An Overview of Network Slicing for 5G

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Abstract

Besides conventional mobile broadband communication service, 5G is envisioned to support various new use cases from vertical industries. These new scenarios bring diverse and challenging requirements, such as a broader range of performance, cost, security protection, and mobility management. The one-size-fits-all design philosophy applied in existing networks is not viable any more. Slicing a single physical network into several logical networks customized to different unique requirements has emerged as a promising approach to fulfill such divergent requirements in a sustainable way. In this article, we provide a comprehensive survey of 5G network slicing. We first present the driving forces and the concept of network slicing. Then related key enabling technologies, including network function virtualization and modularization, dynamic service chaining, management and orchestration are discussed. The latest progress in 3GPP standardization and industry implementation on 5G network slicing is presented. Finally, the article identifies several important open issues and challenges to inspire further study toward a practical network slicing enabled 5G system.

Introduction

As envisioned by world leading operators [1], mobile networks need to support a 1000-time traffic increase in the coming decade. It is fundamentally important to ensure that operators will be able to provide diverse 5G services in an economically sustainable way. Existing networks are populated with a large variety of monolithic and proprietary hardware appliances, which make it more difficult to introduce new network services due to the increasing cost of energy, capital investment and operation. Therefore, new technologies, network deployment and operation paradigm are needed to minimize the total cost of the network infrastructure as well as system operation and management.

The 5G system is expected to support various new use cases from vertical industries, such as automotive and energy, which impose a much wider range of performance and cost requirements than that of traditional mobile broadband services. The existing networks based on conventional "one-size-fits-all" design are not flexible and scalable enough to address these diverse requirements in terms of performance, security, availability and cost. To accommodate various vertical-specific services besides enhanced mobile broadband service with the common physical network infrastructure, network slicing has been proposed by academia and industry as a key enabler to support customized 5G network services on-demand.

The network slicing concept has emerged as a result of the recent advancement in computing and network function virtualization (NFV) technologies. By slicing a physical network into several logical networks, each one can provide tailored services for a distinct application scenario. 5G network slices represented by logically isolated and self-contained networks are flexible enough and highly customizable to accommodate diverse business-driven use cases simultaneously over the same network infrastructure. To achieve expected network services efficiently, it is critical to decompose the existing large monolithic network functions coupled with various legacy hardware into numerous software based smaller modular network functionalities with varying granularity. Such cloud native functionalities can then be chained in flexible ways on demand to form different network slices supporting diverse 5G requirements.

The rest of the article is organized as follows. The following section introduces the driving forces and the concept of network slicing. The key enabling technologies of network slicing are then presented. Following that, we review the latest progress in industry standardization and implementation on 5G network slicing. Then, open issues and potential future research opportunities are discussed. The survey is summarized in the final section.

Driving Forces and Concept

Diverse Requirements

As mentioned in [1], the 5G system is supposed to support various new use cases, which can be classified into three categories.

Enhanced Mobile Broadband Connectivity (eMBB): This type of use case is similar to current ones, but represent the growing scenarios of a fully connected society. New services like augmented reality and three-dimensional service will play a more important role in the 5G timeframe. Moreover, the demand for mobile communications in vehicles, high-speed trains and even aircraft is growing.

Massive Machine Type Communications (mMTC): This family includes both low-cost, low-power, long range MTC and broadband MTC. In the near future, ultra-light, low power sensors may be integrated into people's clothing to measure various environmental and health attributes. Smart services will be pervasive in urban and rural areas for metering, environment monitoring and traffic control. These services result in very high device density.

Ultra-Reliable Critical Communication Services(URCC): This category covers use cases with strong demand on real-time interaction. For exam-

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ple, the autonomous driving scenario requires both ultra-reliable communication and immediate reaction to prevent road accidents. Real-time reaction is expected to be within the sub-millisecond.

It is rather difficult and economically infeasible to fullfil these diverse and even conflicting requirements in the 4G system. To provide customized network services with limited network resources while reducing capital expenditure and operation expense, it is natural to slice a physical network into several logical virtual networks so that each one can be customized and dedicated to a unique type of use cases.

