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Intent-Based E2E Network Slice Management for Industry 4.0

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***Abstract*—Fifth generation(5G) provides one of the cornerstone features in networking, network slicing enables multiplexing virtualised logical networks over the same infrastructure for multiple business services. This research work provides the design and implementation of a novel E2E network slice management framework capable of managing the deployment E2E network slices across the 5G/Pre-6G infrastructure. The contribution has been validated for Industry 4.0 use cases where both horizontal and vertical slicing have been validated. This framework has been designed, prototyped, and empirically validate over a multi-tenant 5G/Pre-6G network infrastructure using the requirements of an Industry 4.0 use case: a production pipeline. The provisioning of a network slice in more than 8096 nodes has been carried out in less than half a second which demonstrate the effectiveness of the proposed framework.**

***Keywords*—6G, 5G, Network Slicing, End-To-End Network Management, Industry 4.0**

I. Introduction

NETWORK slicing is a fundamental key feature of 5G networks and Pre-6G networks. It has the potential to transform Industry 4.0 by allows fain-grain control of network resources. This novel control enables the efficient handling of isolation of network performance, allowing the fulfilment of demanding Pre-6G use cases requirements such as Massive Industrial IoT, Smart Production Lines, Augmented Reality for Industrial Maintenance, etcetera. These uses cases will impose challenging and very diverging quality of service (QoS) requirements [1], which can be categorised into mobile broadband reliable low latency communication (MBRLLC), massive Ultra-Reliable Low-Latency Communication (mURLLC) and human-centric services (HCS).

Fig. 1 contains suppliers, manufacturers and warehouses that are the main key elements of the revolution of the Industry 4.0 together with the different logical network segments involved in a End-to-Edn (E2E) connectivity. The same network segments that need to be slices to warranty such demanding QoS requirements.

This research work define the concept of horizontal and vertical slicing among different network segments to differentiate between two dimensions of the same slice. Horizontal slice is the section of the slice that physically connects the different network segments among physical network devices that interconnect suppliers, manufacturers and warehouses. Vertical slice is the expansion of that slice across the virtualisation and service layers that are present in every of the previous network segments. See Fig. 1 for a graphical representation of the concept.

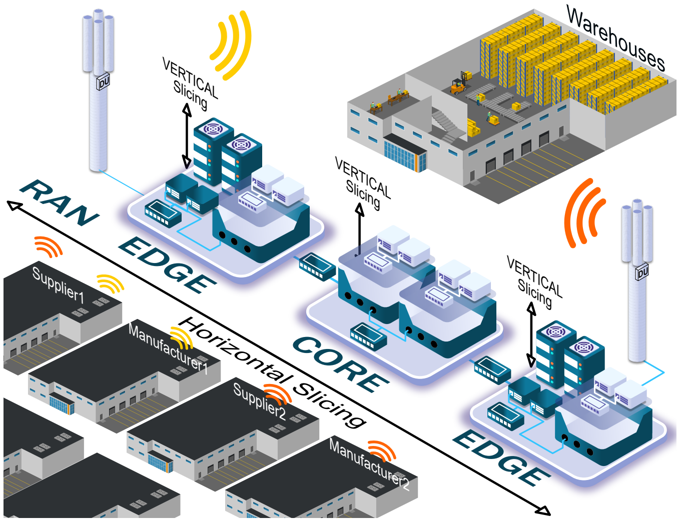

Fig. 1: Service Base 5G Architecture Segments Overview.

The achievement of an E2E 5G/Pre-6G network slice management for Industry 4.0 imposes several challenges. First, to create a intent-based API able to describe and express the E2E network slices. Second, to provide the network control enablers to enforce network slices along the different points of the E2E architecture [2]. Third, to be able to perform an scalable and orchestrated management of in the deployments of network slicing through all the network segments (horizontally) and through virtualised and containerised architectures (vertically). Forth, to control and manage of all the network resources that are involved in the life-cycle of each slice, created on demand at run-time [3]. Even if we manage to address all these challenges, there is yet a clear need to perform an integration along all these functionality to allow a scalable E2E network slice management system to deal with the complete dynamically changing infrastructure.

