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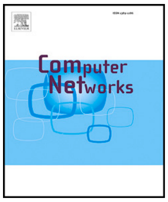

Review article

Technology trends and challenges in SDN and service assurance for end-to-end network slicing

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ABSTRACT

Network slicing is a core technology to enable new services and solutions in 5G and upcoming 6G communications. However, many issues arise when applying network slicing at a commercial scale, as this requires end-to-end management and automation of the network. Network slicing also requires various state-of-the-art technologies based on collaboration across international standards organizations and open-source communities. This paper reviews and summarizes the recent technological trends and challenges related to Software-Defined Networking (SDN) and service assurance for end-to-end network slicing. First, we focus on the essential use cases and technology trends associated with network slicing, followed by a survey of standard organizations and open-source projects related to network slicing and how they have evolved. Then, we overview an end-to-end network slicing architecture considering Open Radio Access Network (O-RAN) standard. For Radio Access Network (RAN) slicing, we zero in on managing RAN and xHaul with an integrated policy. For transport slicing, we discuss SDN architecture and requirements for network slicing with traffic isolation, unified QoS policy, and traffic engineering. We also cover SLA management using protocol-independent active monitoring and passive monitoring. In the later part of the paper, we summarize technical considerations for end-to-end network slicing, including the RAN-integrated xHaul architecture, converged enterprise network for multi-connectivity, 5G edge data center architectures using programmable data plane, and network slicing security. Overall, this paper reviews the various design issues associated with network slicing and the proposals to resolve these issues to facilitate end-to-end network slicing at a commercial scale.

1. Introduction

As 5G communications have recently entered a massive deployment stage, service providers are eager to build new services using 5G technologies. One of the key goals of the 5G technology is to provide Quality of Service (QoS) guarantees for customers and the corresponding Service-Level Agreements (SLAs) reflecting the QoS guarantees [1].

Network slicing is an essential technology for 5G to meet SLAs and to create new revenue streams, and it is also considered a key technology in the upcoming beyond 5G and 6G [2]. Specifically, Network slicing allows for new use cases of various 5G services with SLA requirements and provides new network architectures to autonomously control the 5G network. However, various technical challenges arise with network slicing to satisfy end-to-end SLA (Service-Level Agreement) requirements [3]. A network slice is an independent end-to-end logical network that runs on shared physical infrastructure, which can provide a negotiated service quality [4,5].

5G requires end-to-end automation for heterogeneous networks, including wired, wireless, and various types of virtual devices and existing physical network devices. Service providers can create the new 5G standard services through network slicing technology. As shown in Fig. 1, network slicing can be used to implement various new services defined by the 5G standard, such as enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), massive Machine Type Communications (mMTC), and Vehicle-to-Everything (V2X).

Network slicing can provide the following advantages to service providers. First, network slicing can support efficient resource management by logically separating resources in a sharing infrastructure. Second, network slicing can support new 5G services by integrating telecommunication companies (telco), enterprises, and cloud networks. Third, network slicing can support the end-to-end automation of 5G networks through a network slice policy. In particular, by integrating on-premise telecommunications and public clouds, an end-to-end network slicing architecture can optimize deployment costs and 5G service performance [6–9].

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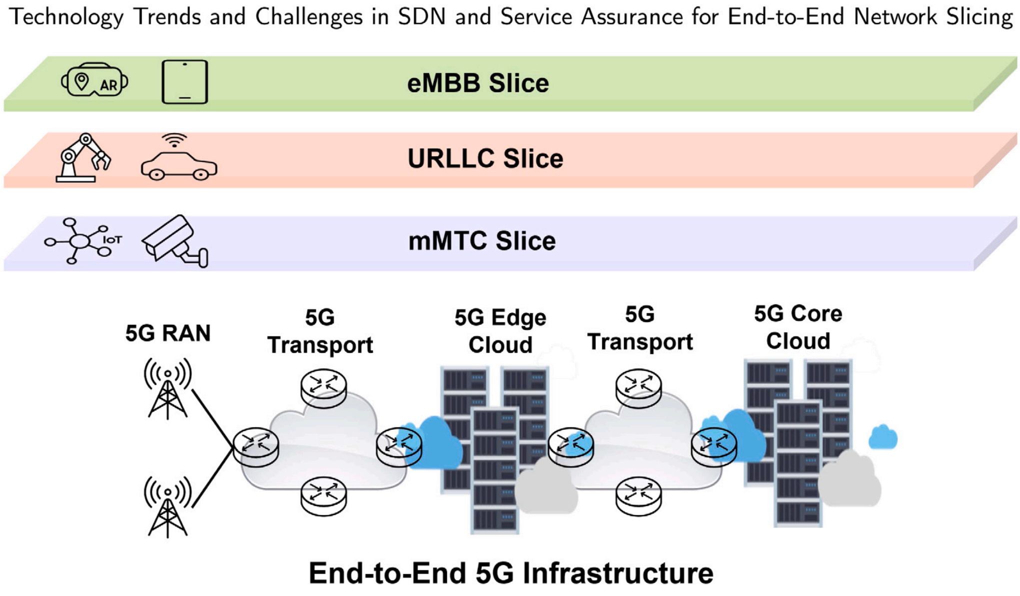


Fig. 1. The concept of network slicing.

In the first section, we introduce the various technology trends and challenges for end-to-end network slicing and explain technical considerations for end-to-end network slicing. In the next section, we present the significant use cases of network slicing and categorize the use cases based on actual project experience. We also explain the state-of-the-art technical trends and issues related to designing and implementing network slicing, including end-to-end network slicing, cloud-native, hyper-scale cloud, openness, programmability, zero-touch operation, and Intent-Based Networking (IBN). As network slicing must follow the recommendations of many standard organizations, we summarize 3GPP, GSMA, ETSI, TM Forum, O-RAN Alliance, IETF, ONF, and TIP's significant activities as the main contribution area of each organization. In Section 5, we also introduce the major opensource communities for network slicing, including LFN (Linux Foundation Networking), ONAP, O-RAN Software Community, Magma, Anuket, Nephio, CNCF, ONOS, P4, FRR, and SONiC and how each of opensource communities engages with other standardization organization and opensource communities. In Section 6, we describe the end-to-end network slicing architecture of 3GPP, including CSMF, NSMF, and NSSMF, and explain the significant domain of each slicing type, including RAN slicing, core slicing, and transport slicing. For core slicing, we present the use cases of core slicing, cloud-native 5G core architecture, and closed loop control architecture for core slicing with NWDAF. For RAN slicing, we describe the use cases of RAN slicing, the vRAN/O-RAN architecture, and RAN-Mobile xHaul integrated management, FHG (Front-Haul Gateway), and dynamic QoS configuration in RAN-Mobile xHaul. For transport slicing, we detail the end-to-end transport network architecture, SDN controller requirement for network slicing, traffic isolation in the transport network, and traffic engineering through Segment Routing.

Section 7 describes the SLA management of network slicing, including active and passive monitoring, a comparison between active monitoring and passive monitoring, and the management and interface of SLAs and Key Performance Indicators (KPIs). This paper proposes a protocol-independent SLA metric generation framework for active monitoring and end-to-end SLA management in a 5G network. In the final section, we suggest the technical considerations for end-to-end network slicing, including open platform/open interface, cloud platform architecture design, RAN integrated xHaul architecture, converged network slicing between private 5G and enterprise network, programmable data plane, network slicing security, and deep learning reinforcement for admission control.

Our contributions are summarized in three categories as follows:

1. **Survey of network slicing use cases, technical trend, standards, and open-source software**: We overview the concept, primary use cases, and important technology trends of network slicing. We also detail various standard organizations and relevant network slicing activities, their direction of evolution, and how they evolve with other organizations, such as open-source communities. Finally, we summarize open-source communities, relevant activities for network slicing, and the technical issues upon which open-source communities focus.
2. **Literature review of current end-to-end network slicing architecture and network slicing SLA management**: This includes an end-to-end 5G network architecture considering current O-RAN standards, including the transport, core, and RAN domains. We propose the integrated 5G RAN/xHaul architecture, end-to-end transport architecture, dynamic network slicing SLA management with dynamic QoS, network isolation, protocol-independent active monitoring, and end-to-end SLA/KPI management.
3. **Study of technical considerations for end-to-end network slicing evolution**: We propose a RAN-integrated xHaul architecture for private 5G and converged network slicing solutions for private 5G and enterprise networks, which can expand network-slicing services for enterprise businesses through a unified user policy. We summarize the evolution to disaggregated and programmable architecture and provide a 5G edge data center architecture using a programmable data plane. Finally, we outline research on and future directions for network slicing security.

2. Motivation of network slicing and use cases

The main drivers of network slicing are monetization by creating new services or using existing infrastructures efficiently. Two categories of network slicing use cases are shown in Fig. 2. First, Network Slice-as-a-Service (NSaaS) can create new services by virtual resource isolation with existing infrastructure. A typical example is 5G enterprise service, private 5G, MEC (Multi-Access Edge Computing), smart factory, 5G automotive, MCPTX (Mission-Critical PTT), patient services, energy transmission control, government surveillance, and emergency services, broadcasting and streaming, production, supply chain, gaming, railway, and automotive. Using network slicing technology, a service provider can provide new 5G services using shared infrastructure and save OPEX

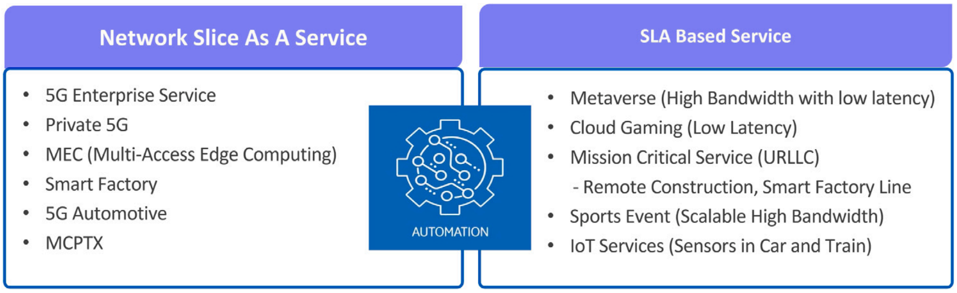


Fig. 2. Categories of network slicing use-cases.

(Operating Expense) and CAPEX (Capital Expenditure). The second use-case is the SLA-based services. Network slicing can support SLA-based service to monitor and guarantee SLA conditions. Network slicing can support the various SLA requirement of services such as eMBB, URLLC, and mMTC. For example, metaverse requires high bandwidth with low latency; cloud gaming requires low latency; remote construction and smart factory line requires mission-critical URLLC services. Sports event requires on-demand scalable, high bandwidth services instantly, dynamic scaling is essential, and 5G services also require many IoT services with a tremendous sensor. Network slicing use cases also can combine the two characteristics above. Network slicing service starts from a B2B use case, but network slicing can also be applied to a B2C use case as SLA management technology evolves. The essential underlying technologies for monetization using network slicing technology are application classification, security policy, big data analytics, and AI. Monetization strategies are also critical from the service provider's perspective. GSMA has defined the various use cases of network slicing [10]. The following sections provide typical net-work slicing use cases [11].

2.1. 5G enterprise service

5G enterprise services are an excellent use case for network slicing. 5G enterprise services can be provided by sharing existing service providers' resources or by establishing a new network; network-slicing technology can be applied in such cases. The 5G enterprise services mentioned above can be divided into slices within each vertical service to construct a network [12]. Representative 5G enterprise vertical services include smart factories, smart offices, smart cities, smart schools, and public safety. The network slicing concept can also be applied to wired and WiFi networks and private 5G networks; the integrated 5G enterprise network architectures are discussed in the next section.

2.2. Automotive

Automotive services are representative services that simultaneously support various types of slices (e.g., eMBB, URLLC, mMTC), defined in 5G standards, that satisfy the SLA conditions for each slice. For example, eMBB service is required for passenger terminals in vehicles providing infotainment services. Mission-critical URLLC services are required for autonomous driving based on a V2X network. In addition, it is possible to offer an mMTC-type slice that collects big data from numerous sensors in a vehicle. Each slice type should support different SLA requirements. In particular, mission-critical services such as autonomous driving require highly reliable and automated management. Large-capacity public transportation (e.g., buses, subways, trams, and trains) can expect a better service effect with network slicing than a single vehicle.

Fig. 3 illustrates an example of a 5G train in terms of network slices. 5G train is a good automotive use case for network slicing. 5G train supports various massive moving services, including PTT (Push-To-Talk) service for disaster situations, emergency control using sensors for preventing accidents, digital signage (e.g., dynamic announcements or advertisements on LCD displays), surveillance camera system services, and passenger mobile services. Network slicing is used to share the infrastructure resource and dynamically allocate and adjust resources considering SLA requirements and situations. 5G train network slice services can comprise eMBB and URLLC services. Passenger mobile phone services, surveillance camera system services, and digital signage are eMBB-type slices. URLLC-type slices include emergency control services with massive IoT sensors in trains to detect the distance from other trains and PTT (Push-To-Talk) voice for high-priority voice service in an emergency situation. Each service has different SLA requirements considering slice type and services, and SLA requirements can be adjusted based on the situation (normal, congested, or disaster). The service provider should dynamically create network slice instances considering the service demand and network utilization using the 5G train service infrastructure.

2.3. Multi-access edge computing

MEC(Multi-access Edge Computing) is the representative service area of network slicing, which offers cloud-computing capabilities and an IT service environment for application developers and content providers at the network's edge. MEC is characterized by ultra-low latency, high bandwidth, and real-time access to radio network information, which applications can leverage [13]. When a MEC service is built with network slicing, it can generate dynamic slices and apply various policies for subscribers [14]. Typical network slicing use cases of MEC are detailed in Table 1.

2.4. Private 5G

Private 5G is a wireless enterprise network using 5G technology. Compared to WiFi6, it supports stable connection, better mobility, network quality, security, and wide coverage, and it can also build new network slices for enterprise services; however, private 5G involves higher costs than WiFi networks. Network slicing can be the key differentiator from a service perspective, which is required to separate networks logically and provide services using the existing private 5G infrastructure [15,16].

3. Network slicing technical trend

With the commercialization of 5G, network slicing has evolved rapidly. Most of the technical trends are essential in network slicing and 5G/6G network automation. This section covers the important technology trends of network slicing as below.

- End-to-end network slicing;
- Cloud native;
- Hyperscale cloud;
- Openness;
- Programmability;
- Zero-touch operation;

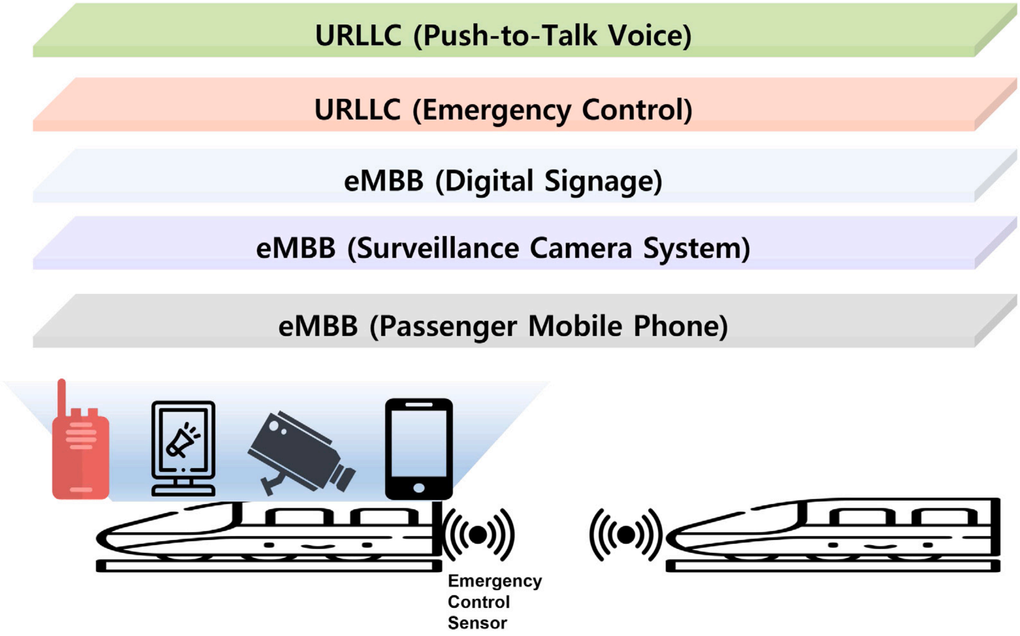


Fig. 3. Example of network slicing in 5G train service.

Table 1
MEC Network Slicing Use-Cases.

Use-case	Description
4K/8K Video Streaming	eMBB Service, Video Codec Compression
Video QoE Optimization	in MEC Data, Radio/Transport resource optimization
AR/VR Virtual Tour	Museum Tours, Model House Tours
CCTV	AI-based Facial Recognition
Metaverse	High-bandwidth, high-capacity, andultra-low latency
Stadium Live Event	Professional Sports, F1 Racing
Autonomous Vehicle	AR-based HUD
Smart Factory/Remote Construction	Industrial Automation (URLLC Service)

- Intent-based networking (IBN)

The following section explains each technical trend and how it is essential in state-of-art network slicing technologies.

3.1. End-to-end network slicing

Network slicing is a concept that includes end-to-end management. It began with core slicing in the initial stage, but it has recently been developed to support end-to-end slicing, including RAN slicing and transport slicing. RAN-integrated transport network automation is vital for RAN slicing. In addition, it is necessary to support the development of a unified management policy for end-to-end network slice segments. As end-to-end network slicing is a goal, there are many technical challenges to reaching this target. We explain an end-to-end network slicing architecture in Section 6 and network slicing SLA management in Section 7 to solve technical issues.

3.2. Cloud-native

Cloud-native technologies empower service providers to build and run scalable applications in modern, dynamic environments such as public, private, and hybrid clouds [17]. It is a significant technology trend that accelerates network slicing, as it should be available in container-based architectures and physical and virtual machine-based architecture.