Existing Approaches

Before the introduction of network slicing, there were similar solutions. In 4G, the dedicated core network (DECOR) makes it possible for an operator to deploy more than one dedicated core network (DCN) within a public land mobile network (PLMN). Each DCN is dedicated to a specific type of application or subscriber. The control plane and user plane functions in each DCN can be customized with unique features. To differentiate the specific group of subscribers and match them with a suitable DCN, a new subscription information named the UE usage type is introduced to select a specific DCN for the UE. However, DCN selection is performed by the control plane function of the default DCN. Before accessing a specific DCN, a UE needs to be redirected from the default DCN. The isolation between different DCNs is not perfect. To reduce the signaling overhead during DCN selection and improve the isolation among DCNs, the UE assisted DCN selection mechanism is introduced in enhanced DECOR (eDECOR). During the network access procedure, the UE informs the required DCN by including DCN-ID in the radio resource control (RRC) message to RAN. This allows the eNB to select an appropriate DCN and forward the UE related signaling to the specific DCN directly. In addition, the RAN sharing mechanism makes it possible for different mobile network operators with their core networks to share a common RAN [2]. However, it requires that each core network is equipped with a unique PLMN ID, and the shared RAN can only provide limited isolation. Network slicing is defined within a PLMN, but network sharing is performed among different PLMNs. Table 1 compares approaches similar to network slicing.

Technology	RAN sharing	DECOR	eDECOR	Network slicing
Sharing range	RAN	CN	CN	RAN and CN
Virtualization based	No	N/A	N/A	Yes
Function modularization	No	No	No	Yes
End-to-end	No	No	No	Yes
Isolation	Poor	Poor	Moderate	Good
Selection mechanism	UE based on PLMN ID	CN based on usage type	RAN based on DCN-ID	RAN based on NSSAI

TABLE 1. Comparison of related approaches.

The Network Slicing Concept

Network slicing refers to the partitioning of a physical network into several virtual networks; each network can be customized and optimized for a specific type of application or subscriber. By leveraging cloud computing and virtualization technologies, the shared physical network resources can be dynamically and efficiently scheduled to logical network slices based on changing user demands. A 5G network slice is composed of a collection of network functions and settings that are combined together for a specific use case or business model [1]. A network slice may span several domains, including radio access networks, core networks running on distributed cloud infrastructure, and transport networks supporting flexible virtual function placement. The basic principle of 5G network slice design is to provide only customized functions that are necessary to treat the traffic of the specific use case. Network slices have not only customized capabilities that are necessary for corresponding services, but also the capability to adapt to changing requirements. Providing a virtualized end-to-end environment that can be opened to third parties is one of the key features that differentiates network slicing from network sharing.

According to the definition in [3], network slicing consists of three layers:

- Service Instance Layer: Represents the end user services or business services that can be supported. Each service is represented by a service instance.
- Network Slice Instance Layer: Includes the network slice instances that can be provided. A network slice instance provides the network features that are required by the service instance.
- Resource Layer: Provides all virtual or physical resources and network functions that are necessary to create a network slice instance.

Key Enabling Technologies

Virtualization and Modularization

Through virtualization, dependencies on dedicated hardware are removed by abstracting resources necessary to run software functions. The virtualization technologies provide an important foundation for network slicing by enabling flexible slice creation on shared physical resources.

Traditional network entities are composed of a group of closely-coupled functionalities based on specific and siloed implementations, which means significant changes upon new requirements. The network slice based on coarse-grained network functionality is simple to deploy and manage but less flexible and adaptive to new vertical service requirements. To improve the programmability of 5G networks, the service-based architecture is introduced to enable more granular and decoupled network functionality [4]. The 5G network is envisioned to comprise small granularity, loosely-coupled, highly cohesive modular network function services. Each service is realized by a specific functionality and self-contained, which makes it possible to update individual services independently with less impact on other services. The smaller and modular network function components (NFCs) can be flexibly chained and connected to form larger network functions or end-to-end network slices on demand. However, it may be problematic to interface and chain these