Our major contribution is the design and implementation of a novel E2E network slice management framework capable of managing the deployment E2E network slices across the 5G/Pre-6G infrastructure. The contribution has been validated for Industry 4.0 use cases where both horizontal and vertical slicing have been validated. This framework has been designed, prototyped and validate over a multi-tenant 5G/Pre-6G network infrastructure using the requirements of a Industry 4.0 use case:

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a production pipeline.

The proposed E2E network slice management for Industry 4.0 provides the following innovations beyond state of the art:

1) To allows Industry 4.0 to create ad-hoc customized Network Slices Templates (NST) for their digital transformation like Autonomous Robots, Big Data, Cloud Computing, Internet Of Things and Cyber Security among other fulfilling data speed requirements, quality, latency and reliability.
2) To allow Industry 4.0 to interconnect different suppliers, warehouses and manufacturers on demand end-to-end with the the demanded QoS.
3) To allows Industry 4.0 to manage the life-cycle of network slice instances (NSI), including provisioning, association/disassociation, instantiation, and decommissioning (termination). It enables a unified monitoring point to determine the current state of each NSI.
4) To allows Industry 4.0 to automatise all the coordination of VNF coming from suppliers, manufacturers and warehouses to achieve a coherent E2E NSI deployment, filling the current gap in enabling a true inter-connection and coordination of their services to achieve an enhanced level of automation .

II. RELATED WORK

There has been a growing interest to rethink development strategies around the challenge of splitting physical networks into multiple logical networks inside the same infrastructure. The network sharing paradigm was predicted years ago to be one of the main enablers for new business opportunities while decreasing capital and operational expenditure (CAPEX/COPEX).

The evolution from the network sharing paradigm has push towards the achievement of network slicing capabilities. Samdanies et at [4] have provided an introduction to the concept of the Network Slice Broker based on the 3GPP network sharing management architectures. Furthermore, standardisation on network slicing has been gaining momentum. 3GPP TS 28.530 introduces the network slice concepts [5], TS 28.531 defines the mechanisms to provision network slicing in 3GPP architectures [6], and TR 28.801 [7] provides recommendations on management and orchestration for network slicing. The proposed design in this paper is compliant with the relevant recommendations.

With the impact of 5G/Pre-6G technologies on industry 4.0 [8], many companies are increasing the migration of its uses cases to a new cost-efficient solutions while guaranteeing an agreed performance of some specific services. Network slicing has now become a key technology to ensure certain levels of well-performing services. Nowadays, there are multiple research and developments in the state of the art leveraging network slicing to guarantee QoS levels among heterogeneous use cases such as the Internet of Things (IoT) [9], Smart Grids [10], Smart Cities [11], eHealth [12], or Intelligent Transport, Education and Media and Entertainment [13], among others.

Despite the aforementioned related work, it has not been yet considered an E2E network slicing framework for the industry 4.0 along with 5G/Pre-6G multi-tenant infrastructures, including wireless, physical and virtualised technologies that expand across different network segments. This has been the main motivation of this research work.

III. 4.0 INDUSTRY WAREHOUSE MULTI-TENANT ARCHITECTURE

Fig. 2 outlines the different network segments of the 5G/Pre-6G multi-tenant warehouse architecture set up in our premises to showcase how our framework fits in and how the traffic is flowing in the data path cross through them. The main architectural components of the network slice management framework are also depicted, used to provide network slicing on demand among different Suppliers, Manufacturer

The presented architecture in Fig. 2 is fully compliant with ETSI MANO GR NFV-EVE 012 v3.1.1 including Management and Orchestration (MANO) [14]. Our contribution to the already standardised architectural components are depicted in other colour. The main components are:

- Management Systems
  - **Virtual Infrastructure Manager (VIM)**, in charge of the life-cycle management of virtual infrastructures.
  - **Virtual Network Function Manager (VNFM)**, in charge of the life-cycle management of the virtual network functions (VNFs)[15]. .
  - **NFV Orchestrator (NFVO)**, in charge of orchestrating the deployment of services and resources [16].
  - **Slice Manager**, in charge of life-cycle management of E2E network slices.
- Management Agents
  - **Element management system (EMS)** enabler for life-cycle management of the virtual network functions
  - **Resource Inventory Agent (RIA)** enabler for discovering for physical and virtual machines and their topological connections.
  - **Flow Control Agent (FCA)** enabler for wired and wireless programmable data-plane technologies, providing a unified control interface for network slicing.
  - **5G Topology Agent (5GTA)** enabler for discovering for the list 5G EU devices and their connection to the 5G network.