Fig. 4 provides a comparison between virtual machines and containers. Compared to the traditional virtual machine architecture, the container architecture has various characteristics, as in Table 2. In the case of virtual machines, since each virtual machine runs independently, resource separation is advantageous for security and has the advantage of supporting multi-OS for each guest OS. Virtual machines require more resources than containers, which can be a disadvantage in scenarios where network slicing needs to be deployed at scale. A container does not require a separate guest OS, requiring relatively fewer resources and supporting fast deployment. These container characteristics enable various cloud native-based services. However, containers share the host operating system and can impact the performance of other containers running on the same host, leading to performance issues in network slicing. The 3GPP standard defines 5G core architecture

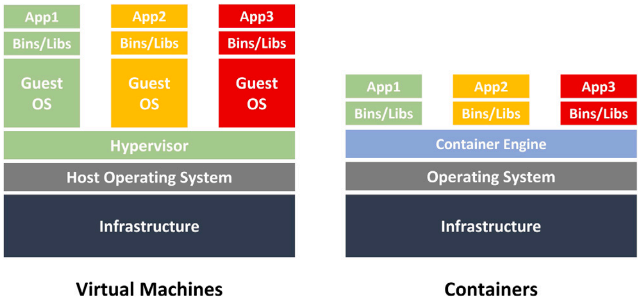


Fig. 4. Structure of virtual machines and containers.

Table 2
Comparison between Virtual Machines and Containers.

Characteristics	Virtual Machine	Container
Resource Requirement	Large	Small
Isolation/Security	High	Low
Deployment Speed	Slow	Fast
Multi-OS	Support	Not Support

as SBA (Service-Based Architecture). SBA is an architectural approach that decomposes network functions into smaller, modular services that can be more easily deployed and managed. Network slicing can be integrated with SBA to create more flexible and scalable network slices adapted to changing requirements. The cloud-native architecture supports rapid expansion in separating the control and data planes. It is suitable for SBA-based 5G network slicing as it can accommodate various IT-based services.

NFV (Network Function Virtualization) has evolved into cloud-native architectures. In the case of a cloud-native architecture for network slicing, it can support rapid end-to-end service and software deployment and operations based on CI/CD [18]. The existing virtualization management architecture has been standardized into the ETSI NFV MANO architecture, including NFVO, VNF-M, and VIM, but it is required to consider cloud-native orchestration for standardization [19]. It has recently become more common that 5G applications are deployed as cloud-native services, for which it is necessary to implement existing IT-based cloud-native technologies to facilitate network slicing as well as considering the following design principles to meet telco application requirements [20,21]:

- Considerations of 5G high-speed traffic processing (5G Core UPF, 5G RAN CU-UP);
- Migration from virtualization network for VNF to container network for CNF;
- Network automation and SDN technology with CNI (Container-Network Interface);
- 5G application software design suitable for cloud-native architecture;
- Cloud platform agnostic software design for heterogeneous cloud infrastructure;
- Lightweight edge data center architecture for vRAN, compact 5G core, and MEC;
- Cloud data center design where VNF and CNF coexist.

3.3. *Hyperscale cloud*

5G services and applications require various types and locations of cloud data centers. Table 3 categorizes 5G applications into RAN, Core, and third-party applications according to the requirements of the 5G service, allocating them to various data centers considering their type and location.

In addition, it is necessary to optimize the location of the data center, the type of virtualization technology, and the cloud-native toolset according to the resource requirements of each 5G service. For example, MEC services should support multi-cloud data centers such that each application that constitutes a slice can satisfy and optimize the slice characteristics (e.g., eMBB, URLLC). A hyper-scale cloud that combines private and public clouds has emerged to fulfill each slice's aspects and optimize costs. It combines public and private clouds by allowing data and applications to be shared between them [24]. Public cloud companies have recently accelerated the movement to provide novel 5G-based services by cooperating with telecom companies such as AWS outposts or building 5G directly from public cloud companies.

3.4. *Openness*

For operating network slicing at a commercial scale, it is essential to design and implement it with a clear principle of openness. Examples of openness are open-source, open standard, disaggregation, decoupling, and open API, as described in the following. Table 4 details the main area where openness is required for network slicing. When network slicing is designed and implemented based on openness, it can prevent vendor lock-in and support interoperability between heterogeneous devices. The openness of design can also reduce the costs associated with building 5G infrastructure and operational costs through enhanced operational efficiency [25]. In addition, new service ideas and commercial services can be shared through an open ecosystem with ease.

3.5. *Programmability*

Network slicing is implementing 5G service requirements through end-to-end automation. For network slicing automation, programmable architecture is essential in each management domain. The advantage of programmable architectures is that they can define and implement new services and use cases with programmable logic and allow for the automation of existing use cases. Table 5 details the programmable domains and methods for network slicing architectures. For API-based automation, a controller architecture is essential to configure the API. Recently, controller architectures have expanded from SDN controllers to RIC controllers of O-RAN. Moreover, application programmability (e.g., P4) has grown from the control plane to the programmable data plane [26]. Examples of applying programmable data plane technology to 5G major traffic processing applications such as CORE UPF and RAN CU-UP, as well as traditional IP-based communication equipment (e.g., data center switches and routers), have been presented [27,28].

3.6. *Zero-touch operation*

Network slicing aims to realize the concept of Zero-Touch Operation, which requires end-to-end network automation for 5G. Zero-touch operation for network slicing aims to automate the entire life cycle, including installation, deployment, configuration, and operation. It can be broadly divided into deployment automation (blue) and operation automation (green), as shown in Fig. 5.

Installation automation requires the massive and automatic installation of cloud infrastructure, including the OS and cloud platform. Deployment automation allows for the automated life cycle management of network slicing, including instantiation, deletion, and scaling of network slices. CI/CD (Continuous Integration/Continuous Deployment) involves agile software life cycle management through a cloud-native infrastructure.

Configuration automation allows for the automatic configuration of the initial or run-time parameters of 5G applications after their instantiation in the slice. Auto-healing and auto-scaling can be used when a fault or resource issue is detected in the network slice to recover it. Closed-Loop Automation (CLA) is used to optimize network slices automatically based on policies such as the SLA requirement of the slice. Closed-Loop Automation can be explained as a circular relationship between automated control, as analyzed in Table 6.

Network automation is a long-term objective involving step-by-step processes, from providing an alternative to repetitive execution actions to observing and monitoring the network environment and network device status, making decisions based on multiple factors and policies, and providing an adequate perception of the end-user experience.

Table 3
Data center types and locations considering 5G applications.

Service area	Private Clou[d			Public Cloud
	Far Edge	Edge	Core	
RAN	DU	CU	N/A	N/A
Core	N/A	UPF (MEC/Private 5G)	AMF/SMF/UPF and so on	AMF/SMF/UPF and so on
Management	N/A	RAN NSSMF Domain Orchestrator (RAN) Domain Controller (SDN/RIC) RAN EMS	CORE NSSMF TRANSPORT NSSMF Global Service Orchestrator (CORE) Domain Controller (SDN) CORE EMS	Global Service Orchestrator Domain Orchestrator
Third Party Application	MEC (Low Latency)	MEC	Cloud-Native Service	Cloud-Native Service

Table 4
Openness for Network Slicing.

Area	Container
Open Standard	3GPP, NGMN, GSMA, IETF, TMForum, TIP ETSI (NFV, ZSM, ENI, MEC), O-RAN
Open-Source	LFN (Linux Foundation Network), ONAP, CNCF, ONOS, P4, FRR, SONiC, O-RAN SC, Magma, CAMARA
Open Hardware	OCP (Server, Switch), O-RAN(WG9)
Disaggregation of S/W and H/W	SONiC (Data Center), DANOS (CSR)
Decoupling of the control plane and data plane	SDN, O-RAN, CUPS
Open Interface	TMForum API, NEF [22,23], Open Front Haul, eCPRI

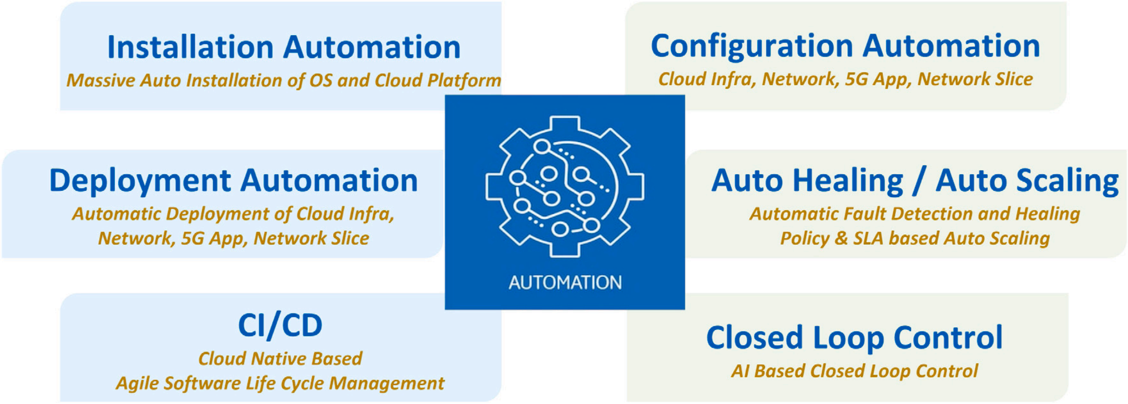


Fig. 5. End-to-end automation for zero-touch operation.

Table 5
Programmable domains and methods for network slicing.

Area	Container
CSMF	CSMF API (OSS/BSS API), TM Forum API
NSMF	Workflow Engine
RAN NSSMF	O-RAN RIC API (near-RT RIC, non-RT RIC)
TRANSPORT NSSMF	SDN Controller API, ONF TAPI
CORE NSSMF	Core API Exposure
Programmable Data Plane	P4 API (P4 Runtime)

Table 6
Types of Closed-Loop Automation (CLA).

CLA Type	Triggering	Description
Auto-Healing	Fault	Detect fault and control slice to recover
Auto-Scaling	Resource	Scale-in/out to adjust resource status
Policy-Based CLA	Policy	Detect and control slice policy (QoS, Security)
Intent-Based CLA	Intent	Detect and control the intent of the slice
Analytics/AI-Based CLA	Analytics	Analyze big data or use AI algorithms for complicated RCA (Root Cause Analysis)

3.7. *Intent-based networking*

IBN (Intent-based networking) has been spreading to advance network slicing automation, defined as follows [33]: IBN is a piece of networking software that helps to plan, design, implement, and operate networks that can improve network availability and agility. It comprises lifecycle management software for networking infrastructure.

1. Translation and validation;
2. Automated implementation;
3. Awareness of network state;
4. Assurance and dynamic optimization and remediation.

In recent years, intent-based networking products, standardization, and open-source activities have been actively progressing, each developing with mutual influence [34]. In-tents are the business or IT

Table 7
Intent-based networking standards organization activities.

Organization	Project/ Working group	Description
TM Forum	Autonomous Network Project	Define fully automated zero-wait, zero-touch, zero-trouble innovative network/ICT services
ETSI	ENI ISG	The Experiential Networked Intelligence Industry Specification Group (ENI ISG) [29].
	ZSM ISG	The ETSI ZSM (Zero-touch network and Service Management) group [30].
	GANA	GANA (Generic Autonomic Networking Architecture) Reference Model [31].
3GPP	NWDAF	Network Data Analytics Function [22].
IETF	ANIMA	Autonomic Networking Integrated Model and Approach (ANIMA) [32].

Table 8
Intent-based networking open-source activities.

Organization	Project/Working Group	Description
ONAP	Intent Framework	ONAP Intent Framework
OpenStack	GRP	Group-based Policy (GBP) abstractions for OpenStack provide intent-driven declarative policy models [39]
ONOS	Intent Framework	ONOS SDN controller sub-system that allows applications to specify their network control desires in form of policies [40]
O-RAN	RIC	Near-RT RIC/non-RT RIC for closed-loop control

outcomes that an organization needs. Translation, activation, and assurance are the main functions of an intent-based network. The translation captures intent into policies that the network can act. Activation is the installation of these policies across the physical and virtual network infrastructure through the use of network-wide automation. Assurance involves continuous monitoring through analytics and machine learning and verifying the desired intent to apply, and the business outcomes are achieved [35]. Table 7 describes major standards organizations related to IBN [36]. The detailed content of each standardization body is explained in the following standardization body section below [37].

The concept of intent-based networking has been applied in various areas, such as OpenStack, ONOS, ONAP, and O-RAN. Table 8 describes the use of intent-based networking in open-source projects. A typical use-case of IBN in network slicing is to define and optimize SLA for each slice through closed-loop control. Recent industrial management and orchestration include the concept of IBN [38].

4. Network slicing standards

Network slicing requires the effort of many standard organizations because it is evolving in the following areas: wireless communication, transport network, telecommunication, service provider, infrastructure, and cloud technology. Furthermore, these standards have mutually evolved along with the open-source communities. This section covers the following standard organizations for network slicing.

- 3GPP (3rd Generation Partnership Project);
- GSMA (GSM Association);
- ETSI (European Telecommunications Standards Institute);
- TM Forum;
- O-RAN Alliance;
- IETF (Internet Engineering Task Force);
- ONF (Open Networking Foundation);
- TIP (Telecom Infra Project).

Table 9 summarizes network slicing organizations and focus areas. It describes how the various standard bodies are interlinked.

4.1. 3GPP

Since network slicing was defined based on the 5G standard, the 3GPP standard has become the essential standard compared with others. In 3GPP, the following working groups described in Table 10 have been actively focusing on the area.

3GPP network slicing standards have developed through interactions with ETSI standards and open-source projects such as ONAP. Table 11 describes the major 3GPP standards of network slicing. In particular, 3GPP standardizes the following areas:

- The basic concept of network slicing;
- The architecture of network slicing;
- Management and orchestration;
- 5G Network Resource Models (NRMs);
- 5G end-to-end Key Performance Indicators (KPIs);
- Network Data Analytics Services for closed-loop control (e.g., NWDAF);
- Network Slice Selection Services.

4.2. GSMA

GSMA is an organization representing the interests of mobile operators, considering the concepts and use cases of network slicing from the operator's point of view [56]. GSMA has also been working to define a generic slice template [57], which provides a universal description of a network slice type that could be used by infrastructure vendors, mobile operators, and slice buyers. The Generic network Slice Template (GST) is a set of attributes that can characterize a type of network slice and service, which is generic and not dependent on any specific network deployment. The Network Slice Type (NEST) is a GST filled with values. The values are assigned to express a given set of requirements, supporting a particular customer use case of network slice. The NEST is used as an input to the network slice preparation performed by the Network Slice Provider (NSP).

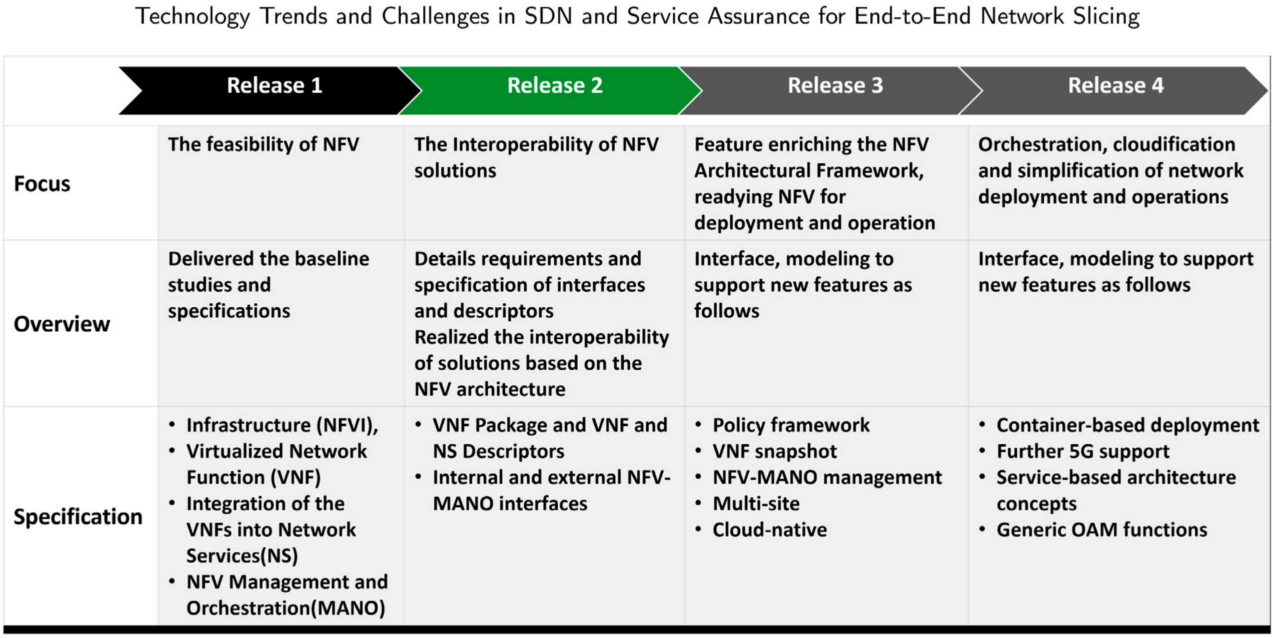
4.3. ETSI

ETSI is a European Standards Organization that deals with telecommunications, broadcasting, and other electronic communications networks and services. The ETSI Industry Specification Groups (ISGs) have been working on standardization activities related to network slicing:

- NFV (Network Function Virtualization);
- ZSM (Zero-touch network and Service Management);
- ENI (Experiential Networked Intelligence);
- MEC (Multi-access Edge Computing).

Table 9
The Summary of Network Slicing Standard Organization and Area.

		3GPP	GSMA	ETSI	TML Forum	O-RAN Alliance	IETF	ONF	TIP
5G Architecture	5G Architecture	O	O						
	5G SA Standard	O							
	Service Based Architecture	O		O					
Network Slicing	Architecture	O		O			O		O
	Slice Management	O		O					
	Slice Template	O	O						
Management & Orchestration	5G Management & Orchestration	O		O	O				
	NFV			O					
	Cloud Native Architecture	O		O	O				
	Service Management	O	O		O				
APIs	Open API	O			O	O	O	O	O
RAN	5G RAN	O				O			
	O-RAN	O				O		O	O
	RIC					O		O	
Transport	xHaul					O	O	O	O
	SDN						O	O	
Core	5G Core	O						O	O
	Network Slice Selection	O							
SLA Management	5G KPI	O							
	SLA Measurement	O					O		
Analytics/AI	NWDAF	O							
	AI/ML	O		O	O				
Automation	Zero Touch Provisioning	O		O	O		O	O	O
MEC	MEC Architecture	O		O				O	
	MEC Services			O					


Technology Trends and Challenges in SDN and Service Assurance for End-to-End Network Slicing

	Release 1	Release 2	Release 3	Release 4
Focus	The feasibility of NFV	The Interoperability of NFV solutions	Feature enriching the NFV Architectural Framework, readying NFV for deployment and operation	Orchestration, cloudification and simplification of network deployment and operations
Overview	Delivered the baseline studies and specifications	Details requirements and specification of interfaces and descriptors Realized the interoperability of solutions based on the NFV architecture	Interface, modeling to support new features as follows	Interface, modeling to support new features as follows
Specification	• Infrastructure (NFVI), • Virtualized Network Function (VNF) • Integration of the VNFs into Network Services(NS) • NFV Management and Orchestration(MANO)	• VNF Package and VNF and NS Descriptors • Internal and external NFV-MANO interfaces	• Policy framework • VNF snapshot • NFV-MANO management • Multi-site • Cloud-native	• Container-based deployment • Further 5G support • Service-based architecture concepts • Generic OAM functions

Fig. 6. Summary of NFV standard releases.