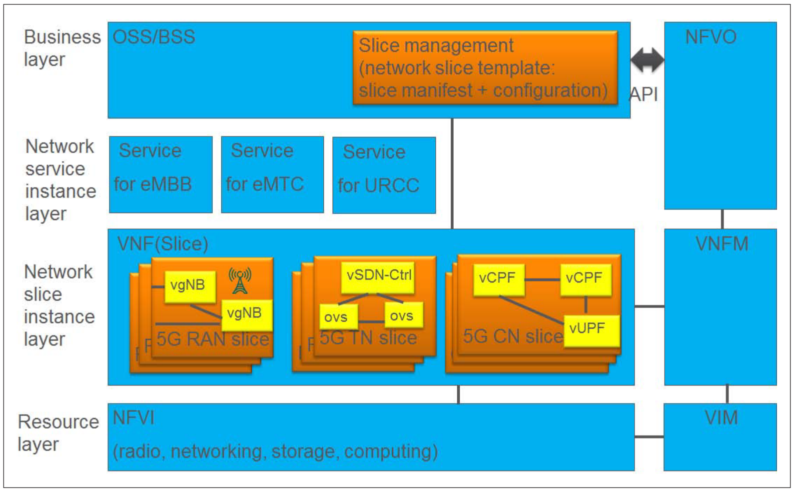

FIGURE 1. Slice management and orchestration architecture.

fine-grained services since more interfaces need to be defined for inter-communications.

SDN and Service Chaining

Software-defined networking (SDN) introduces network programmability by decoupling the control plane from the data plane, and logically centralized network intelligence, which can be leveraged to create new network services by dynamically chaining various functions based on user requirements and network conditions [5]. SDN enables a common infrastructure to support multiple client instances efficiently. As the client context provides a complete abstract set of resources isolated by the SDN controller's virtualization, it is natural for SDN to support network slicing. The SDN controller could dynamically orchestrate resources for network slices belonging to the same context by programmable interfaces and corresponding client-server context. Moreover, the recursion in SDN architecture enables end-to-end federated or recursive network slices across different domains.

Service chaining is a network capability that enables application-driven-networking through the ordered connection of network functions [6]. Service chaining makes it possible to flexibly chain both data and control plane functions so that the traffic of certain users or applications only traverses a particular set of functions. The specific type of traffic is steered to necessary network functions based on service chaining policies. With dynamic service chaining, network operators or third parties can create, scale, modify and remove network functions of a network slice based on changing demand, networks and cloud context information.

Management and Orchestration

Network slicing increases the complexity of network management, especially in the context of large numbers of network slices. Thus, it is critical to find automated management and orchestration solutions. So far, there is not a unified vision about the exact form and scope of network slice management and orchestration (MANO) [7]. To enable automated and flexible slice management, the concept of network services developed by the ETSI NFV group can be reused. Based on the current technology trend, it is natural that the existing NFV MANO framework [8] is leveraged to manage and orchestrate 5G network slices.

Fig. 1 presents a solution architecture of network slice MANO based on the enhancement of the NFV MANO framework. The existing OSS/BSS system is enhanced with the slice MANO functionality, which consumes the capability exposed by NFV orchestration for network service and VNF lifecycle management, as well as other capabilities enabling fault, configuration, performance, and security management of network slice instances (NSIs). The slice MANO includes slice template