This contribution can be considered as a prototype implementation of that standard ETSI MANO, which advances significantly beyond the state of the art in terms of the network slicing control functionalities. Firstly, the management agents refer to the components which provide the enablers for the management system of the architecture. Secondly, the different network segments shown in Fig. 2 are referred to as the Front-Haul, Edge, Mid-Haul, Core and Back-haul segments respectively. The Radio Access Network (RAN) is usually deployed in the Front-Haul to provide wireless coverage. The Edge network segment is either co-located with the RAN or located in its proximity to allow the deployment of services in the last mile close to final users. The Mid-haul network interconnects the Edge with the Core network, which is usually a large-scale data centre of the telecommunication operator. The back-haul is the telecommunication network infrastructure that is

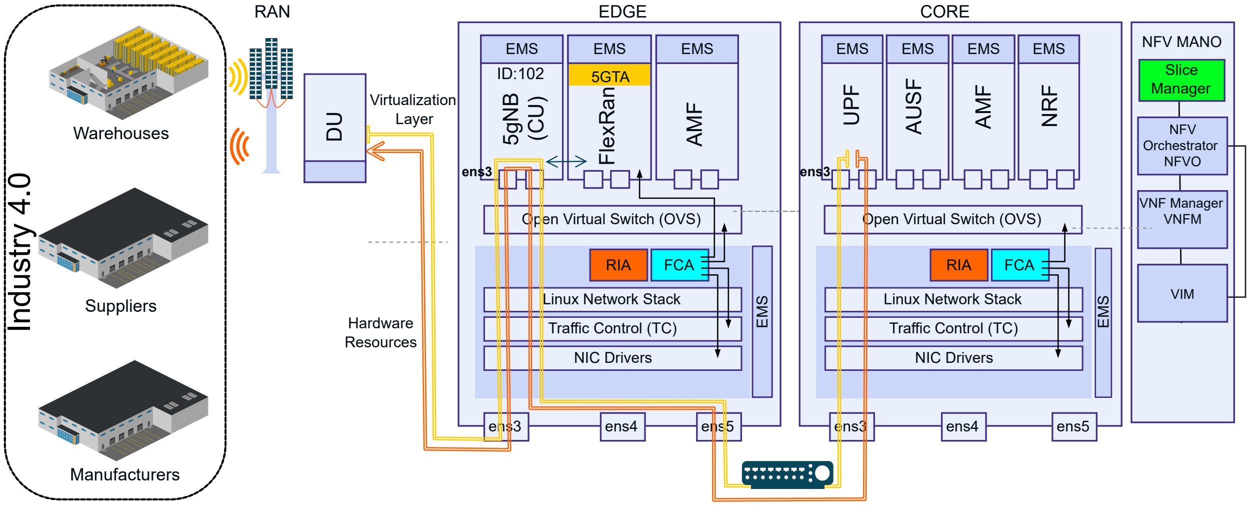

Fig. 2: Industry 4.0 over a 5G Multitenant Architecture

typically managed by infrastructure operators for connecting different systems.

The coloured components that are shown in Fig. 2 represent the main building blocks of the proposed and consequently our main extensions to the Industry 4.0 over a 5G Multi-tenant architecture. Section IV will present more detailed information on their roles, responsibilities and tasks.

Figure 2 also overviews an example of an E2E network slice created to ensure E2E performance and the overall QoS warranties. The data path depicted as yellow and orange lines in this figure shows the main points of the infrastructure from where the network traffic passes through. It is noted that this is just a representative example of a network slice and other scenarios are also supported.

IV. SLICE MANAGER FRAMEWORK FOR INDUSTRY 4.0

The overall architecture of the proposed framework is mainly composed of four architectural layers as shown in Fig.3. Bottom-up approach the first layer is composed of network monitoring, discovering and control agents spread throughout the entire network infrastructure. These are the enablers for network slicing [17] [18] [19] and monitoring [20] [19] and topology discovery [21], along wire and wireless network segments.