The ETSI ISG Network Function Virtualization (NFV) was founded in 2012 to build a software-based network. ETSI ISG NFV was undertaken as work comprising two-year phases, as shown in Fig. 6. In this context, network slicing is based on virtualization technology, making the ETSI NFV standard a vital standard, along with the 3GPP standard [58]. In particular, the life cycle management of the slice defined in 3GPP is an extension of the standard based on ETSI NFV, and both standards have been developing in a cross-referenced manner [59–64]. The recent NFV release 4 focuses mainly on NFV enhancement for 5G, such as network slicing, service-based architecture (SBA), and cloud-native services.

The ETSI ZSM (Zero-touch network and Service Management) group was formed in December 2017 to accelerate the definition of the required end-to-end architecture and solutions. Like the 3GPP network slicing architecture, the ZSM architecture considers domain-specific management (i.e., closed-loop control in an access management domain, a core management domain, and a transport management domain) and is integrated and managed in the E2E service management domain. Table 12 provides the ETSI ZSM specifications.

Artificial Intelligence (AI) has recently become the core technology for the high-level automation of autonomous networks [72]. The ETSI Experiential Networked Intelligence (ENI) ISG has been working on

Table 10
3GPP Network Slicing Working Groups.

Working Group	Main Focus Area
SA1	Slicing Use-Cases and Requirements
SA2	Slicing System Architecture
SA5	Slicing Management
RAN 1/2/3	RAN Slicing

Table 11
3GPP Network Slicing Standards.

Specification	Title
TS 23.501	3rd Generation Partnership Project (3GPP), Technical Specification [41]
TS 29.500	5G system; technical realization of service based architecture [42]
TS 28.530	Management and orchestration; Concepts, use-cases, and requirements [43]
TS 28.531	Management and orchestration; Provisioning [44]
TS 28.532	Management and orchestration; Generic management services [45]
TS 28.533	Management and orchestration; Architecture framework [46]
TS 28.540	Management and orchestration; 5G Network Resource Model (NRM); Stage 1 [47]
TS 28.541	Management and orchestration; 5G Network Resource Model (NRM); Stage 2 and Stage 3 [48]
TS 28.552	Management and orchestration; 5G performance measurement and assurance data [49]
TS 28.554	5G end-to-end Key Performance Indicators (KPIs) [50]
TS 29.520	Network Data Analytics Services [51]
TS 29.531	Network Slice Selection Services [52]
TR 23.791	Study of Enablers for Network Automation for 5G (eNA) [53]
TR 23.799	Study on Architecture for Next Generation System [54]
TR 28.801	Study on management and orchestration of network slicing for next-generation network [55]

Table 12
ETSI ZSM Specifications.

Specification	Title
ZSM 001	Requirement [65]
ZSM 002	Reference Architecture [66]
ZSM 003	E2E Management and Orchestration of network slicing [67]
ZSM 004	Landscape [68]
ZSM 005	Means of Automation [69]
ZSM 006	Proof-of-Concept Framework [70]
ZSM 007	Terminology for concepts in ZSM [71]

Table 13
ETSI ENI Specifications.

Specification	Title
ENI 001	ENI use-cases [73]
ENI 002	ENI requirements [74]
ENI 003	Context-Aware Policy Management Gap Analysis [75]
ENI 004	Terminology for Main Concepts in ENI [76]
ENI 005	System Architecture [77]
ENI 006	Proof-of-Concept Framework [78]
ENI 007	ENI Definition of Categories for AI Application to Networks [79]

standardizing cognitive network management architectures using AI. Table 13 details the ETSI ENI specifications.

MEC is a crucial use-case and business driver for network slicing, and it is the representative service of 5G. The ETSI MEC ISG has been developing Mobile Edge Computing standards since 2014 and changed its name to reflect Multi-access Edge Computing to standardize wired, wireless, and integrated edge computing. MEC provides low latency services to mobile users and reduces transport traffic bandwidth. In addition, it has the advantage of offering local awareness, a regional-specific service, and providing high QoE (Quality of Experience) using information collected through edge computing.

Table 14
O-RAN Working Group.

Working Group	Work Item
WG1	Use-Cases and Overall Architecture [83,84]
WG2	RIC (non-RT) and A1 Interface
WG3	RIC (near-RT) and E2 Interface
WG4	Open Front-haul Interfaces
WG5	Open F1/W1/E1/X2/Xn Interface
WG6	Cloudification and Orchestration
WG7	White-box Hardware (ORD)
WG8	Stack Reference Design
WG9	Open X-haul transport
WG10	OAM

4.4. TM forum

The TM Forum is a global industry association for service providers and suppliers in the telecommunications industry. The TM Forum is working towards an Open Digital Framework, Open Digital Architecture (ODA), Framework, and open APIs [80]. The TM Forum Open APIs is a suite of 50+ REST-based Open APIs for network slicing architectures (e.g., APIs between OSS to CSMF interface).

4.5. O-RAN alliance

In February 2018 by major mobile operators. Its mission is to reshape the RAN industry toward more intelligent, open, virtualized, and fully interoperable mobile networks. For this purpose, the O-RAN ALLIANCE has been working on O-RAN specifications, interoperability testing, and an O-RAN open-source community with the Linux Foundation. The O-RAN architecture has the following benefits. First, O-RAN reduces CAPEX through open interfaces, open-source software, hardware reference design, and cloud-native features; furthermore, it reduces OPEX as it enables reduced RAN automation. Second, O-RAN can improve network efficiency and performance through closed-loop control. Third, O-RAN supports the agility of software through the use of cloud-native infrastructure. Table 14 details the O-RAN working group and work items for standardization.

RIC inherits an open interface-based automation architecture trend, which started with an SDN controller for automating switch/router and expanded to the RAN domain. Based on the O-RAN architecture, various network slicing use cases can be applied, such as RAN slice SLA assurance, multi-vendor slices, and NSSI resource allocation optimization [81,82]. For O-RAN mobile X-haul standardization, O-RAN WG9, which is the Open X-haul Transport Workgroup, has been working on the following items:

- O-RAN Xhaul packet-switched architecture and solutions;
- O-RAN management interface for transport network element;
- O-RAN Xhaul transport testing.

4.6. IETF

Transport network slicing requires standardizing transport network architectures and network control technologies based on SDNs. IETF has been conducting the following standardization activities in connection with existing network-slicing standards organizations:

- Transport network architecture for network slicing;
- SDN-based transport network control architecture, such as SR (Segment Routing);
- Service assurance measurement to measure the SLA of a network slice.

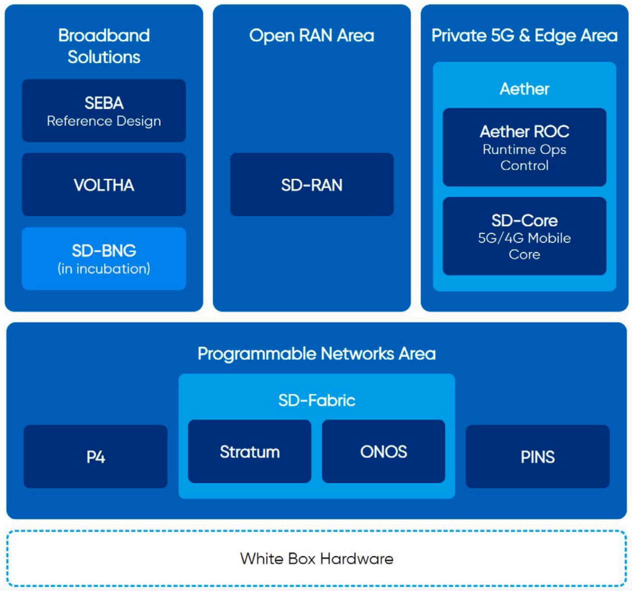


Fig. 7. ONF area and projects.
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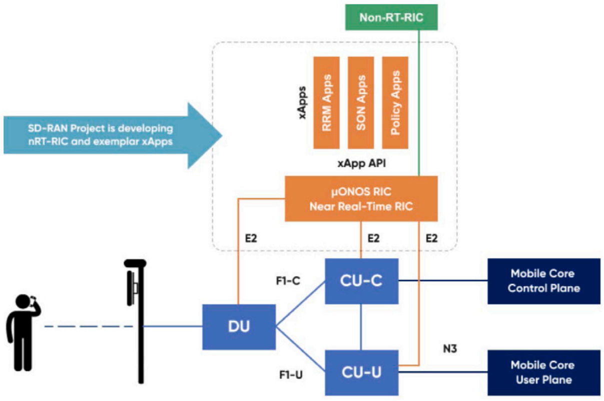

Fig. 8. ONF SD-RAN.
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For network slicing architectures, IETF has defined the IETF network slice framework [85], ACTN (Abstraction and Control of Transport Networks) [86], and framework for end-to-end IETF network slicing [87]. In order to apply network slicing in the transport domain, it is necessary to separate the network for each slice, apply network slicing policies such as QoS and security, and optimize it through traffic engineering. The existing transport network must evolve into an architecture capable of dynamic policy-based control using SDN, where the most representative technology for this purpose is Segment Routing. IETF has also defined the DetNet (Deterministic Networking) architecture to provide a time-sensitive network architecture for real-time network slicing [88]. An active measurement protocol that uses a probe packet, such as TWAMP, is widely used to measure the SLA of a slice in the transport section. IETF IPPM (IP Performance Measurement) is working towards standardizing performance measurements, an essential technology in network slicing.

4.7. ONF

ONF is a non-profit organization that has previously focused on SDN areas such as OpenFlow, ONOS open-source controller, and P4 [89]. ONF has recently been conducting various research, development, standardization, and reference design activities for the transformation of wired and wireless infrastructure, led by operators of broadband, private 5G, O-RAN, and programmable networks. ONF is currently working on various 5G projects, such as SD-RAN (see Fig. 7), which allows for near-real-time RIC (nRT-RIC) of O-RAN, based on the ONF SDN controller platform (uONOS), and has cooperated with the O-RAN Alliance and TIP (see Fig. 8).

For transport networks, the Open Transport Configuration and Control (OTCC) project aims to promote standard configuration and control interfaces in SDN, defining these interfaces with open-source SDN software and standards such as 5G xHaul applications and ONF Open Transport API (TAPI). ONF has also represented an SDN architecture for 5G slicing [91].

4.8. Telecom Infra Project

The Telecom Infra Project (TIP) is a global community of companies and organizations seeking to provide infrastructure solutions to advance global connectivity since 2016 [92]. TIP project groups consist of access, transport, and core and services projects. The E2E-NS (End-to-End Network Slicing) project group in the core and service projects has set the target of developing commercially viable end-to-end network slicing ecosystems [93]. Open platforms, such as Open RAN, Open Core Network (OCN), and Open Optical and Packet Transport (OOPT), are also used in the TIP. The Open RAN Project Group aims to define and build RAN solutions based on general-purpose vendor-neutral hardware, open interfaces, and software [94,95]. The OCN group has been working to develop an open, cloud-native, and converged core, which is a collection of micro-services implementing various core network functions. OCN has also been collaborating with the Mag-ma open-source project. The OOPT project group is currently divided into seven sub-groups, as in Table 15.

5. Network slicing open-source

Various open-source organizations and projects related to network slicing have been cooperating and competing with each other and creating new use cases and technologies with standard organizations. Network slicing requires technologies in various fields (e.g., wired, wireless, and cloud), so it is essential to verify the feasibility of new open-source technologies and develop them in connection with standards organizations. Table 16 summarizes relevant open-source organizations and projects.

5.1. Linux foundation networking

LFN (Linux Foundation Networking) is an open-source networking project under the Linux Foundation, which targets 5G, cloud-native, and edge computing. LFN software and projects provide platforms and building blocks for network infrastructure and services across various service providers, cloud providers, enterprises, vendors, and system integrators, enabling rapid interoperability, deployment, and adoption [97]. The 5G Super Blueprint is an industry-moving initiative, including an open-source industrial collaboration that covers RAN, edge, and core. Fig. 9 depicts the 5G Super Blueprint, composed of the component projects detailed in Table 17.

5.2. ONAP

The ONAP (Open Network Automation Platform) is an open-source networking project under LFN. The project aims to develop a widely used platform for orchestrating and automating physical and virtual network elements, including complete life cycle management. ONAP is evolving through cooperation with various standards and open-source

Table 15
OOPT Sub-Groups.

Working group	Work item
DCSG	The Disaggregated Cell Site Gateways group works on the definition of open and disaggregated white box cell site gateways
PSE	The Physical Simulation Environment group represents the effort to develop an open-source multi-vendor tool for optical network planning
CANDI	The Converged Architectures for Network Disaggregation and Integration group defines operator use-cases in open converged packet and optical networks
MUST	The Mandatory Use Case Requirements for SDN for Transport SDN group drives the adoption of SDN standards for IP/MPLS, Optical, and Microwave transport technologies
DOS	The Disaggregated Optical Systems group defines and builds open and disaggregated optical devices
OOPT-NOS	The Network Operating Systems group focuses on a reference open-source Network Operating System for OOPT disaggregated hardware platforms
DOR	The Disaggregated Open Routers group defines an open and disaggregated core router

Table 16
Open-Source Organizations and Projects.

Name	Summary
LFN	Open-source network projects under Linux Foundation (5G, cloud-native, and edge computing projects)
ONAP	Orchestration and automation platform (End-to-end orchestration)
O-RAN Software Communities	O-RAN open-source (collaboration between the O-RAN ALLIANCE and Linux Foundation)
Magma	Mobile core network solution (Wireless access, WiFi access, private networks, and 5G mobile broadband)
Anuket	Common model, standardized specifications of reference infrastructure, and conformance and performance frameworks
Nephio	Kubernetes-based, cloud-native intent automation (Domain orchestration and automation comparing with ONAP)
CNCF	Container and cloud-native open-source ecosystems
ONOS	Open-source SDN controller by ONF
P4	Programming language for data plane programmability
FRR	Open-source internet routing protocol suite from Zebra project
SONiC	NOS open-source project for cloud data center switch, led by Microsoft and OCP
P4	Programming language for data plane programmability
FRR	Open-source internet routing protocol suite from Zebra project
SONiC	NOS open-source project for cloud data center switch, led by Microsoft and OCP

Table 17
5G Super Blueprint main components.
Source: Adapted from [96] with permission.

Component Project	Description
Magma	Open, flexible, and extendable mobile core network solution
ONAP	End-to-end Orchestration, automation, life cycle management, and service assurance solution for network services
EMCO	Edge Multi-Cluster Orchestrator (EMCO) is an intent-based orchestration engine for cloud-native network functions (CNF) and cloud-native applications (CNA)
Anuket	Anuket is a project merging previous Open Platform for Network Function Virtualization (OPNFV) and Cloud iNfrastructure Telco Taskforce (CNTT) efforts. Anuket seeks to create a common reference architecture for the NFVI or the network cloud layer
O-RAN	The O-RAN Software Community (O-RAN-SC) is the open-source software for RAN

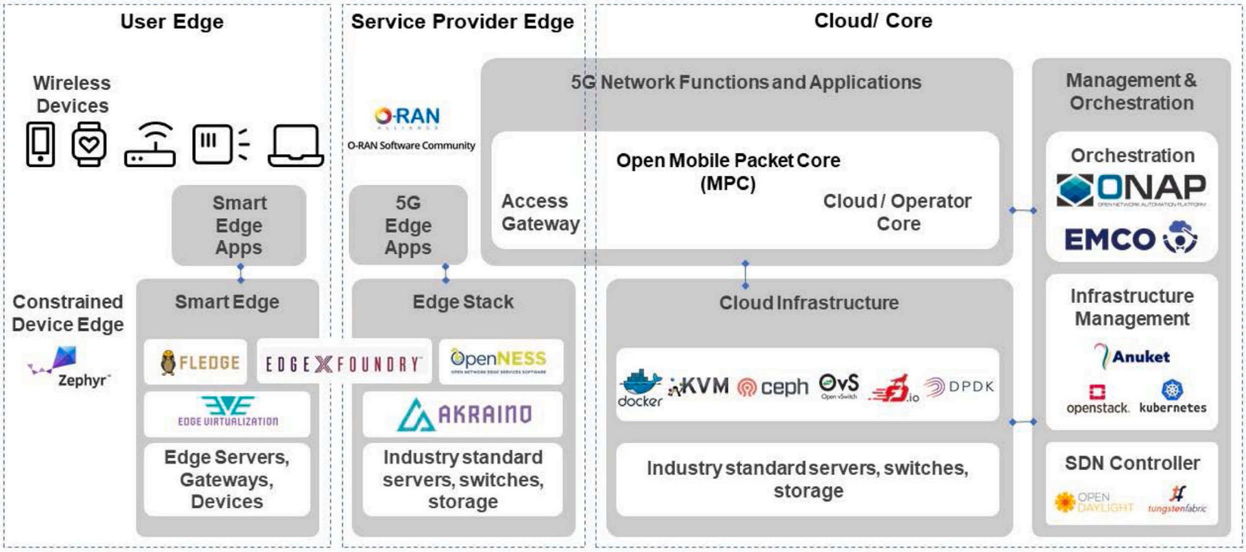

Fig. 9. 5G Super Blueprint.
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Table 18
ONAP Release Status and Plan.

Release	Initial release date	Main feature
Amsterdam	2017.11	Initial release
Beijing	2018.6	Scale-out VNF/NS on demand
Casablanca	2018.11	Hybrid networks with PNF support Closed loop automation (auto-scaling)
Dublin	2019.7	5G network slicing modeling
El Alto	2019.10	Security enhancement
Frankfurt	2020.6	ONAP based E2E Network Slicing management, PNF software upgrade
Guilin	2020.12	ONAP/3GPP and O-RAN Alignment, E2E Network Slicing (RAN Slicing)
Honolulu	2021.4	5G Service Modeling, 5G SON, ONAP/3GPP, and O-RAN Alignment
Istanbul	2021.11	Intent Framework, Modeling, and Translation(5G Slicing Support)
Jakarta	2022.6	O-RAN integration, 5G Blue Print integration, Intent-based networking (IBN) for E2E Network Slicing
Kohn	2022.11	5G SON with O-RAN, E2E Network Slicing KPI

Table 19
ONAP Blueprints.