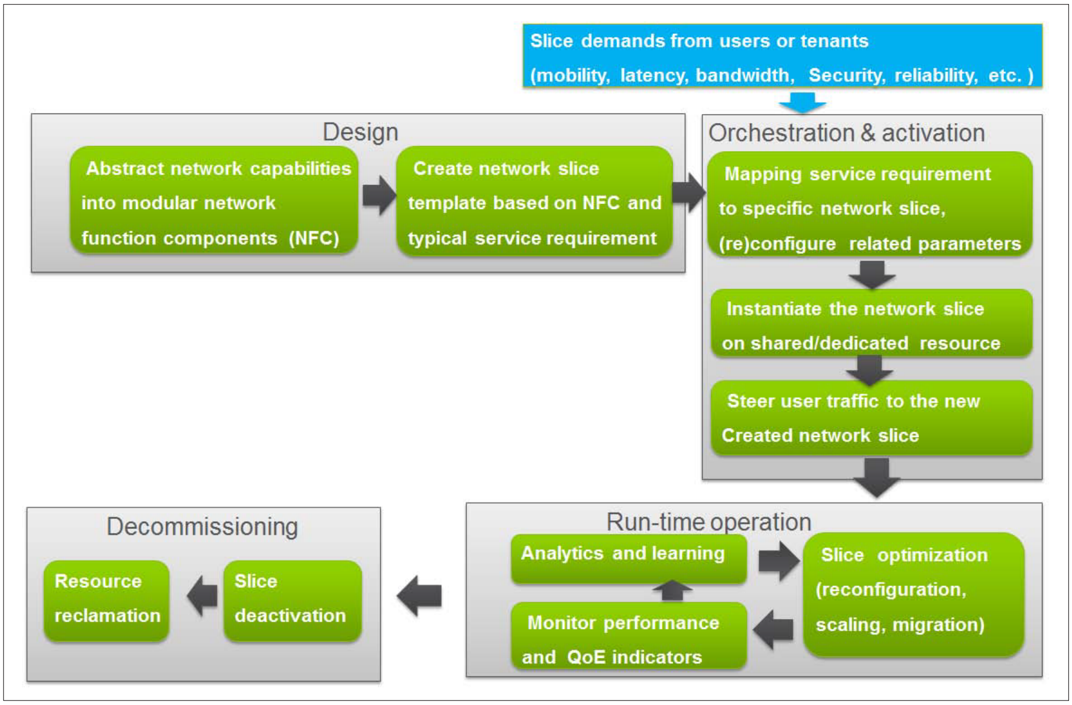

FIGURE 2. Lifecycle management of network slices.

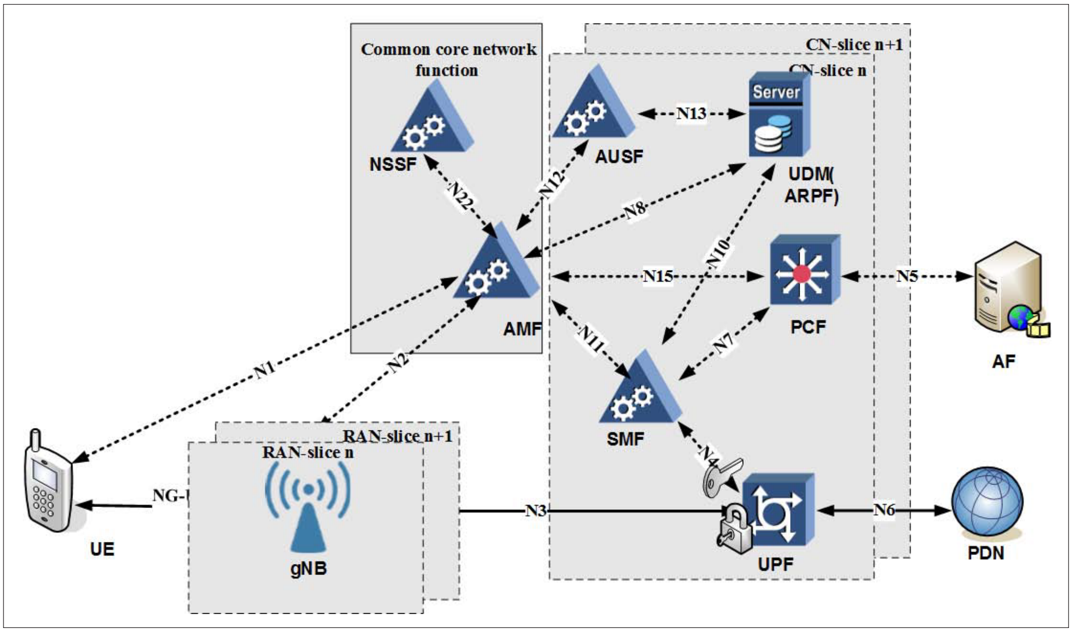

FIGURE 3. 5G Network slicing architecture.

Each network slice is identified with a single network slice selection assistance information (S-NSSAI), which is comprised of a slice/service type (SST) and a slice differentiator. The slice type represents the expected network slice behavior in terms of feature and service. The differentiator is used to differentiate multiple network slice instances of the same slice type.

management and NSI life cycle management. The life cycle of a network slice can be logically divided into four phases as illustrated by Fig. 2.