The explanation of these enablers is out of scope of this contribution, however, the references indicated provide a complete explanation of such enablers. The second layer is the communication middleware layer that allows all our components to share messages using publication and subscription. Four different topics are used to receive topological information (Topology), send Intents to each FCA deployed along the nodes (Intents), receive acknowledge from FCAs (ACK) and receive slicing metrics from FCAs deployed (Metrics).

The third layer is the management layer which in turn is divided into two main blocks

- On the left of the figure, NFVO is incharge to coordinate all the NFV and their life-cycles management and network services,
- On the right of the figure , our Slice Management extension to MANO architecture to manage network slices and their life-cycle.

The fourth layer is the North Bound Interface (NBI), from which any external authorised agent can access to the exposed functions to create, modify or monitor either NSTs or NSIs. The next subsection explains three and forth layer in detail.

A. *Management Modules*

The component is composed of the following modules, required to provide the management functionality expected.

Topology Engine: maintains topological information of the physical and virtual machines and their associated network interfaces with the logical and physical connections between such interfaces. This information is used to know the points of the network where the control functions need to be configured throughout the data-path of the E2E slice.

Slice Provisioning Engine: is responsible of interacting with the control plane. When a NSI requires to be enforced along the E2E datapath, this component will process and filter all the affected network interfaces along the way. Therefore, once each NSI is created, it will produce a set of intents that will be sent to the *FCAs* where each network interface belongs. These intents define the aim of enforcing network slices on such interfaces and provide the network requirements for this action to be carried out.

Metric Aggregator Engine: receives metrics from the infrastructure and keeps them up to date. Such metrics can be aggregated in temporal and spatial domains. To allow spatial aggregation, the topological information is required by the module. This module inspects the state of the NSIs to determine how to aggregate raw metrics to provide metrics associated to the NSIs. Such metrics are exposed in real-time using the northbound API of the framework.

B. *Network Slice Template and Network Slice Instance*

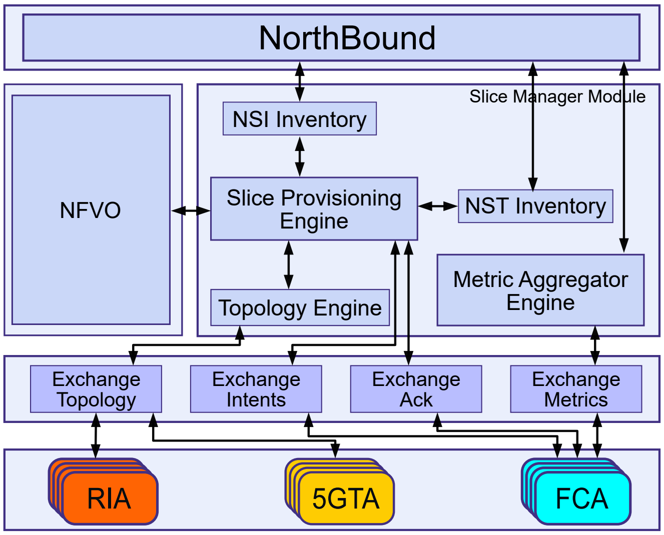

Fig. 3: Slice Manager Architecture Design

The module is the main architectural component of the proposed framework that deals with the complete life-cycle management of both NSTs and NSIs. In this context, it is essential to concisely define these two managed entities:

NST is a generic blueprint structure where to define a set of network requirements that are related to the Network slice definition in the context of the data-plane. For example, Minimum bandwidth warranted for the slice (bps); Maximum bandwidth available for the slice (bps); Priority of the traffic that belongs to the slice; Incoming or Outgoing Traffic direction; Coverage area indicates the area to be deploy and the set of physical and/or virtual network interfaces will be employed to program the network devices through the E2E slice data-path. If some of the values are not selected default parameters will be inserted. Once the NST is create will be stored in the NST Catalogue.

NSI represents an network slice instance. NSIs are create base on NSTs descriptions forming a complete set of actions to be triggered across the entire E2E data-path.

The management of NSI-related and NST-related functions are reachable from the Northbound Interface (NBI) of the . That NBI is following an Intent-based approach, described in section V.

V. INTENT-BASED NBI FOR INDUSTRY 4.0

The Intent-based NBI is a message driven API. The Intent messages are composed by one or more resources describing the flows over which to apply the slice, one intent that defines which kind of action (e.g. create a slice), and a list of parameters for fine-grained specifications (e.g, encapsulation).