Blueprint	Description
5G Blueprint	End-to-end service orchestration, network slicing, PNF/VNF lifecycle management, PNF integration, and network optimization
Virtual CPE	Residential gateway between CPE edge/cloud
Broadband Service (BBS)	Multi-gigabit residential internet connectivity services based on PON
VoLTE	Voice over LTE to create and manage the underlying vEPC and vIMS services
CCVPN	Cross-Domain and Cross-Layer VPN (CCVPN) is a cross-carrier solution combining SOTN (Software-defined Optical Transport Network) and SD-WAN
MDONS	Multi-domain Optical Network Service for Optical Transport Network Automation

organizations for end-to-end orchestration and automation, such as 3GPP, ETSI NFV ISG, ETSI ZSM, TM Forum, MEF, CNCF, OPNFV, O-RAN, and so on [98–103]. Table 18 provides the ONAP release status and plan.

The ONAP Blueprints shown in Table 19 are mature and verified ONAP use cases, of which the 5G Blueprint focuses on E2E network slicing. The detailed architecture and operation of ONAP are described in the network slicing architecture section.

5.3. Open RAN software community

The O-RAN SC(Open RAN Software Community) is a collaboration between the O-RAN ALLIANCE and Linux Foundation to support software creation for the Radio Access Network [104]. O-RAN software has been released every six months, starting with the Amber (2019.12), Bronze (2020.6), Cherry (2020.12), D (2021.6), and E (2021.12) releases. Projects described in Table 20 are in progress for each component implementation of O-RAN software architecture in Fig. 10 [105]. SMO (Service Management and Orchestration Framework) performs import roles and interfaces with other O-RAN components.

SMO comprises an end-to-end service orchestrator, a domain orchestrator, and a RAN domain orchestrator, which allows for O-Cloud management, SDN controller, RAN NSSMF, and non-RT RIC. O-RAN has Near-RT RIC, Non-RT RIC, and closed-loop control so that network slicing SLA optimization can be implemented through each RIC and interface [106–108]. In the end-to-end O-RAN architecture, O-RAN components interface with the transport domain and core domain architecture, where SMO manages the end-to-end service and closed-loop

Table 20
O-RAN Release Status and Plan.

Release	Initial release date	Main feature
Amber	2019.11	Initial Release
Bronze	2020.6	xApps and architecture (TS, Traffic Steering)
Cherry	2020.12	Traffic steering use case has been extended to include data collection by E2, ML-based xAPP
D	2021.6	xAPP (Bouncer; RIC performance measurement; LP cell, Load Predictor; and so on)
E	2021.12	RC (RAN Control), QP (QoE Prediction)
F	2022.6	TS use-case integration with RC xApp
G	2022.12	Non-RT-RIC and rApp

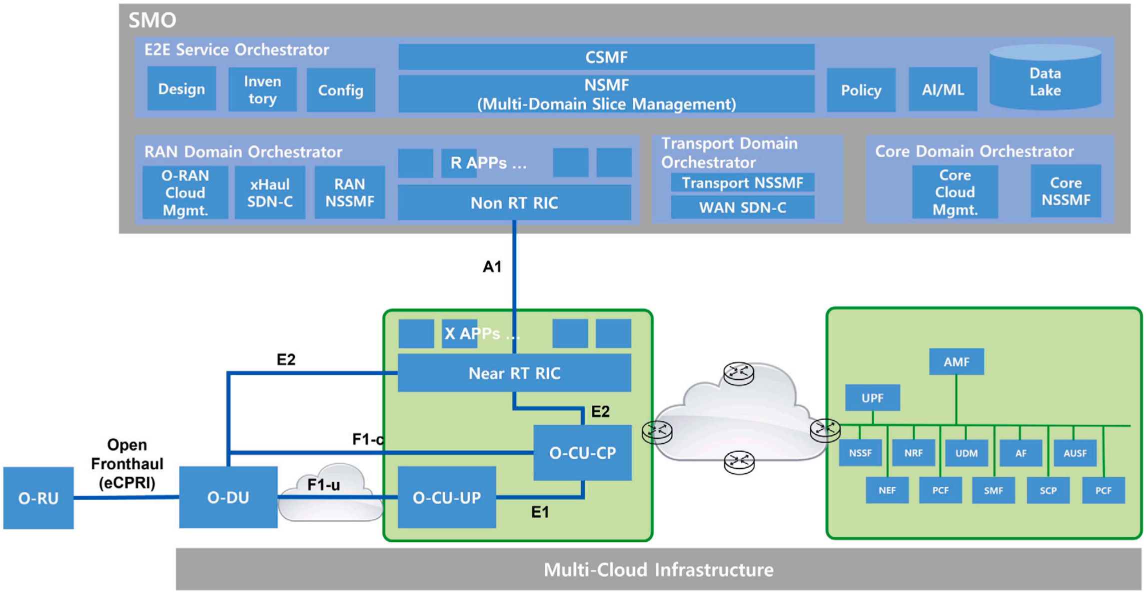

Fig. 10. End-to-End O-RAN architecture.

Table 21
O-RAN Components.

Component	Description
SMO	Service Management and Orchestration
RICAPP	xAPP RIC Applications
RIC	Near-Real-time RAN Intelligent Controller
NONRTRIC	Non-Real-time RAN Intelligent Controller
OCU	O-RAN Central Unit
ODU(High)	L2 Functional Block
ODU(Low)	L1 Functional Block
OAM	O-RAN-OAM interface (O1-interface) such as CM, FM, and PM
INF	Infrastructure Building Block

control for network slicing. For end-to-end network slicing, the O-RAN components detailed in Table 21 should be managed through a unified policy for each slice, including the transport and core domains. As described in the previous section, it is essential to isolate, monitor, and optimize the network slicing re-source on hyper-scale and multi-cloud infrastructure.

5.4. *Magma*

The Magma project started as part of Facebook connectivity and developed into a mobile core open-source project under the Linux foundation. Magma is an open-source software platform that provides network operators with an open, flexible, and extendable mobile core network solution, including fixed wireless access, WiFi access, private networks, and 5G mobile broadband [109].

5.5. *Anuket*

Anuket is a virtualized infrastructure for telecom operations that started from NFV, has evolved with cloud-native technology, and provides an open-source telco cloud infrastructure that reflects the business requirements of operators, such as network slicing, and guarantees multi-vendor interoperability. For network slicing implementation, standardized infrastructure specifications and a conformance- and performance-promoting framework based on cloud-native architecture are required for commercial-scale deployment facilitating interoperability.

Anuket is an LFN project formed through the merger of Open Platform for NFV (OPNFV) and Cloud iNfrastructure Telco Taskforce (CNTT) on 27 January 2021, which works in partnership with GSMA, ETSI, and 3GPP, as well as open-source communities including CNCF, ONAP, and OpenStack [110]. Anuket delivers a standard model, standardized specifications for reference infrastructures, and conformance and performance-promoting frameworks for virtualized and containerized network functions, enabling faster and more robust onboarding into production, reducing costs, and accelerating the digital transformation of communications (see Fig. 11).

5.6. *Nephio*

Nephio is a Linux foundation project based on Google Cloud, designed to provide Kubernetes-based, cloud-native intent automation and automation templates to make it easier for telecom operators to deploy and manage multi-vendor cloud infrastructures and network functions across large-scale edge deployments [111].

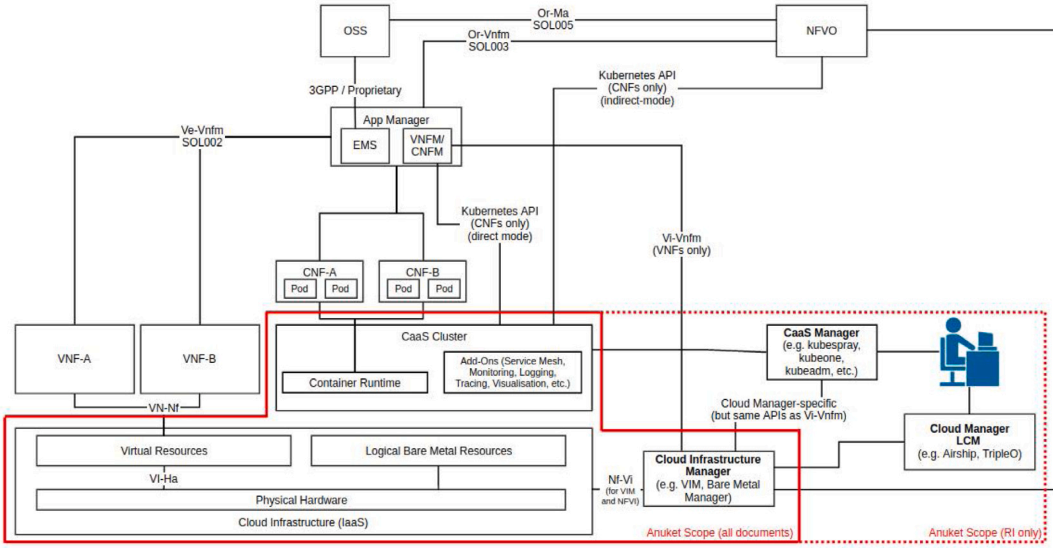

Fig. 11. Anuket Scope.
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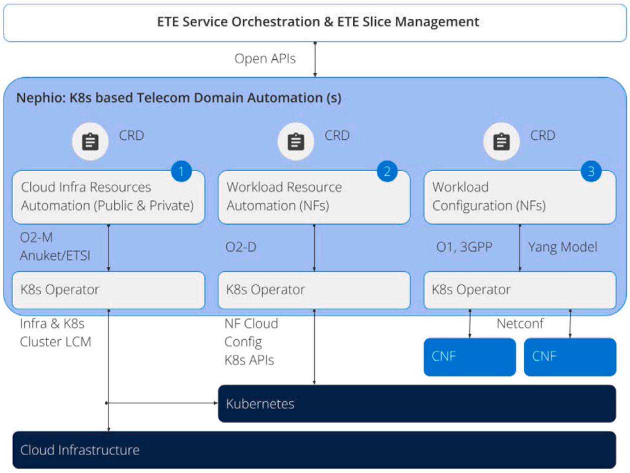

Fig. 12. Nephio.
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Nephio focuses on domain orchestration and automation rather than end-to-end orchestration and automation, such as ONAP. The primary advantages of Nephio are that Kubernetes provides a uniform automation control plane in each site to configure all aspects of the distributed cloud and network functions and an automation framework that leverages Kubernetes declarative management, an actively reconciled methodology, along with machine-manipulable configuration. Nephio establishes open, extensible Kubernetes Custom Resource Definition (CRD) models for cloud infrastructure, network function resources, and configuration in conformance with 3GPP and O-RAN standards (see Fig. 12). The advantage of Kubernetes-based automation is that it is a robust, proven framework for declarative management, which can support automated changes, bulk operations, and human-initiated modifications which are not just API-driven, but API-centric, using Kubernetes Resource Model (KRM) and Configuration as Data (CaD).

5.7. Cloud-native computing foundation

As virtualization technology evolves in cloud-native-based architectures, various cloud-native-based open-source technologies, including Kubernetes, have been developing rapidly, a significant trend in network slicing. The Cloud-Native Computing Foundation (CNCF) is a Linux Foundation project founded in 2015 to help advance container technology and drive ecosystems of open-source, vendor-neutral projects [112]. Cloud-native technology was developed by IT companies. For applying it to 5G network equipment, including network slicing, it is necessary to consider the telecom infrastructure and application characteristics. CNCF launched the Telecom User Group (TUG) for operators and their vendors using (or aiming to use) cloud-native technologies in their networks. CNCF TUG has been developing a practical telecom solution based on cloud-native technology by discussing CNFs suitable for telecom characteristics and operating CNF testbeds [113].

5.8. ONOS

Automating various network equipment, such as switches or routers, is essential for transport network slicing through an SDN. ONOS is one of the representative open-source SDN projects led by the SDN standards organization ONF [114]. The most characteristic feature of ONOS is that it uses a clustering-based distributed SDN controller architecture, which aims to satisfy telco-grade requirements such as high availability. SD-RAN projects that leverage near-real-time RIC (nRT-RIC) based on existing ONOS controllers have recently been aligned with O-RAN alliances, as shown in Fig. 13 [90].

5.9. P4

For improving the performance of network slicing or implementing a new use case, data plane programmability is required for devices and applications. P4 (Programming Protocol-independent Packet Processors) is a programming language facilitating data plane programmability [115,116]. It is designed to be independent of the implementation and can be compiled on different execution machines, such as general-purpose CPUs, FPGAs, SoC, Network Processors, and ASICs. The concept of API-based programmability has spread to the idea of SDN with the advent of OpenFlow. In the OpenFlow architecture, the operation of the data plane is basically performed by calling the pipeline operation

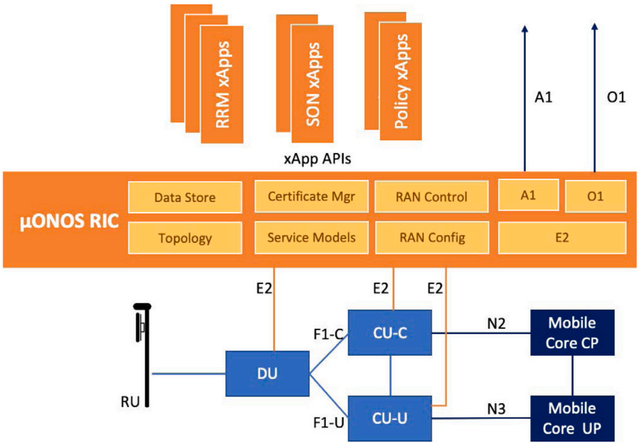

Fig. 13. microONOS RIC.
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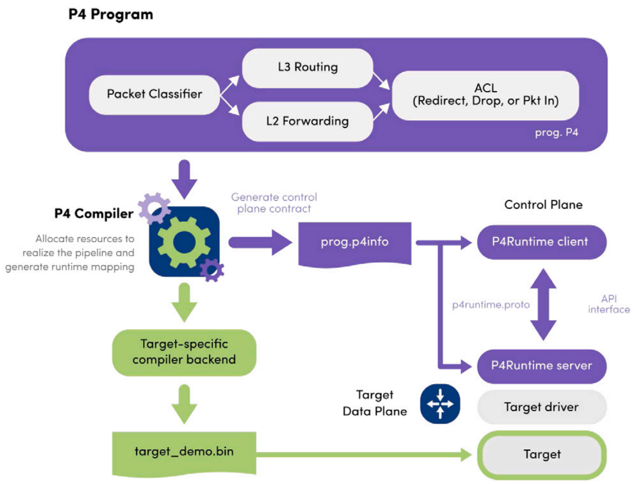

Fig. 14. P4 Workflow.
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determined by a switching chip using predefined APIs, and the function of the data plane cannot be changed.

In contrast, a programmable data plane architecture can implement all or part of the data plane functions using a programmable chip, enabling the implementation of a use-case that handles new data plane functions, including 5G user plane functions [117,118]. Fig. 14 describes the P4 workflow for programming the data plane using P4 language, including compiling and loading binary into target devices. A programmable data plane enables data plane offload; as such, the performance can be increased, and new use cases, such as in-band telemetry for intent-based networking, are allowed [119].

5.10. FRR

Open architectures for transport networks are essential for network slicing. There has recently been an open and disaggregation movement to prevent vendor dependency on hardware and software for transport product software, such as switches and routers. In particular, the transition to an open-source-based NOS (Network Operating System) has been accelerating, where a representative open-source project is FRRouting (FRR). FRR is a free, open-source internet routing protocol suite that implements BGP, OSPF, RIP, IS-IS, PIM, LDP, BFD, and so on [120]. FRR originates in the Quagga project, forked from the Zebra project, and is the core routing protocol suite of many commercial and open-source projects, such as SONiC.

5.11. SONiC

NOS (Network Operating System) projects based on open-source routing software such as FRR have emerged steadily. Software for Open Networking in the Cloud (SONiC) is a NOS open-source project for cloud data center switching, led by Microsoft and OCP (Open Computing Project), with the participation of many commercial vendors [121]. It uses an intent-based, API-centric, and containerized architecture for data center fabric automation. Fig. 15 illustrates the SONiC architecture. SONiC is not a monolithic architecture but, instead, a container-based micro-service architecture, such that it can easily change and update applications on the NOS and provide BYO (Build-Your-Own) applications. It is possible to provide specialized and customized applications based on the entire open-source architecture for core applications. The Open Networking Foundation (ONF) announced the upstream contribution of its collaboratively developed P4 Integrated Network Stack (PINS) into SONiC [122]. The SONiC architecture can quickly deploy and upgrade the software of switches and routers, allowing for rapid network slicing.

6. End-to-end network slicing architecture

This section covers the end-to-end network slicing architecture, including network slicing architecture, network slicing manager, RAN slicing, core slicing, and transport slicing [123,124]. In this section, we propose the various view of end-to-end network slicing architecture considering recent technologies and standards such as 3GPP standard, O-RAN standard, RAN-Mobile xHaul architecture, transport network standard, SDN technologies, and cloud-native 5G core.

6.1. Network slicing architecture

Network slicing is hierarchical, and a subnet-based architecture composed of CSMF, NSMF, RAN NSSMF, TRANSPORT NSSMF, and CORE NSSMF is used [125]. It requires the consideration of management from an end-to-end point of view and slice management from a domain point of view, and it is necessary to consider the interoperability of solutions from various vendors using standard APIs. Fig. 16 depicts the network slicing architecture based on the 3GPP standard.

6.1.1. CSMF

The CSMF (Communication Service Management Function) receives the network slicing service request from OSS/BSS, interprets it as a network slice-related requirement, and delivers it to the NSMF [126]. In general, the interface between OSS/BSS and CSMF uses the standardized interface of the TMF API defined by the TM forum.