Design: The first step is to create a catalog of NFCs, which contains the building blocks of network slices. The catalog may keep developing with new service requirements and new network capabilities. The network slice template with related configuration is generated based on available NFCs, functional and performance requirements from users or tenants. The forwarding graph is generated based on required NFCs and associated relationships.

Orchestration and Activation: Based on service requirements from users or tenants, a specific network slice template is selected, that is, mapping service and performance requirements to a slice template. The deployment flavor in the template is used to describe the specific deployment supporting required performance such as capacity and Quality of Service (QoS). The NFCs of the network slice are instantiated in cloud infrastructures accordingly. Related NFCs are chained together through virtual connections according to the forwarding graph.

Run-Time Assurance: Related performance indicators such as network function load, resource utilizations, and QoS are continually monitored. These indicators are correlated with the service quality such as outages, data throughput, and end-to-end delay. Advanced big data analytics and machine learning tools can be used to analyze monitored performance information. The output of analytics can be used to reconfigure NSI to ensure the service-level agreement.

Decommissioning: Based on dynamic service requirements from tenants or the business strategy of operators, an active NSI is deactivated and related resources are released.

Standardization and Implementation

Overall network Slicing Architecture

Figure 3 shows the 5G network slicing architecture. Both the RAN and core network can be sliced. To support network slice selection for UEs, a new function called the network slice selection function (NSSF) is defined in 5G core networks [9]. Its main functionality includes selecting a set of network slice instances for a UE, generating the allowed NSSAI, and determining the access and mobility management function (AMF) set to serve the UE. In addition, new slice-related subscription information is introduced and managed by the unified data management (UDM). It can be found that some network functions are slice-specific, whereas other functions are common for all network slices. The advantages of the design include reducing slice management complexity and signaling over the air interface in case a UE connects to many network slices. However, it is at the cost of lightly compromised slice isolation. Each network slice is identified with a single network slice selection assistance information (S-NSSAI), which is comprised of a slice/service type (SST) and a slice differentiator. The slice type represents the expected network slice behavior in terms of feature and service. The differentiator is used to differentiate multiple network slice instances of the same slice type.

Working Principles

As illustrated by Fig. 4, when a UE registers with a PLMN, it should inform the network with a requested NSSAI corresponding to the slice type to which the UE expects to access, if the UE has a configured NSSAI or allowed NSSAI. During the connection establishment processes, different UEs may indicate the NSSAI with different slice type values based on requirements from users. Upon receiving the RRC message from the UE with a request NSSAI, the RAN selects a suitable AMF according to the requested NSSAI and forwards the UE related message to the AMF, which may query the UDM to retrieve the user subscription information including the subscribed S-NSSAI. The AMF verifies whether the requested NSSAI is permitted or not based on the subscribed S-NSSAI. Given various subscriptions, different network slice types may be approved to different users. When the local UE context does not

