing digital twin. It acts as a controller that connects

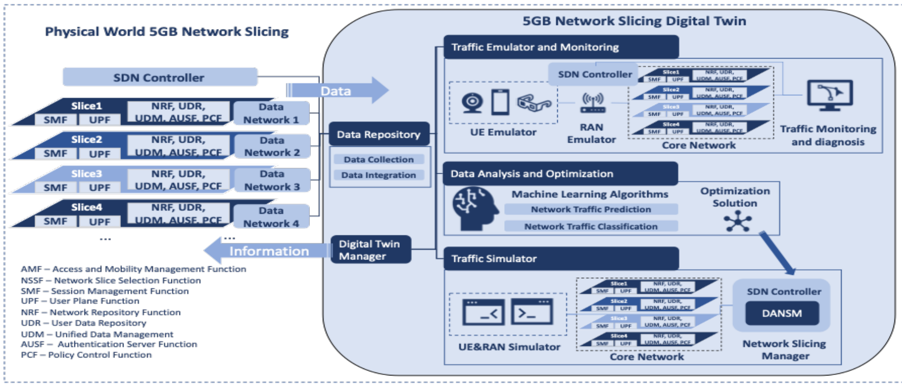

Fig. 2: A 5G+ network slicing digital twin architecture

and synchronizes the data and operations between different modules. This module provides feedback to network operators for network optimization and management. Additionally, it provides an interface for network operators to interact with the digital twin and access its data and functionalities.

IV. Conclusion and Future work

This paper presented the challenges in utilizing digital twin technology in Industry 4.0 applications for efficient monitoring and maintenance, which require extensive data transmission and may result in delays and network-related issues. Although 5G and beyond (5G+) network technology is widely adopted to overcome these challenges, real-world digital twin applications still pose challenges in delivering dynamic and real-time network services for multi-task applications with varying traffic patterns. To address these challenges, a dynamic 5G network slicing provisioning approach has been proposed. To address the additional challenges of managing and optimizing 5G network resources in a proactive, dynamic, and continuous manner, a 5-module 5G+ network slicing digital twin architecture is presented. In the future, several research directions will be explored. Firstly, we aim to implement an edge-centric distributed deep learning approach [12] to identify suitable network resources. Secondly, we plan to integrate the zero-trust security module [13] into our current 5G+ network slicing digital twin architecture to enforce zero-trust access controls to critical assets and resources. Lastly, we aim to extend our current 5G+ network slicing digital twin architecture to a federated learning framework, enabling collaboration across different organizations while ensuring data privacy.

V. Acknowledgment

This work is supported in part by funding from Siemens Technology. Any opinions, findings, and conclusions or recommendations expressed in this material are of the author(s) and do not necessarily reflect the views of the sponsor.

References

[1] S. Aheleroff, X. Xu, R. Y. Zhong, and Y. Lu, "Digital twin as a service (dtaas) in industry 4.0: an architecture reference model," *Advanced Engineering Informatics*, vol. 47, p. 101225, 2021.

[2] J. Zhang, T. Deng, H. Jiang, H. Chen, S. Qin, and G. Ding, "Bi-level dynamic scheduling architecture based on service unit digital twin agents," *Journal of Manufacturing Systems*, vol. 60, pp. 59–79, 2021.

[3] 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.

[4] W. Wu, C. Zhou, M. Li, H. Wu, H. Zhou, N. Zhang, X. S. Shen, and W. Zhuang, "Ai-native network slicing for 6g networks," *IEEE Wireless Communications*, vol. 29, no. 1, pp. 96–103, 2022.

[5] 3rd Generation Partnership Project (3GPP), "Technical specification group services and system aspects; study on new services and markets technology enablers," Tech. Rep. TR 22.874, 3GPP, 3GPP Support Office, 650 Route des Lucioles, F-06921 Sophia-Antipolis Cedex, France, 2018.

[6] 3rd Generation Partnership Project (3GPP), "Technical specification group services and system aspects; study on 5g phase 2," Tech. Rep. TR 22.874, 3GPP, 3GPP Support Office, 650 Route des Lucioles, F-06921 Sophia-Antipolis Cedex, France, 2019.

[7] 3rd Generation Partnership Project (3GPP), "Service requirements for machine-type communications (mtc); stage 2," Tech. Rep. TS 22.261, 3GPP, 3GPP Support Office, 650 Route des Lucioles, F-06921 Sophia-Antipolis Cedex, France, 2016.

[8] G. Wang, Z. Gao, and M. Xu, "Integrating link-based discrete credit charging scheme into discrete network design problem," *European Journal of Operational Research*, vol. 272, no. 1, pp. 176–187, 2019.

[9] M. Irazabal, E. Lopez-Aguilera, and I. Demirkol, "Active queue management as quality of service enabler for 5g networks," in *2019 European Conference on Networks and Communications (EuCNC)*, pp. 421–426, IEEE, 2019.

[10] Z. Min, S. Shekhar, C. Mahmoudi, V. Formicola, S. Gokhale, and A. Gokhale, "Software-defined dynamic 5g network slice management for industrial internet of things," in *2022 IEEE 21st International Symposium on Network Computing and Applications (NCA)*, vol. 21, pp. 251–259, 2022.

[11] D. Kreutz, F. M. Ramos, P. E. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proceedings of the IEEE*, vol. 103, no. 1, pp. 14–76, 2014.

[12] Z. Min, R. E. Canady, U. Ghosh, A. S. Gokhale, and A. Hakiri, "Tools and techniques for privacy-aware, edge-centric distributed deep learning," in *Proceedings of the Workshop on Distributed Infrastructures for Deep Learning*, pp. 7–12, 2020.

[13] A. Manan, Z. Min, C. Mahmoudi, and V. Formicola, "Extending 5g services with zero trust security pillars: a modular approach," in *2022 IEEE/ACS 19th International Conference on Computer Systems and Applications (AICCSA)*, pp. 1–6, 2022.