Listing 1: Intent-based Message

```
{  "Resources": [{
        "resourceId": "1",
        "encapsulationID": "vxlan/445",
        "srcIP": "146.191.50.231",
        "dstPort": "4789",
},{
        "resourceId": "2",
        "encapsulationID": "gtp/625c0ff2",
        "srcIP": "10.100.0.19",
    "dstPort": "2152",
},{
        "resourceId": "3",
        "encapsulationID": "gtp/1",
        "srcIP": "192.188.0.140",
        "dstPort": "5004",
  }],
  "Intent": {
    "actionType": "INSERT",
    "actionName": "CREATE_SLICE",
    "slice_id": "production-line",
    "priority": "1",
    "MAB" : "23000000",
    "MGB" : "14000000"
 },
  "Params": [{
    "paramName":  "interfaceName",
    "paramValue": "eth0"
    },{
    "paramName":  "device",
    "paramValue": "edge1"
    },...] }
```

VI. IMPLEMENTATION

The complete network slice management framework for Industry 4.0 has been designed and prototyped. RIA and were implemented in Java 8 whereas FCA was implemented in Python 3.7 and 5GTA was implemented in C, mainly due to facilitating the integration with the underlying control plane functions.

OpenStack Rocky has been used as VIM implementation. The softwarized 5G network employed was the RAN and Core of the OpenAirInterface software components. In terms of network slicing, OpenAirInterface FlexRAN [17] was utilized for 5G RAN slicing. The NetFPGA-based 5G Network Slicing Core [18] was adopted for network slicing over the physical infrastructure[19], and OVS network slicing extensions [20] were employed for network slicing over virtual infrastructures, respectively. The prototype implementation of the matches exactly the design described in Figure 3 and the infrastructure used for the testing and empirical validation matches exactly the one described in Figure 2.

VII. EXPERIMENTAL RESULTS

This section explains the set of experiments carried out to validate the proposed E2E framework. The experiments are based on the empirical analysis of topological scalability in the Slice Manager and the empirical analysis of NSI Scalability in the Slice Manager.

A. *Execution Testbed*

The testbed used for experimentation is composed of 6 machines Dell T5810 with Intel Xeon CPU Xeon E5-2665 v4, 8 Cores with hyper-threading, 20 MB Intel Smart Cache, 256GB of RAM, 2TB solid-state drive (SSD) and 2 x Intel X540-AT2 10 GbE. The six machines are divided as follow: the first machine contains the , the second machine hosts OpenStack infrastructure with two virtual machines (VMs). One VM is acting as a network controller and the second VM is acting as a cloud controller[22]. The remaining 4 machines are acting as a OpenStack compute. Each of the 4 different physical machines is a different physical zone. The VIM contains two tenants sharing the cores and edges among them. This configuration creates a star network topology among all machines creating an overlay physical infrastructure. The VIM is running the OAI with one virtual machine in the edge connected directly to a Ettus USRP X310 and 5 virtual machines in the core. This OAI infrastructure overlay a GTP tunnel per UE between 5gNB(CU) to SPGW-U creating, in some parts of the infrastructure, a double overlay network.

B. *Empirical Analysis of Topological Scalability in Slice Manager*

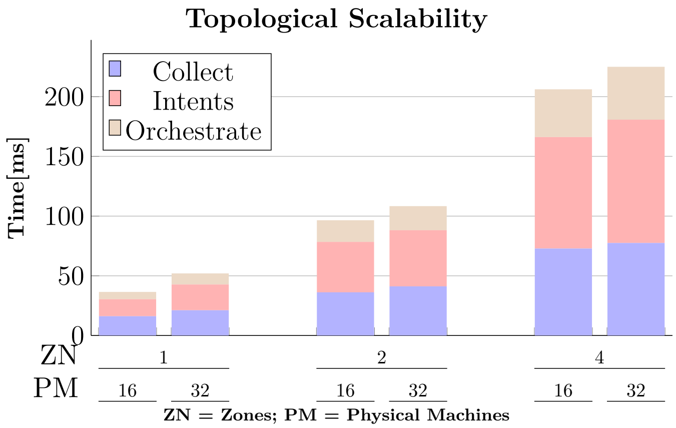

Fig. 4: Industry 4.0 Framework NSI Provisioning Times

In order to evaluate the topological scalability in the industry 4.0, these experiments create different scenarios allowing to stress the in heavy conditions in terms of large-scale size of the infrastructures and to analyse the time required to manage slices in such scenarios.