6.1.2. NSMF

The NSMF (Network Slice Management Function) plays the most crucial role in network slice management from an end-to-end point of view. It is responsible for end-to-end management and orchestration of network slices. In addition, the NSMF needs to manage the end-to-end SLA of each slice and control network slice components to optimize SLA. After the NSMF receives an API-based request for slice creation from the CSMF, it creates a network slice instance and transmits parameters related to the slice for each subnet to the NSSMF, which is in charge of subnet slice management. To implement the NSMF practically, it extends the existing concept of the service orchestrator to network slicing and must include various functions, such as life cycle management, self-healing, and closed-loop slice control.

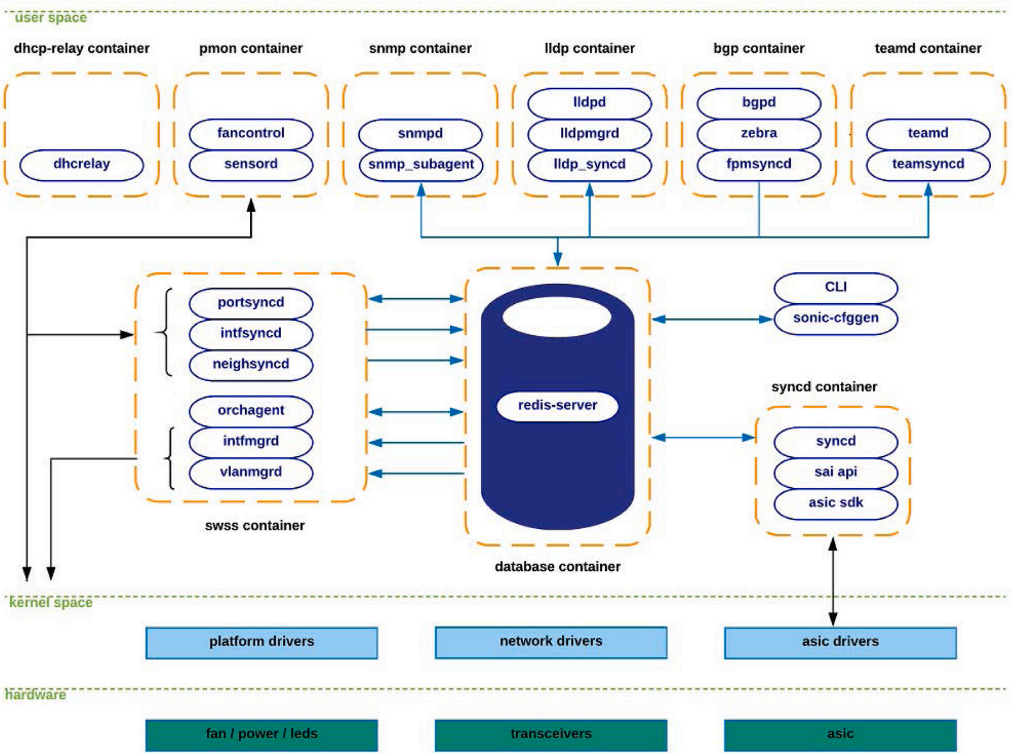

Fig. 15. SONiC Architecture.
Source: Reprinted from [121] with permission.

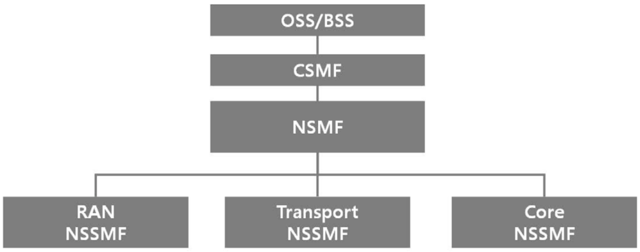

Fig. 16. Network slicing architecture in 3GPP.

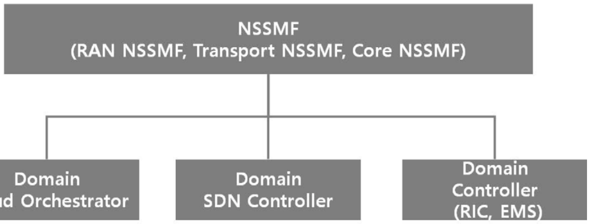

Fig. 17. NSSMF management and orchestration elements.

6.1.3. NSSMF

The NSSMF (Network Slice Subnet Management Function) performs the life cycle management of network subnet instances that compose the network slicing domain. There are three types of management elements (shown in Fig. 17) in NSSMF.

As cloud-native technology expands from Core to RAN and the roles of API-based controllers expand from SDN to RIC, various management and orchestration to implement network slicing in the NSSMF layer. Table 22 describes the functions of the domain orchestrator, domain controller, and SDN controller in the RAN NSSMF, Transport NSSMF, and Core NSSMF. In each NSSMF, the actual slice instance is a PNF (Physical Network Function), VNF (Virtualized Network Function), and CNF (Containerized Net-work Function). From the perspective of orchestration for managing the life cycle inside the subnet slice, it is vital to develop a method for silo orchestration of VNFs and CNFs to integrate and manage them as one orchestration.

6.2. Network slicing manager

The end-to-end network slice manager is crucial in managing the entire network slice service, as shown in Fig. 18. It can be implemented by extending an end-to-end orchestrator's SO (Service Orchestrator) to support the network slice and include various design considerations, detailed in the following [127]. For optimal design of the network slice manager, it should manage end-to-end network slices by extending the service orchestrator function. In other words, it should support expanding the role of managing network slices by recombining the service orchestrator function. The network slice manager needs to recycle and reassemble the traditional jobs of the FCAPS, that is, fault management, configuration management, account management, performance management, and security management functions. In addition, it can provide a closed-loop control function by integrating the end-to-end network slicing control function with the analytics and AI modules.

The traffic isolation concept is essential in network slice management, and the 5G VINNI project has defined a reference architecture for end-to-end service orchestration and network slicing [128]. There are also open source projects in network slice manager such as ETSI TERRAFLOW SDN [129] and the KATANA [130]. The most influential architecture allows the network slice manager to be designed as a micro-service architecture to maximize reusability and create an architecture that can be recombined through various plugins when necessary. ONAP, a representative open-source network slice manager platform, comprises such a micro-service architecture (see Fig. 19).

Table 22
Role of Management and Orchestration in Each NSSMF.

Component	RAN NSSMF	Transport NSSMF	Core NSSMF
Domain Orchestrator	vRAN(vDU/vDU) NFV Orchestrator	N/A	vCore NFV Orchestrator
Domain Controller (RIC, EMS)	RAN Intelligent Controller (RIC) RAN Application Management (EMS)	N/A	Core Application Management (EMS)
SDN Controller	Fronthaul/Midhaul Automation vRAN Data Center Network Automation	Transport Network Automation (Backhaul/Core Network)	vCore Data Center Network Automation

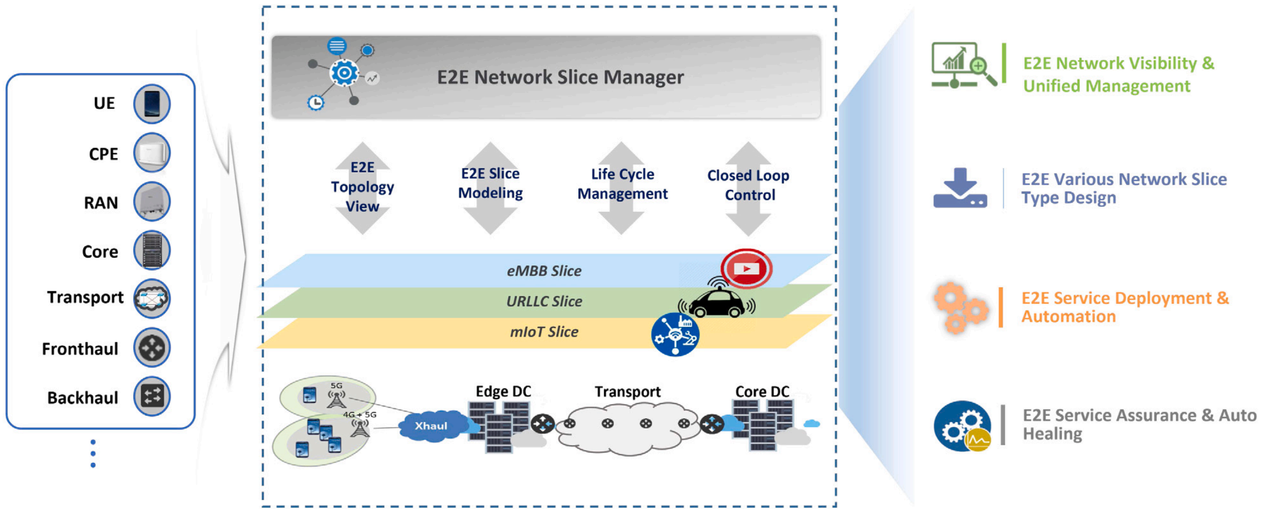

Fig. 18. The key functions of the network slice manager.

Table 23
ONAP components for network slicing.

Category	Component	Description
Design-time Framework	SDC (Service Design and Creation)	Supports the onboarding of Network Services packages; CNF, VNF, and PNF packages; and models 5G network slicing using Slice Profile and Service Template
Run-time Framework	Inventory (AAI)	Real-time views of a system's resource, services, products, and their relationships with each other
	Controller	Execute the configuration, real-time policies SDN-C (Network), App-C (Application)
	Orchestration (MSO)	Executes the specified processes by automating sequences of activities, tasks, rules, and policies
	Multi Cloud Adaptation	Provides an infrastructure adaptation layer for VIMs/Clouds and K8s clusters
	OOF (ONAP Optimization Framework)	Provides a policy- and model-driven framework for creating optimization applications
Closed Control Loop Automation	DCAE	Collectors and an analytic engine (performance, usage, and configuration data from the managed environment)
	CLAMP	Enables the design of closed loops

ONAP is a micro-service-based architecture integrated with a micro-services bus. The main components of ONAP for network slicing comprise the design-time framework, run-time framework, and closed-loop automation, following Table 23 [131,132]. ONAP is also the reference implementation for SMO (Service Management and Orchestrator) in O-RAN. In network slice management, it is crucial to take measures for self-healing when a failure occurs and automatically carry out optimization when resources for each slice are insufficient or SLA conditions are not satisfied [133].

The network slice manager performs the Life Cycle Management (LCM) of the network slice. Regarding LCM, the NSMF performs overall life cycle management from an end-to-end perspective, while the NSSMF performs domain orchestration for slices in each subnet perspective.

Table 24 lists standardized SST values for slice type, including eMBB, URLLC, Massive IoT, V2X, and High-Performance Machine-Type Communications (HMTC) in 3GPP standard. E2E 5G network slice model is the key issue in network slice management [135,136].

6.3. RAN slicing

The concept of network slicing has evolved from core slicing to RAN slicing, which is essential in network slicing. The evolution of the idea is accelerating, according to the implementation of 5G SA (Stand Alone).

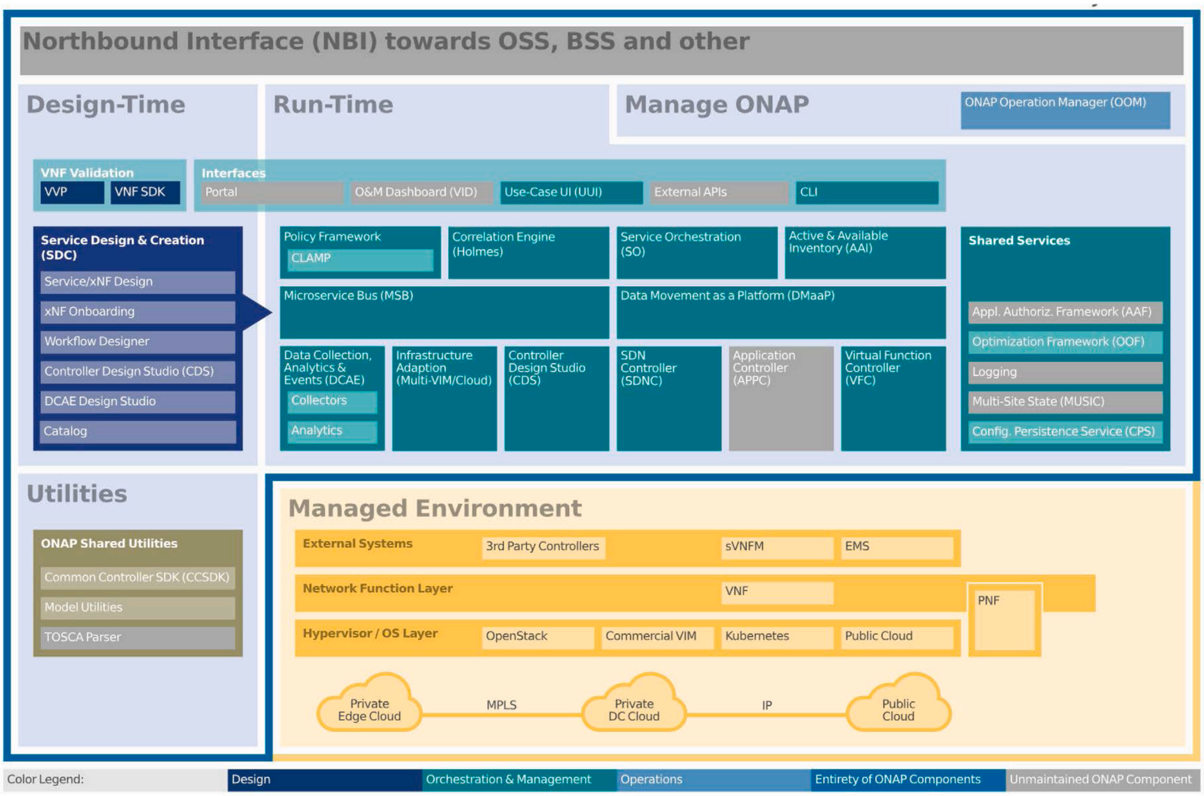

Fig. 19. ONAP architecture (Jakarta).
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Table 24
Standardized SST values for network slicing.

SST	Slice type
1	eMBB
2	URLLC
3	Massive IoT (MIoT)
4	Vehicle-to-everything (V2X)
5	High-Performance Machine-Type Communications (HMTC)

RAN slicing is critical in 5G services, including URLLC, which supports low latency, as the RAN domain has the most target equipment and can effectively control experience services by being close to the 5G devices [137].

6.3.1. RAN slicing use case

The consistent principles of network slicing are logical separation and optimal control of resources for slice requirements. In RAN Slicing, for logical separation of resources, it is necessary to separate resources for each slice and to control the physical and virtualized components constituting 5G RAN, including RU, DU, and CU. In this context, the following use cases can be applied [138]:

- Slice-aware AMF/CU-UP selection;
- Flexible Physical Resource Blocks (PRBs) portion control;
- RAN traffic separation.

In RAN Slicing, it is necessary to separate DU and CU traffic and perform optimization for separation and SLA conditions for air resources.

6.3.2. Virtualized RAN

vRAN (Virtualized RAN) is one of the critical technologies in 5G, providing an optimal architecture for dynamically partitioning virtualized resources in network slicing. Network virtualization has recently rapidly spread from 5G core to 5G RAN through cloud-native architecture, and container-based vRAN can allow for rapid and agile slice creation and deletion; furthermore, based on micro-service architecture, it can provide a platform for standard functions. vRAN has the following advantages [139–141]:

- Flexible deployment and dynamic scaling;
- Efficient resource utilization through pooling;
- Open RAN and RAN intelligent controller.

6.3.3. O-RAN

O-RAN comprises a significant technical evolution of 5G architecture. O-RAN de-fines RAN components as an open standard interface based on O-RAN standards, sup-porting RAN solutions for various vendors and providing an optimal architecture for various RAN slicing use cases [142]. Virtualized RAN is the key technology of O-RAN for dynamically assigning resources using an open interface [143].

In the O-RAN architecture, RIC is introduced to provide intelligent radio resource management, higher layer procedure optimization, policy optimization, and AI/ML models, as shown in Fig. 20 [144,145]. In the RIC architecture, there are non-real-time (non-RT) control functionalities (with run-time execution over 1 s) and near-real-time (near-RT) control functionalities (with run-time execution under 1 s). Near-RT RIC provides near-real-time control and optimization of RAN elements and resources through fine-tuned data collection and actions. From the perspective of network slicing, RIC plays a key role in optimization control by network slicing SLA policies, and containerized vRAN provides the optimal architecture to apply rapid closed-loop control [146,147].

6.3.4. RAN-mobile xHaul integrated management

Compared to 4G, the 5G mobile access network has experienced a significant architectural change in the evolution to Mobile xHaul. In the 4G access network, a CSR (Cell Site Router) aggregates various devices

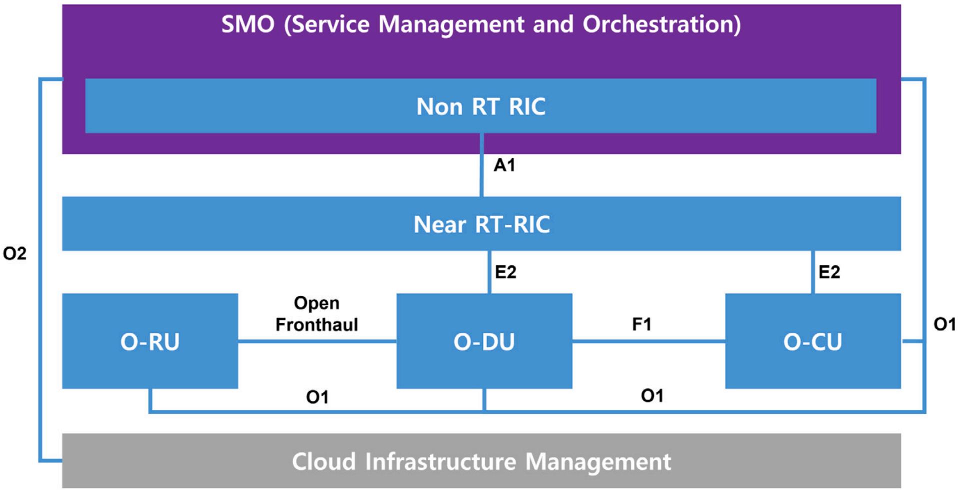


Fig. 20. RIC in O-RAN Architecture.