Figure 4 shows 2 X-axis groupings for various scenarios. The first X-axis, called *Zones (ZN)*, is the number of physical zones available in the infrastructure associated to each scenario, exponentially ranging from 1 to 4. The second X-axis, called *Physical Machines (PM)*, ranges from 16 to 32 PMs associated to each of the zones available in that scenario. The number of *Virtual Machines (VM)* is always 32 allocated in each PM for a shake of simplicity. The Y-axis shows the time required for the to collect the topological information, generate the Intents associated to the NST, and orchestrate those intents to achieve and E2E network slice installation (units are expressed in milliseconds). Each of the stacked bars plotted in Figure 4 shows the three different steps measured along the execution of the scenarios. These times start when a new E2E network slice request is received in NBI until all NSI are completely sent to the distributed FCA deployed in the infrastructure. Notice this experiment is large enough to represent a real infrastructure. The first time stacked in blue called *Collect* is the time the spends collecting all the topological information associated to the infrastructure used for the scenario. The second time stacked (red) called *Intents* is the time taken to the to create all the Intents to be enforced in the context of the NSI. The third time stacked (orange) called *Orchestrate* is the time that the consumes to submit all the Intents to the different FCA instances.

The proposed system for Industry 4.0 yields high scalability from the fact that it performs impressively well of no more than half a second even in the most stressed scenario with four zones and 32 physical machines per zone and 32 VMs per physical machine (8192 nodes) . It clearly validates support for large-scale scenarios.

C. *Empirical Analysis of Network Slice Instance Scalability for Industry 4.0*

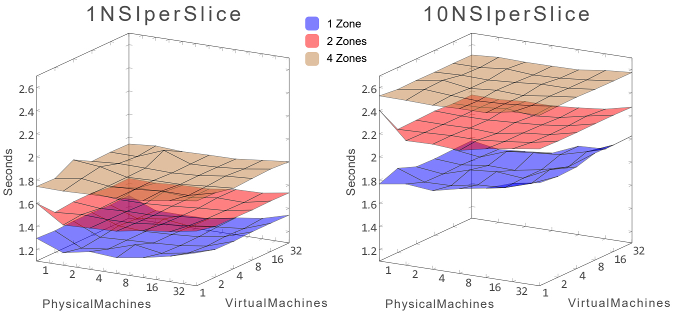

Fig. 5: Industry 4.0 Framework NSI Scalability

Figure 5 shows two surface plots where the X-axis are ranging the number of physical machines from 1 to 32, the Y-axis is composed of a number of (per Zones) Virtual Machines. The number of Virtual Machines are ranging from 1 to 32 in each zone within each physical machine. There are six different experiments to measure the time with different number of NSIs (1, 10) created per network interface. Each of the layer in each plot represent different zones, the blue is 1 zone, red 2 zones and brown 4 zones. For 1 NSI, a Industry 4.0 production line ultra-low latency slice is deployed. For 10 NSIs, the following slices for Industry 4.0 use cases are deployed: SCADA control, production-line, inter-line controller, control center, industry surveillance service, augmented reality maintenance, customer management services, internet broadband, network control, mission-critical. The larger scenario (32 PMs, 32 VMs and 4 Zone) takes around 1.8 seconds for 1 NSI and this number is increased 2.6 for 10 NSIs. These numbers clearly indicates the scalability with different numbers of concurrent slices.

VIII. CONCLUSION

This paper presents a framework to automate E2E network slice management. Also presents a detailed design including overall architecture and components, network slice life-cycle management, the deployment of the proposed network slice management framework for the industry 4.0 over a 5g network infrastructure. The framework is able to define network slices managing the whole life-cycle end-to-end. All the operations after slice definition are automated for high efficiency and to reduce operating expenditure been this one of the KPIs for the industry 4.0. The framework has been prototyped and empirically validated regarding the main functionality. Experimental results have demonstrated the high efficiency and scalability of the implemented system in terms of rapid network management operations over an emulated realistic large-scale 5G infrastructure. In the worst case scenario, creating a network slice instance only takes 1.17 seconds.

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