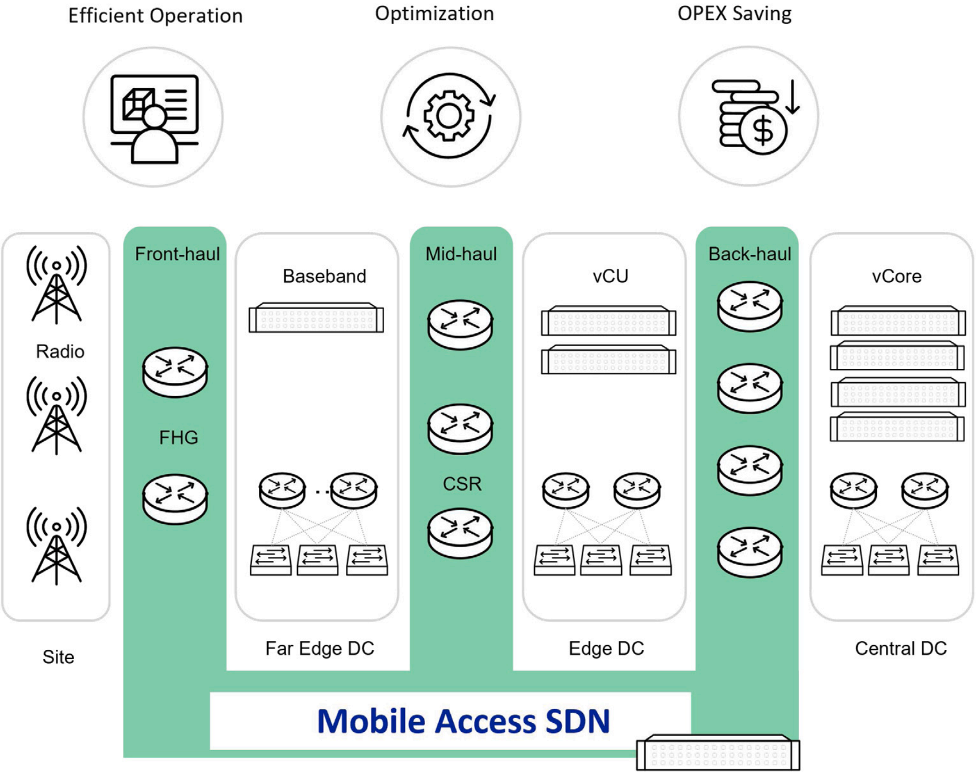


Fig. 21. RAN-Mobile xHaul integrated management.

in a cell site and transmits them to the back-haul network. The 4G RAN architecture uses D-RAN (Distributed RAN) or C-RAN (Centralized RAN), but a 5G RAN architecture may utilize various combinations, in which a functional split of RU, DU, and CU, as well as D-RAN and C-RAN architectures, is possible. In the 5G mobile access network, there exists a front-haul between RU and DU, a mid-haul between DU and CU, and a back-haul between core and CU. These sections are generally called mobile xHaul.

Fig. 21 shows the architecture and integrated management of a 5G access network, including mobile xHaul. The most significant change in the front haul between RU and DU is the migration of the existing closed interface of CPRI to the ethernet-based open interface of eCPRI. Mobile xHaul supports low latency and time synchronization functions, such as URLLC, PTP, and TSN (Time Sensitive Network) [148,149]. Mobile xHaul switches and routers require the integration of front-haul, mid-haul, and back-haul, integrating functions such as L2, L3, MPLS, and segment routing controlled by SDN. In a 5G network slicing architecture, slice management of the RAN domain can be carried out through mobile xHaul switches, routers, and data center (e.g., Far Edge and Edge DCs) switches, in addition to RAN equipment (e.g., RU, DU, and CU). Such an architecture should be able to provide RAN slicing by managing it. Due to the properties of 5G Mobile xHaul, RAN slicing increases the amount of network equipment to be managed, with associated increased complexity. Therefore, to properly implement network slicing in the RAN domain, it is crucial to manage the RAN and mobile xHaul in an integrated manner. When RAN and mobile xHaul equipment can be automatically built together, deployment and operation costs can be reduced, as this supports a single management

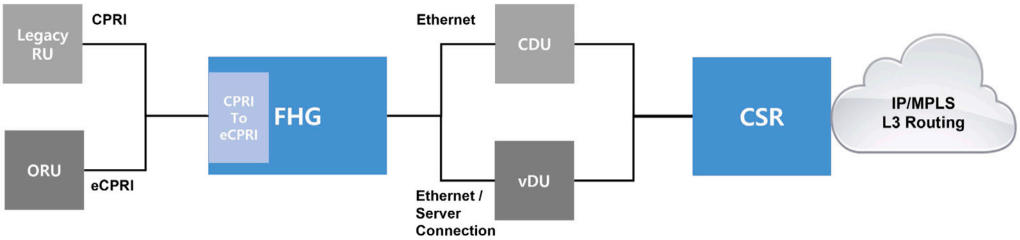


Fig. 22. Front-haul gateway (FHG) in 5G network.

system instead of multiple management systems. In addition, integrated resource management can be performed through federated inventory management, and RCA (Root Cause Analysis) can be quickly and automatically performed when a failure occurs between the RAN and xHaul equipment. For network slice management, this provides the optimal architecture to guarantee the SLA of slices using closed-loop control.

6.3.5. Front-haul gateway

The evolution of vRAN and O-RAN in 5G increases the need for Front-Haul Gateway (FHG), which has the following requirements.

- Conversion between CPRI and eCPRI when legacy RU and O-RAN RU (ORU) are mixed when vRAN is introduced
- Efficient use of front-haul bandwidth through aggregation effect when configuring C-RAN
- A universal router that integrates the FHG, CSR, and ToR (Top of the Rack) switch into a device when configuring vDU
- RAN and mobile xHaul network automation and end-to-end network slicing

Fig. 22 describes the role of FHG in the 5G network. FHG is required when RU and CU cannot be connected directly. For example, when RU and DU capacity is not one-to-one mapping relation or the type of RU and DU is different such as legacy RU and ORU or traditional DU and virtualized DU. FHG should also support the functionality of CSR (Cell Site Router), such as routing and time synchronization, and it should also support server connection and the conversion of CPRI and eCPRI.

6.3.6. Dynamic QoS configuration in RAN/mobile xHaul

In network slicing, dynamic QoS management for each domain is a pivotal technology to satisfy the SLA of dynamically created slices. Dynamic QoS management based on a unified policy between RAN and Mobile xHaul equipment is essential.

QoS policy parameter setting is established statically through network traffic engineering analysis, and it is difficult to change a policy dynamically. Fig. 23 depicts the QoS policy configuration for each queue in a 4G CSR (Cell Site Router). For 4G QoS settings, network operators must manually set QoS parameters, such as the number of queues, type of queues, bandwidth, and buffer size in the CSR.

Fig. 24 depicts the QoS settings of an xHaul router for network slicing. A dynamic QoS setting for each slice and a hierarchical configuration according to the slice type are essential for network slicing. For QoS management of RAN Slicing, the QoS policy of xHaul router must be set dynamically through life cycle management, addressing aspects such as the creation, deletion, activation, and deactivation of slices in the RAN domain. In addition, when the operator dynamically changes a slice's SLA policy, closed-loop control for SLA optimization of the RAN domain should be performed [150].

For this dynamic and complicated policy automation of hierarchical QoS parameters, it is important to use an SDN controller with a unified network slicing policy of RAN and xHaul.

6.4. Core slicing

The core domain was the initial transition to virtualization, and cloud-native was rapidly introduced. For this reason, the use-case for network slicing is applied to core slicing first, including the separation of 5G application resources [151].

6.4.1. Core slicing use-case

The main use cases of Core Slicing are as follows:

- Separation of resources of 5G core application per slice;
- Dynamic scaling of 5G core application including CUPS (Control and User Plane Separation);
- Bandwidth monitoring and optimization per slice;
- Application of slice change of UE and resource sharing;
- Vertical application support for MEC or private 5G support.

6.4.2. Cloud-native 5G core and service-based architecture

Cloud-native architectures have the advantage of being able to manage dynamic life cycles by increasing the instantiation speed of applications. Designing the 5G core with an SBA (Service-Based Architecture) provides the advantage of service agility that builds new services efficiently and quickly with higher flexibility and better modularization. A typical use case is a dynamic scale network slice by usage, separating the control plane and user plane of the 5G core [152]. With this architecture, network operators can efficiently scale the 5G core workload for network slicing. In addition, it enables core network programmability for vertical applications using the NEF (Network Exposure Function) [153].

6.4.3. Slice selection optimization and NWDAF

An essential issue in core slicing is that the UE selects and optimizes a particular slice. The UE Route Selection Policy (URSP) is used to manage network slice information for the UE in the 3GPP standard. URSP is a network slice feature enabled by the PCF, which informs the network slice status to the UE using the AMF. For 5G network slicing, URSP dynamically selects and configures the slice selection policy [154]. For slice optimization in the 5G core, data analytics for closed-loop control defined in the 3GPP standard is required. The Network Data Analytics Function (NWDAF) is a new Network Function (NF) introduced as part of the 3GPP standards for the 5G Core, as defined in TS 29.520 [155]. The NWDAF collects data and provides analytics services using a request or subscription model [156]. The network slicing use case of NWDAF involves slice load level monitoring, slice selection policy updates, and slice SLA assurance for closed-loop automation [157].

6.5. Transport slicing

For end-to-end network slicing, transport slicing manages the traffic of the slice transport network, automatically controlling it to meet SLA conditions [158]. This section describes end-to-end transport network architecture, SDN controller requirement for network slicing, traffic isolation for slices, and SR (Segment Routing).

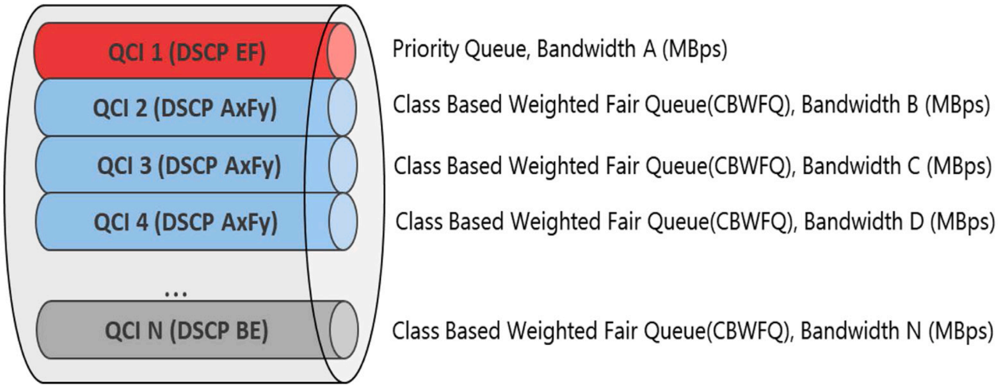


Fig. 23. CSR QoS policy example.

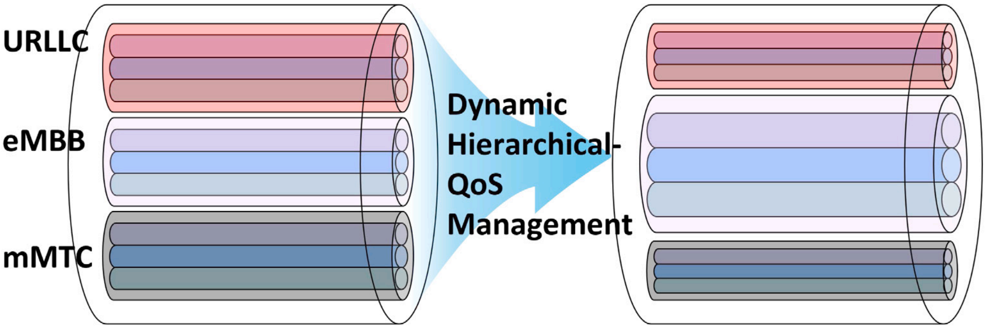


Fig. 24. xHaul Router QoS Configuration for Network Slicing.

6.5.1. *End-to-end transport network architecture*

The transport network in 5G consists of central offices, various types of telco data centers (e.g., far edge, edge, core, and cloud data centers), and various transport network switches and routers connecting them. The network slicing architecture defines SDN-based automation and management layered with NSMF and NSSMF. For end-to-end network slicing, the Transport NSSMF should consider slice management, with the RAN NSSMF and CORE NSSMF interoperating with the transport network and slice management of the transport section [159,160].

Fig. 25 describes the network slicing architecture for the transport network in 5G. The transport domain is composed of multiple IP (Internet Protocol) domains and optical domains, and TN NSSMF delivers network slicing ID and SLA information for each slice interfacing with domain SDN controllers.

6.5.2. *SDN controller requirement for network slicing*

The SDN controller automatically controls the switches and routers in the transport domain, which has the following requirements for network slicing:

- Open protocol, interface, and APIs;
- Unified, cloud-native SDN platform (SDN in-a-box);
- Converged SDN solution.

Fig. 26 shows the open SDN controller architecture for network slicing. It is necessary to be able to control switches and routers of various vendors with open standard protocols for interoperability. SLA management of a network slice is a typical use-case of an intent-based network [161]. Based on the intent, such as SLA information, for each slice received from the network slice manager, the SDN controller should be able to control the various types of switches and routers managed by standard and open APIs.

For workflow automation of network slicings, such as massive deployment automation, software updating of switches and routers, and massive network slicing policy up-dates, it is efficient to use a workflow engine (e.g., the Ansible plug-in) along with an SDN southbound API, to manage the state of automation, including exception handling. For Multi-vendor support, the SDN controller can use NAPALM (Network Automation and Programmability Abstraction Layer with Multi-vendor support), a Python library that implements a set of functions to interact with different router vendor devices using a unified API [162].

The 5G transport network requires integrated management of networks with various attributes, combining existing mobile access, data centers, and enterprise networks due to recent vertical solutions, including vRAN and private 5G. It is efficient to manage the integrated network as a single SDN controller platform for network slicing rather than driving a separate domain as an existing individual product.

A unified and cloud-native SDN-in-a-box platform, as shown in Fig. 27, can be combined into micro-service units integrating various functions, such as those relevant to mobile access, data centers, and enterprises, in addition to common SDN functions. The key idea is that most SDN products for mobile access, data centers, and enterprises include joint management and automation functions, such that a unified and cloud-native SDN-in-a-box platform provides a very efficient means to support these various functions of multiple SDN products within a single SDN platform.

By combining a cloud-native SDN architecture and 5G solutions, the SDN platform can compose different converged 5G vertical solutions with SDN, such as network slicing, private 5G, and vRAN (see Fig. 28).

6.5.3. *Traffic isolation for slices*

The essential principle of network slicing in the transport network is to divide traffic by slices and to optimize QoS parameters to meet SLA conditions dynamically; that is, physical devices such as switches and routers must be logically and dynamically divided into slices, and resources should be appropriately allocated to slices. Logical segmentation of infrastructure through network slicing minimizes CAPEX and

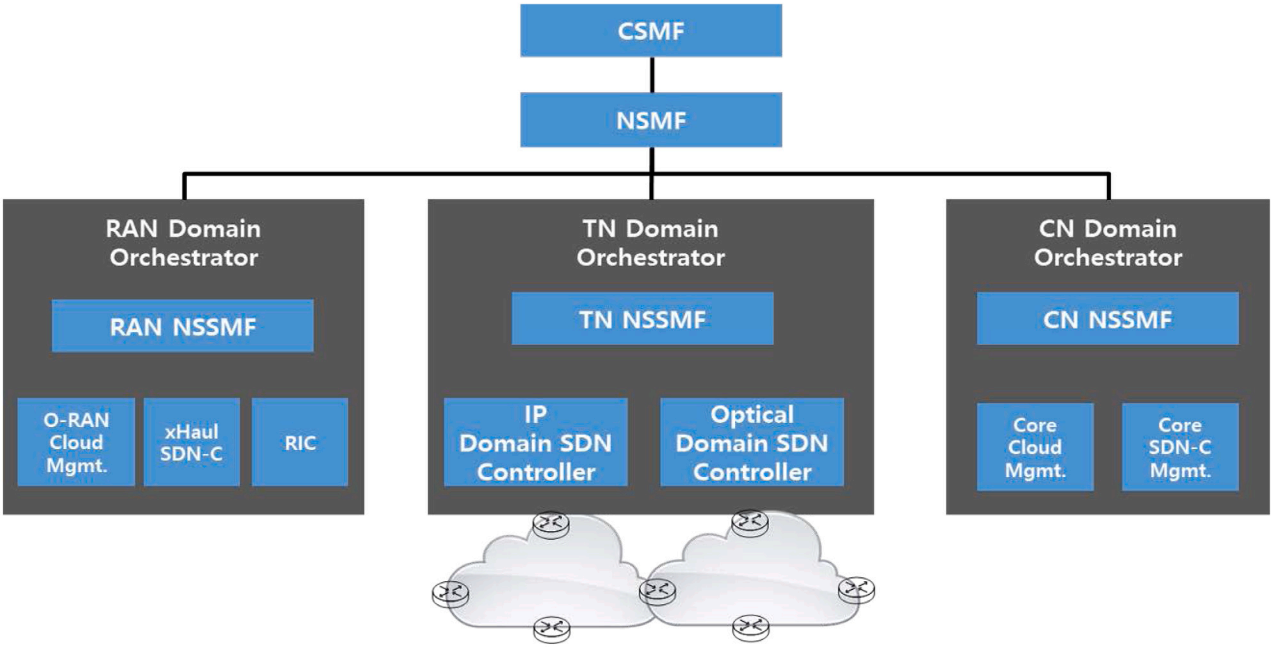


Fig. 25. Network slicing architecture for transport network in 5G.

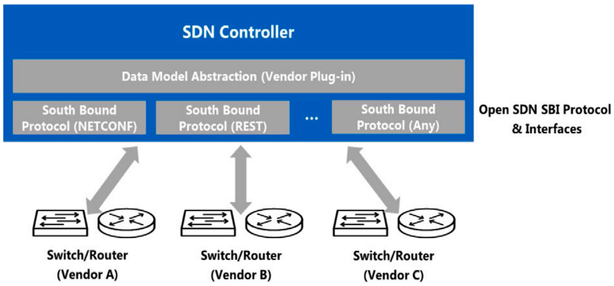


Fig. 26. Open protocol, interface, and APIs in an SDN controller.

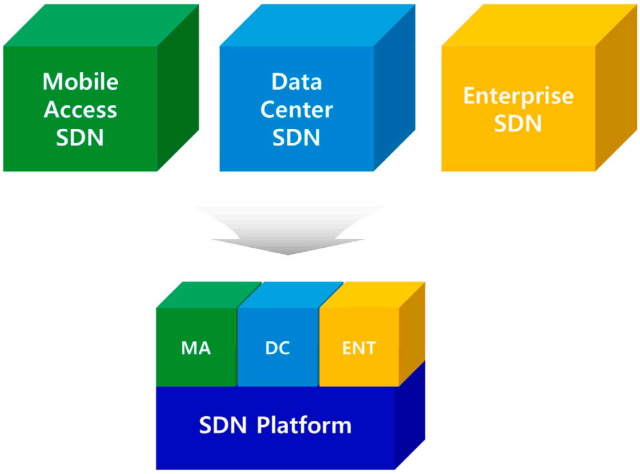


Fig. 27. Unified cloud-native SDN platform (SDN-in-a-box).

provides new 5G-based services for monetization. Implementing network slicing with existing static network configurations is challenging, so it is necessary to carry out dynamic network configuration through an SDN. In addition, low latency services require local break-out and automatic traffic control, according to SDN policies. The logical separation of the network mentioned above is called network virtualization. There are two types of network virtualization for network slicing, as follows:

- Hard slicing—slice resources are fully dedicated (e.g., FlexE);
- Soft slicing—slice resources are reserved but not physically separated.

FlexE is a technology for extending standard Ethernet PHYs to add support for bonding, sub-rating, and channelization, as well as providing support for management channels and time synchronization. It can be used for traffic isolation of each slice [163,164]. Most network virtualization technologies that logically separate network resources can be classified into the soft slicing, such as:

- VLAN, Virtual Routing, and VxLAN;
- MPLS, L2VPN, L3VPN, and Segment Routing (SR-MPLS, SRv6).

Fig. 29 depicts traffic isolation for a network slice. In each interface of SDN switches and routers, traffic can be logically separated by network slice using a virtual interface (VLAN), Virtual Routing (VR), VxLAN, and segment routing [165,166]. For traffic engineering of a network slice, segment routing is an important technology to steer the optimized path of network slice traffic by SDN, considering the SLA condition of each slice.

6.5.4. Segment routing

Intelligent traffic engineering involves maximizing transport network utilization and optimizing network slices' traffic control. Segment Routing involves a source-routing architecture that seeks the right balance between distributed intelligence and centralized optimization. IETF standardizes Segment Routing [167], and there are two types of Segment Routing: SR-MPLS (based on the MPLS label) and SRv6 (based on the IPv6 header), from the data plane point of view. Segment Routing is a method to intelligently control the entire network based on an SDN controller [168]. With APIs related to network slicing, the SDN controller can receive requirements for slice policies and form various traffic engineering algorithms into SDN applications [169]. In addition, different network optimization methods to meet network slice SLA, such as closed-loop control, can be implemented based on analytics information such as real-time telemetry from transport networks. SRv6 is

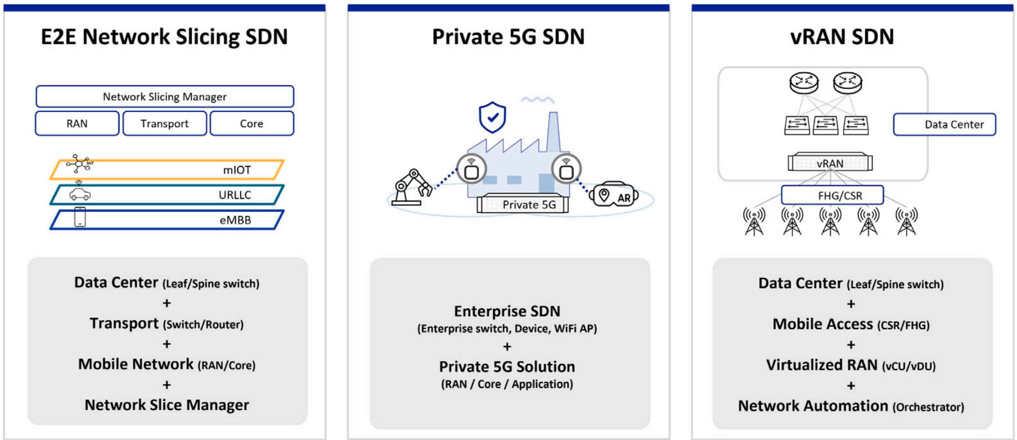
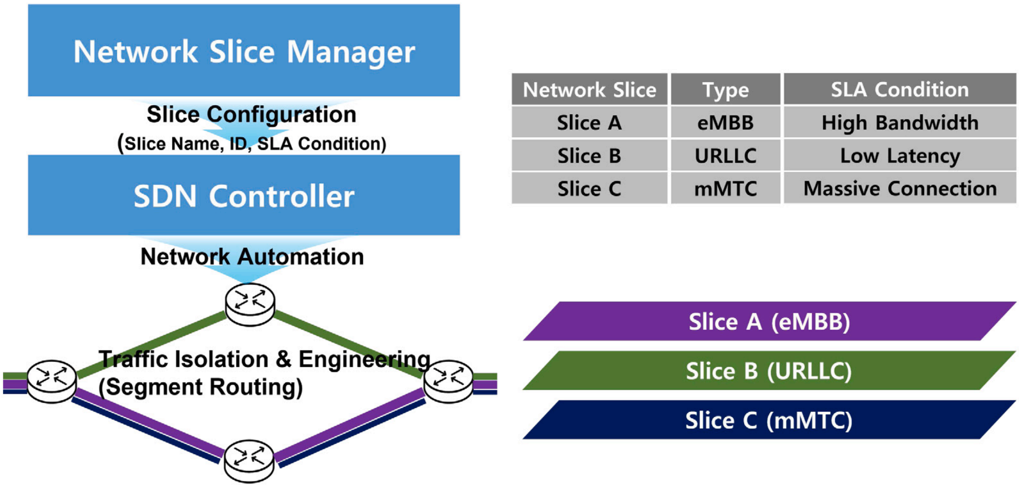


Fig. 28. The use case of cloud-native SDN platforms.



Network Slice	Type	SLA Condition
Slice A	eMBB	High Bandwidth
Slice B	URLLC	Low Latency
Slice C	mMTC	Massive Connection

Fig. 29. Traffic isolation for a network slice.

a technology that can be applied to policy application of slicing from an end-to-end network point of view, as it can also apply network slicing policies to 5G applications, as well as transport routers [170–172].

7. Network slicing SLA management

An essential network slicing operation technology is managing and optimizing the SLA policy allocated to each slice in real time. This section covers the key technologies used for the SLA management of network slicing, including SLA management network slicing overview, SLA monitoring and assurance, active monitoring, passive monitoring, comparison between active and passive monitoring, and SLA/KPI management and interfaces. We propose a protocol-independent SLA metric generation framework and the example of network slicing SLA management using active monitoring in a 5G network.

7.1. SLA management of network slicing

SLA (Service-Level Agreement) denotes the agreement on service quality between network operators or between network operators and customers. In network slicing, SLA management automatically sets parameters with the given SLA policy when creating a slice, monitors it in real-time during operations, and optimizes it by reflecting the network and resource status. The SLA parameters of network slicing consist of common KPIs, such as bandwidth, packet loss, delay, and jitter, according to each slice type, such as eMBB, URLLC, and mIoT, and some variable KPIs for each slice [173].

7.2. SLA monitoring and assurance

Service assurance is a core technology that monitors the current SLA status of the network in real-time and manages the SLA of each slice. For SLA monitoring, active monitoring and passive monitoring are representative means of monitoring network slice SLAs and KPIs. For service assurance of network slicing, there are key design factors as follows:

- Hybrid monitoring (a combination of active monitoring and passive monitoring);
- Protocol-independent SLA management;
- Interface with network slice management function (NSMF, NSSMF);
- Performance and accuracy for 5G SLA requirement (High throughput, Low latency);
- Service assurance appliance (Cloud-native appliance).

7.2.1. Active monitoring

Active monitoring is a technique for diagnosing the quality of a network by transmitting and receiving a probe packet for quality measurement. The disadvantage is that an additional probe packet is required for network quality measurement, but it has the advantage of accurate diagnosis under the desired measurement condition. For end-to-end measurement, active monitoring can support various standard protocols using a single SLA management system, set measurement conditions, and analysis of the measurement results. Supporting standard

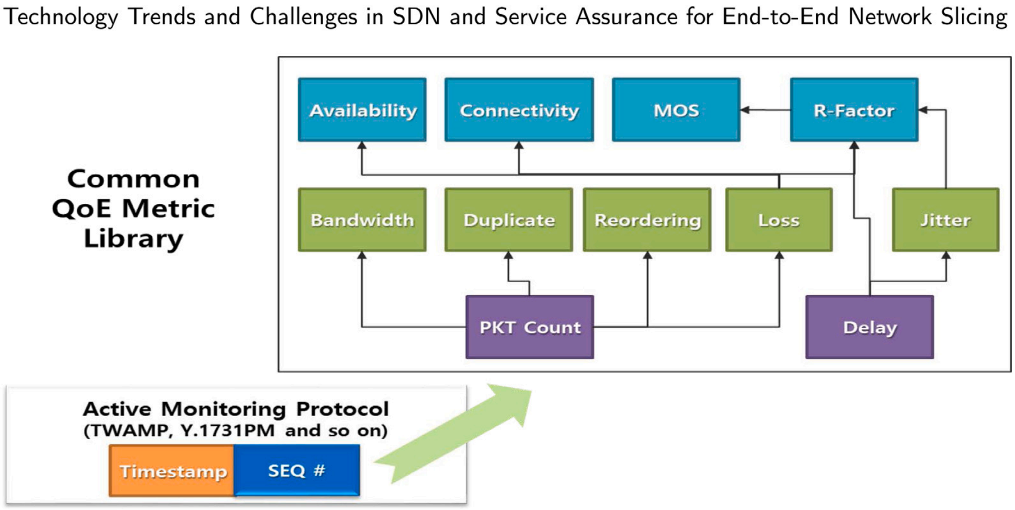


Fig. 30. Protocol-independent SLA metric generation framework.

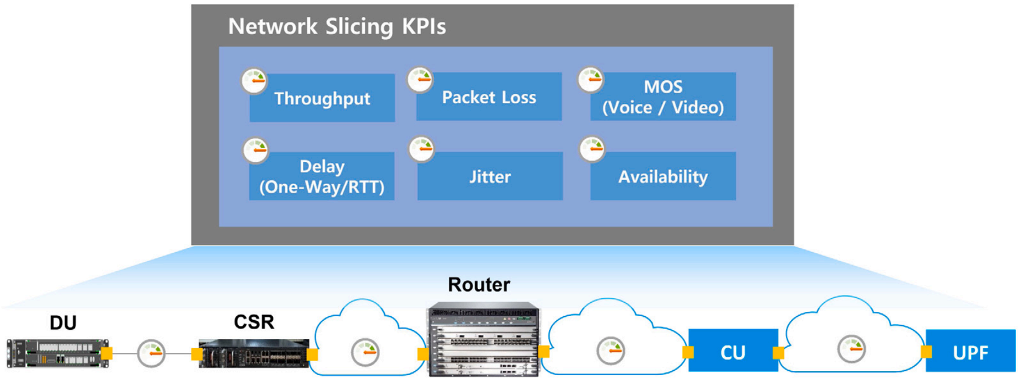


Fig. 31. Network slicing SLA management using active monitoring in 5G network.

protocols for each layer and particular protocols defined by vendors is also vital for the interoperability of SLA measurements. Standard protocols for active monitoring include Y.1731 PM for the Ethernet layer and ICMP for IP layer; however, TWAMP is the most widely used as a de facto standard protocol [174], as most 5G network appliances support it, and applications, including RAN, Transport, and Core. In particular, TWAMP provides functions to support various measurement conditions at the level of commercial packet generators and supports many switches, routers, and 5G applications. For protocol-independent active monitoring, the two most important pieces of information in the probe packet are the timestamp and sequence number, which are common in any such protocol. Based on this information, many metrics, such as bandwidth, packet loss, delay, and jitter, can be obtained, regardless of the protocol. Hence, it is possible to design a protocol-independent active monitoring architecture using a unified SLA metric generation framework [175–178].

A fundamental principle of the framework is to generate a hierarchical QoE metric from any active monitoring protocol, such as ICMP, Y.1731, and TWAMP, using the timestamp and sequence number information (see Fig. 30).

Fig. 31 shows an example of measuring SLA management of network slicing in a 5G network through active monitoring technology such as TWAMP. Each significant section of the network slice can be measured through active monitoring, and this result can be managed as a whole in the network slice management domain for each KPI characteristic interfacing with the NSMF and NSSMF defined in the network slicing standard. For real-time closed-loop control, it is recommended to use a real-time telemetry interface, such as the A1 interface in the O-RAN reference architecture, with a network slice management element. If high performance and large capacity measurements are required, a dedicated service-assurance appliance for active monitoring can be built as needed. In this case, cloud-native CNF is preferable. It can be used with existing 5G applications (e.g., containerized DU, CU, and UPF) and physical equipment (e.g., PNF), providing scalable architecture when service assurance performance and scalability are dynamically required.

7.2.2. *Passive monitoring*

Passive monitoring involves analyzing packets passing through each section without requiring probe packets, as in active monitoring. Typically, these techniques use statistics-based PM (Performance Measurement) information; meanwhile, more recently, real-time telemetry or analytics and machine learning have also been used. The passive monitoring information required for a network slice may vary depending on the slice type and the domain of the slice (e.g., RAN, Transport, or Core). Based on the collected information, closed-loop control can be performed through the controller of each domain. In passive monitoring, a dedicated application for analysis can be used; typical examples are passive probe equipment with TAP and DPI (Deep Packet Inspection). With DPI, it can analyze DPI signature-based applications based on deep packet inspection, so it becomes possible to construct an application and context-aware network slice that can conduct policy control for the allocation of an actual user application to a slice [179]. INT (In-band Network Telemetry) is crucial for analyzing end-to-end network slice SLA metrics across the domain. It can generate user-defined KPI parameters from telemetry information for special-purpose analysis.

Table 25
Comparison between active and passive monitoring.

	Active monitoring	Passive monitoring
Packet in used	Probe packet (Out-of-band) Need to use emulated probe packet	Original packet (In-band)
On-demand Monitoring	O	X
Packet Size	Depends on probe packet condition (Can adjust the packet size)	Same or Increased size
Time Synchronization	Not required in case of two-way measurement	Required

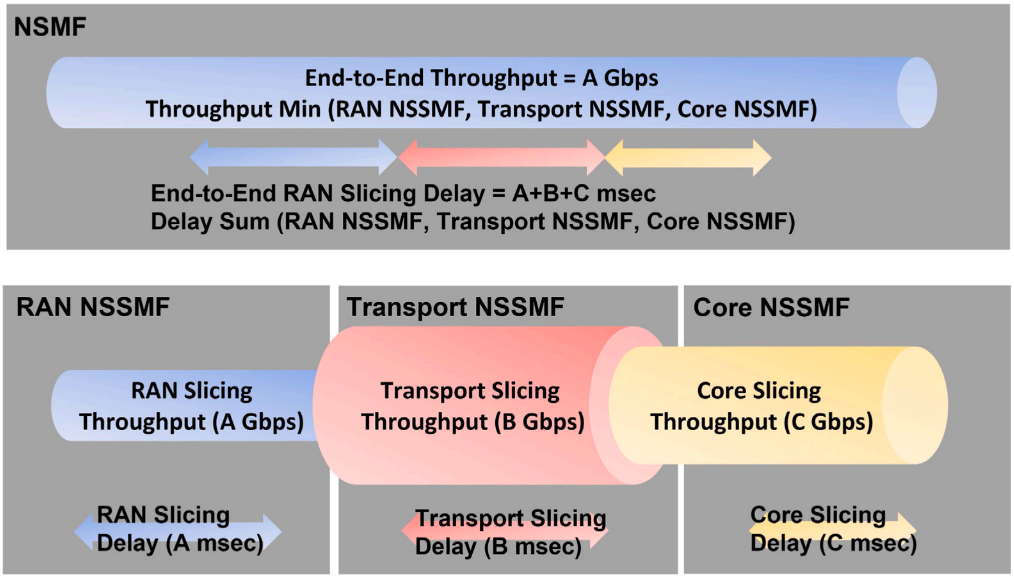


Fig. 32. End-to-end SLA/KPI management for network slicing.

Table 25 provides a comparison between active monitoring and passive monitoring. It is strongly recommended to use hybrid monitoring, the combination of active and passive monitoring, as network slicing SLA monitoring and optimization incur various requirements concerning the use case. For the in-band telemetry use case, a programmable data plane using a P4 switch can be used, which supports flexible options to encode timestamps and sequence numbers in a user-defined field for network slicing SLA monitoring [180].

7.2.3. SLA/KPI management and interfaces

Network slicing management involves a hierarchical architecture in the 5G standard, such that it is necessary to consider how to derive end-to-end KPI metrics using the network slicing management architecture. However, this is dependent on the SLA metric of the end-to-end KPI. The NSMF manages the end-to-end SLA parameters, while the NSSMF manages the domain-specific SLA parameters.

Fig. 32 depicts end-to-end SLA/KPI management in network slicing. End-to-end throughput primarily represents the bottleneck point domain, but the end-to-end delay provides the summation of each domain of network slicing.

- End-to-end throughput in NSMF = Throughput Min (RAN NSSMF, Transport NSSMF, Core NSSMF)
- End-to-end delay in NSMF = Delay Sum (RAN NSSMF, Transport NSSMF, Core NSSMF)

To deliver the SLA/KPI metric, two types of interfaces exist real-time and non-real-time. In the O-RAN architecture, the A1 interface is an example of a real-time interface, while the O1 and O2 interfaces are examples of non-real-time interfaces.

8. Technical considerations for end-to-end network slicing evolution

End-to-end network slicing has been developed by many standards and open-source organizations, as well as operators and vendors, but many issues regarding its technical evolution need to be considered in the future. The following topics are major technical discussion points that require further research and development to promote the evolution of network slicing.

8.1. Open platform and open interface

As mentioned above, the philosophy of openness is essential for network slicing. For this purpose, many open standards and open-source activities are in progress, and operators have been investing interest in this area. The most representative example of network slicing is the open-source network slicing management platforms such as ONAP and O-RAN. Network slicing is an end-to-end technology and requires many components, complex standards, and technologies for its implementation, such that there may be various types of blueprints practically. However, mutual development with open-source concepts is an important issue. In particular, O-RAN plays a vital role in network slicing from an open platform and interface point of view.

8.2. Cloud platform architecture design

Cloud management technology for network slicing has been commercialized, mainly for virtual machine-based VNFs with the ETSI NFV MANO standard, and the evolution to cloud-native technologies has been progressing rapidly. For end-to-end network slicing, the VNF and CNF must coexist for a considerable period, and cloud platform

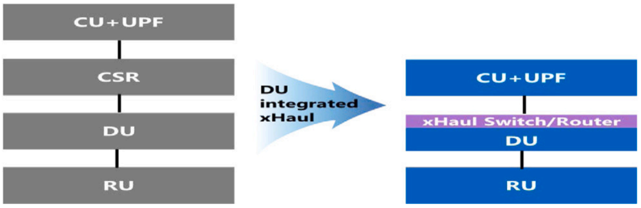


Fig. 33. RAN-integrated xHaul architecture in private 5G.

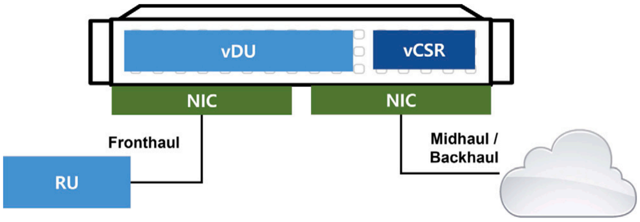


Fig. 34. vCSR Architecture.

architecture design is required for this purpose. In this context, an architecture that can manage VNFs and CNFs simultaneously and perform life cycle management in a single orchestrator is needed, rather than managing VNFs and CNFs individually as a silo. The 5G data center architecture differs from existing IT data centers. There are edge data centers close to base stations and far-edge data centers for low-latency services, such as vRAN and MEC. It is necessary to manage compact data center architectures by combining lightweight and existing components. Therefore, standardization activities for cloud-native orchestration are a crucial design issue for network slicing. Hyper-scale 5G deployment, in which public and on-premise clouds coexist or are built by mixing, has recently been increasing. In this case, managing platform-agnostic end-to-end network slicing is essential, regardless of the cloud infrastructure or platform type.

8.3. *RAN-integrated xHaul architecture*

5G network architecture requires the complex integration of each element—this is the essential principle to consider when developing an optimized architecture for operating network slicing. 5G xHaul switches and routers must fulfill complex functions:

- CSR (Cell Site Router), which integrates multiple DUs (Data Units) and value-added equipment at the cell site;
- FHG (Front-haul Gateway), which has the functionality to convert between CPRI and eCPRI;
- Server connection for virtualized 5G applications, such as virtualized DU, CU, and UPF, considering vRAN and private 5G.

For RAN slicing, it is vital to manage RAN and xHaul efficiently with the same slicing policy. Fig. 33 depicts the RAN-integrated xHaul architecture, including xHaul switches and routers integrated with DU. It is a compact and simple architecture, which can reduce the CAPEX and deployment costs. It helps deploy compact cell sites with limited space from a hardware system perspective.

The advantage of this architecture is a dramatic reduction of operational costs through integrated management for network slicing, as it can use integrated management between RAN and xHaul. For network slicing, integrated management can support many advantages in various use cases of network slicing, as detailed in Table 26.

8.4. *Virtual router*

It can be allocated as needed on-demand to fit the network slicing policy. It allows running other applications on the server and utilizing the remaining resources that the router can drive using cloud-native technology. In addition, it can be built with simple settings compared to physical router settings, and the server and router settings can be automatically installed and operated as one. Fig. 34 shows vCSR (Virtualized Cell Site Router). Based on container-based virtualization technology, vCSR runs a virtualized CSR by utilizing the remaining resources of the server where the existing containerized vDU is loaded. Although this structure has limitations such as throughput, latency, and the number of interfaces, it can reduce TCO, save total power consumption, simplify deployment by the unifying server and CSR installation, and eliminate the external connection between DU and CSR. It has the advantage of reducing the possibility of failure during operation. It is suitable for a rural environment with less capacity for 5G cells and required traffic than the existing macro environment.

8.5. *Converged network slicing between private 5G and enterprise network*

Enterprise SDN technology, which supports user group policies such as security, QoS, and IP mobility, has recently become more prevalent in enterprise networks. For example, when an enterprise network connects various networks, such as wired networks, WiFi6, and private 5G, it is essential to support network slicing, including network separation, QoS, and security based on the same policy, regardless of the type of network connection. In addition, when building network slicing in private 5G, the same user must consider the same policy between the enterprise and private 5G networks.

Fig. 35 depicts the network slicing architecture with a unified user and user equipment policy for an enterprise network. Integrated authentication allows unified user policy management, including wired, WiFi, and private 5G networks, whereas UDM and AUSF perform UE management. This architecture supports multiple connectivities of networks (e.g., wired, WiFi, or Private 5G) with a unified policy, such as network slicing. The SDN controller controls the dynamic policy of network isolation in enterprise networks based on the unified policy and network slicing management for the transport network. The Integrated Enterprise Network Management System (IENMS) manages the overall enterprise network, supporting a converged enterprise network featuring multiple connectivities using integrated user authentication. With this proposed architecture, enterprise users can connect private 5G, WiFi, and wired network with a unified user policy, and network slicing is the key technology to support network isolation with unified SLA and security policies.

8.6. *Programmable data plane*

Packet processing devices have evolved from the proprietary ASICs of vendors to merchant chip, disaggregation, and programmable devices, as shown in Fig. 36. The evolution of a disaggregated and programmable architecture for an open platform has accelerated recently, and a new use case of the data plane can be implemented accordingly. Network slicing requires new use cases based on stateless packet processing, such as in-band telemetry, TAP, NAT, and load balancing. It is possible to develop a high-performance, low latency, and compact edge data center by processing 5G packet forwarding applications on a chip that supports a programmable data plane [181]. 5G user plane applications, such as UPF and CU-UP—previously implemented with x86 server-based user plane functions such as DPDK and VPP—can be offloaded to a programmable switch device using programmable data plane technology. In addition to the existing switch function, stateless packet processing for 5G user plane applications can be implemented in programmable switch devices to develop relatively high performance, low latency, and compact edge data centers [182, 183]. Fig. 37 depicts the evolution of 5G edge data centers using programmable data planes [184].

Table 26
Advantage of integrated management of RAN and xHaul for network slicing.

Use-Case	Description
Auto Deployment	Auto deployment of integrated RAN and xHaul. Plug-and-play deployment from infrastructure automation including server, switches, and routers to RAN application
Unified Visibility	Integrated RAN and xHaul visibility such as topology, traffic monitoring (including discovery and monitoring)
Unified Inventory and Resource	Integrated and hierarchical inventory and resource management
RCA (Root Cause Analysis)	Integrated fault management using alarm and event correlation, supporting easy trouble-shooting, including RCA (Root Cause Analysis)
PKG Upgrade	Integrated software package management of RAN and xHaul (Upgrade and rollback)
Slice Traffic Isolation	RAN-aware xHaul traffic isolation using unified network slice ID and policy
Unified SLA Policy	Unified network slicing QoS policy automation, such as RAN-aware xHaul QoS policy configuration using 5QI-to-DSCP mapping
Unified SLA Monitoring (Service Assurance)	Integrated service assurance management between RAN and xHaul using active and passive monitoring

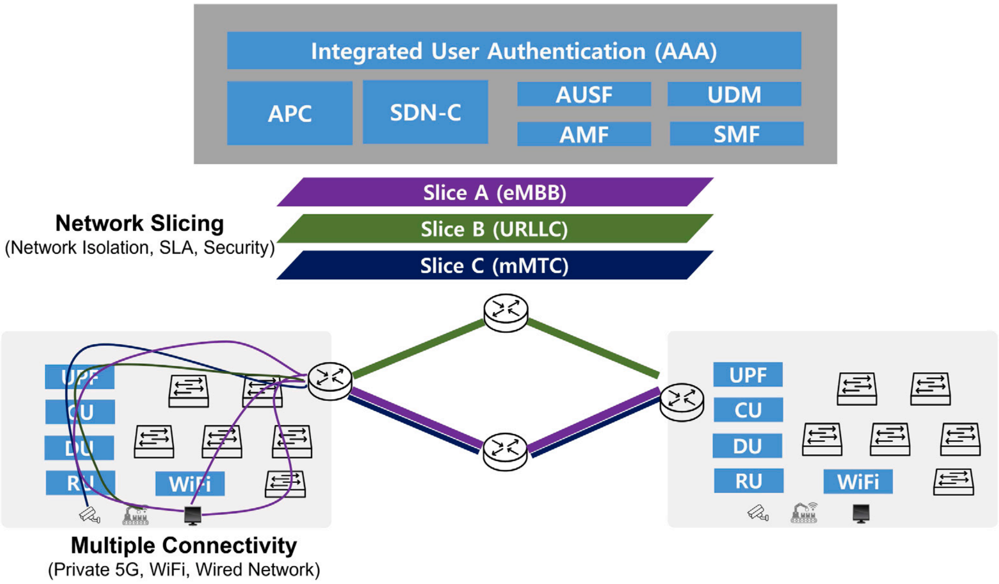


Fig. 35. Unified network slicing user and UE policy in enterprise network.

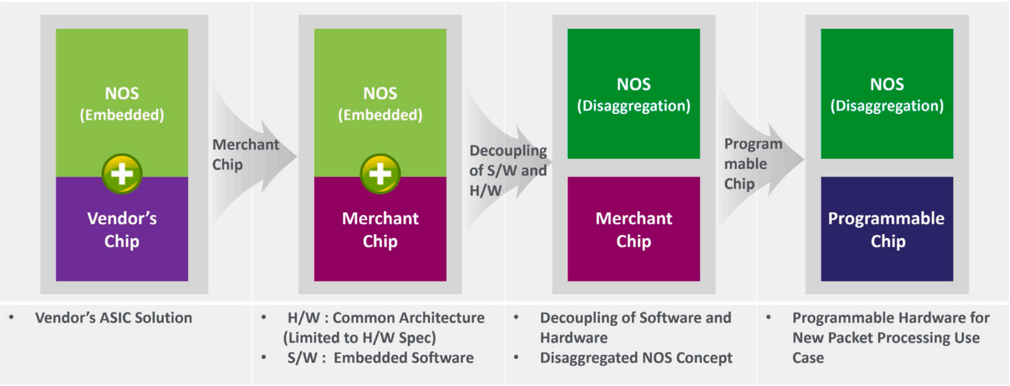


Fig. 36. Evolution towards disaggregated and programmable architectures.

Programmable devices are composed of programmable ASICs, such as Tofino, FPGAs, or CPUs. Programmable ASICs accelerate stateless packet processing, including programmable use cases. However, programmable ASICs support only limited TCAM memory; in this aspect, an FPGA can be used for massive flow processing look-up. CPUs mainly process control plane operations. For example, when implementing UPF functionalities, a programmable ASIC handles packet encapsulation, decapsulation, steering, and QoS processing. Session look-up, which requires processing millions of flows, can be done using an FPGA and DPI (Deep Packet Inspection), while fragmentation and reassembly need to

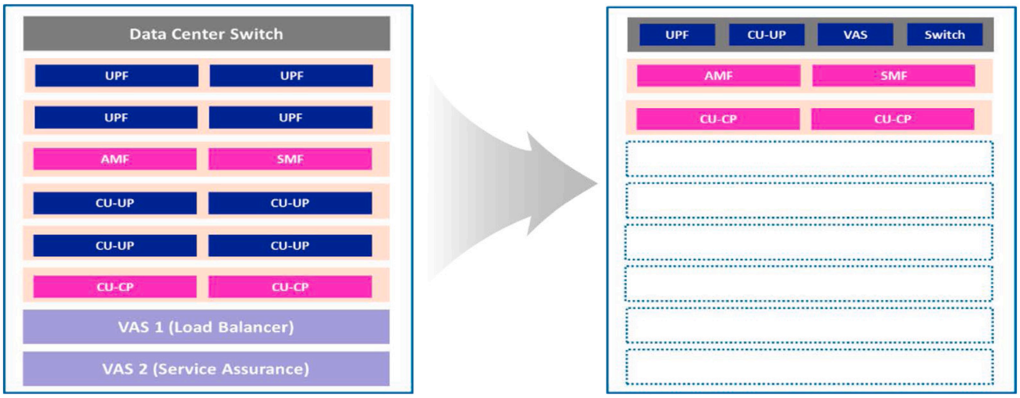


Fig. 37. 5G edge data center evolution using a programmable data plane.

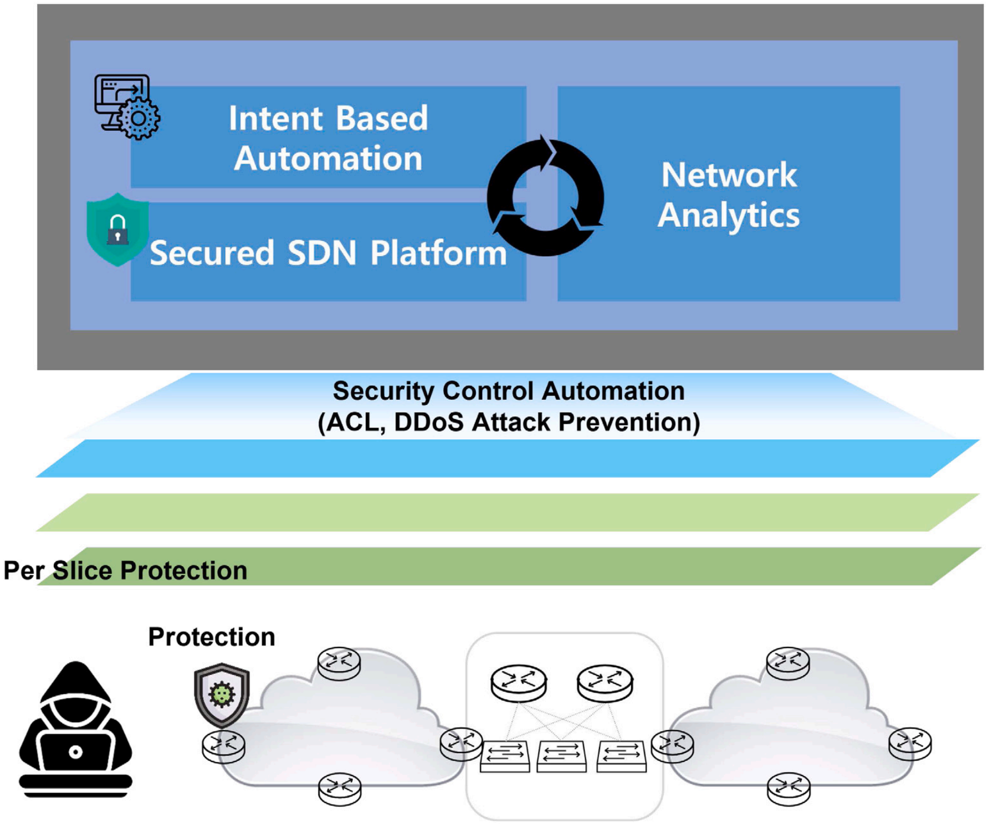


Fig. 38. Network slicing security architecture.

be processed on CPUs for stateful operations. The application of programmable data planes has recently expanded to vRAN/O-RAN through SRv6 technology, as SRv6 is very efficient in forming unified control and policy architectures across multiple domains, including vDU, vCU, and transport networks, as well as telco data center infrastructure.

8.7. Network slicing security

As network-slicing technology matures, important security issues are emerging. A security policy is applied with each slice's intent, and various security policies from the network operator's or actual terminal user's point of view are used based on this, which must be managed for each slice. In addition, secure authentication and encryption between components constituting the network slice should be supported [185,186].

Fig. 38 describes network slicing security architecture. For network slicing security, intent-based automation, secure platform, and network analytics are essential. As network slicing enables network isolation, network slicing protection per slice is crucial. There are many complicated attack scenarios, intent-based automation with closed-loop control by analyzing the complex signature of attack. Even if network slicing seems more secure than other public network connectivity modes, network slice security is also a vital issue across the life cycle of a slice. Micro-segmentation is a critical issue for secure slice isolation in a multi-cloud environment. For network slicing security, machine learning becomes vital as recent security attacks have become more complicated and complex, making them difficult to detect using existing algorithms [187].

8.8. Deep learning reinforcement for admission control

In the life cycle management of end-to-end network slicing, admission control is an important and challenging topic, as it requires dynamic resource management of slices considering the need to meet QoS requirements. There are many research areas in deep reinforcement learning-based admission control and resource management in each network slicing area, including RAN resources, transport resources by SDN, and 5G core resources [188–192]. Moreover, to implement fully autonomous, end-to-end network slicing in B5G and 6G contexts, accurate simulation through modeling of the resources required for actual network slicing is required before dynamically creating and updating each slice. Digital Twin networks and graph-based deep learning are hot research topics to solve issues in this area [193–197].

9. Conclusions

Network slicing is the critical technology of 5G for service providers to create new services, and the commercialization of 5G services is spreading. Although the demand for new services based on network slicing is increasing, there are still many technical difficulties in service network slicing at a commercial level. This paper discusses various topics on the implementation of network slicing at a commercial level. As a survey, we detail the major technological trends and issues of end-to-end network slicing, including end-to-end network slicing, cloud-native, hyper-scale cloud, openness, programmability, zero-touch operation, and intent-based networking (IBN). We present the significant use cases of network slicing and categorize the use cases based on actual project experience. For essential understanding and interrelationships with a wide range of open standards and open sources for end-to-end network slicing, we summarize network slicing standards organizations, open-source communities, and how they have evolved.

In this paper, we propose an end-to-end network slicing architecture, including RAN slicing, transport slicing, and core slicing. We also explain the state-of-the-art design, including vRAN/O-RAN architecture, RAN-Mobile xHaul integrated management, FHG (Front-Haul Gateway), end-to-end transport network architecture, SDN controller requirement, traffic isolation, and traffic engineering through segment routing in the transport network. End-to-end SLA management is also a key challenge of network slicing. We also proposed the end-to-end SLA management of network slicing using active monitoring, passive monitoring, the architecture of SLA management, and the scheme of end-to-end SLA KPI. Specifically, Section 8 explains the technical considerations for end-to-end network slicing evolution such as including open platform/open interface, cloud platform architecture design, RAN integrated xHaul architecture, converged network slicing between private 5G and enterprise network, virtual router, programmable data plane, network slicing security, and deep learning reinforcement for admission control.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hokeun Kim reports financial support was provided by National Research Foundation of Korea. Jae-il Jung reports financial support was provided by Korea Ministry of Trade Industry and Energy.

Data availability

No data was used for the research described in the article.

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