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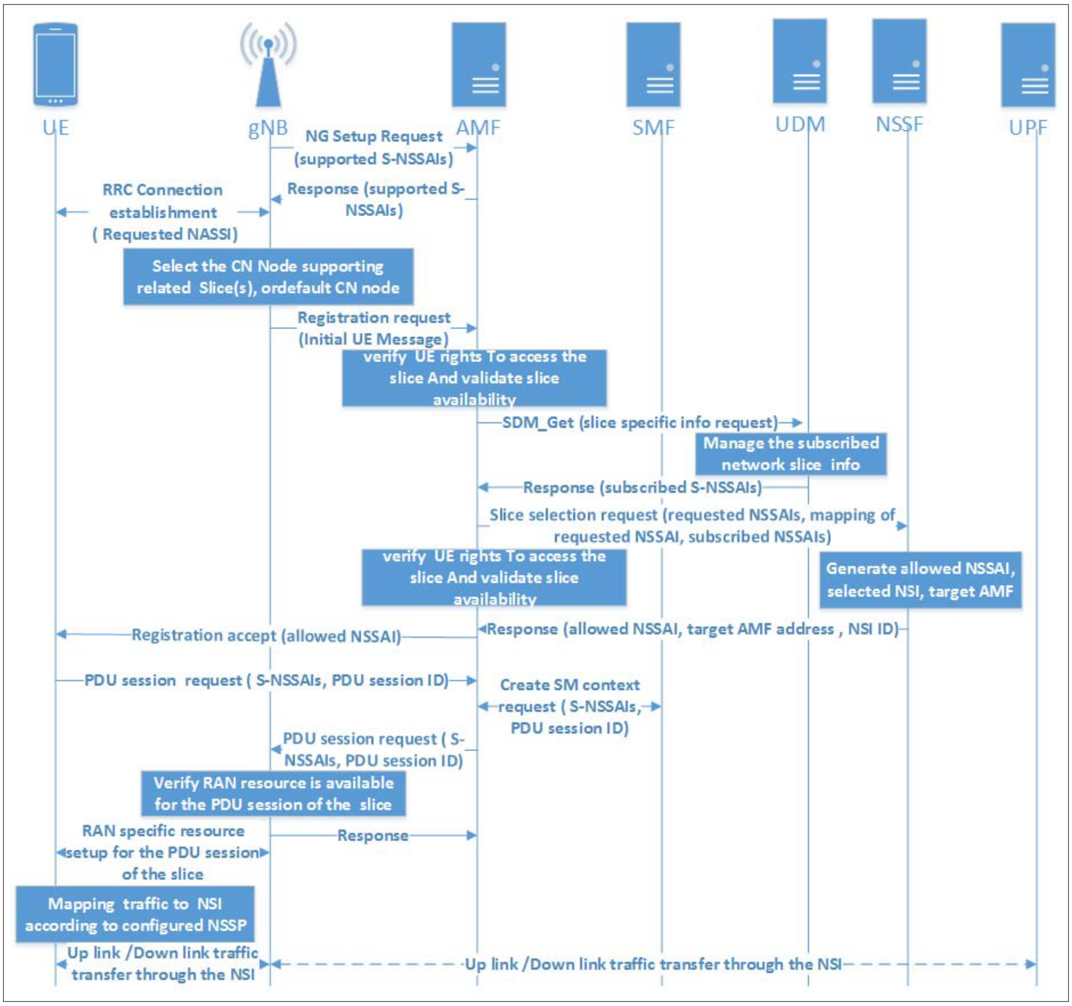

FIGURE 4. 5G network slicing working process.

include an allowed NSSAI, the AMF needs to query the NSSF. The NSSF selects an appropriate network slice instance including control plane and user plane network functions, and determines the target AMF set to serve the UE. Then the NSSF replies to the current AMF with the allowed NSSAI, which is forwarded to the UE.

The network slice selection policy rules associate an application with one or more network slices corresponding to the subscribed S-NSSAI of the UE. When an application associated with a specific S-NSSAI requests traffic transmission, the UE will instantiate the protocol data unit session establishment process with the control plane network functions of the slice. Subsequently, the user data traffic is processed by the customized user plane functions of the network slice.

RAN Slicing

In 3GPP, it has been agreed that 5G RAN should be slice-aware to treat slice-specific traffic according to customer demands. Based on assisted information provided by the UE or core network, the RAN performs radio-related network slice selection and applies an appropriate configuration to handle the slice-specific traffic. Currently, different RAN slices can be realized by providing different L1/L2 configurations and scheduling [10]. 5G RAN supports differentiated handling of data traffic belonging to different SSTs.

Cloud-RAN (C-RAN) is a promising paradigm by the virtualization of the centralized BBU pool, which facilitates network slicing in RAN. However, the high speed fronthaul network as required by traditional C-RAN is not always available, especially in urban small cell environments. This gives rise to the study of the flexible 5G radio functional split between central and distributed units. The split will have a big impact on the performance of RAN slicing. The optimal functional split depends on many factors such as the QoS requirement of applications, user density and load demand of the geographic area, and the quality of fronthaul transport networks. A configurable and flexible functional split is necessary for network slicing to support various use cases.

The densification of 5G cellular networks via C-RAN can be realized by deploying many distributed units (DUs) around the central unit (CU). Backhauling for an ultra-dense network (UDN) is challenging. Given the limited wired backhaul resources, the non-ideal wireless backhaul is important for densely deployed small cells. The conventional radio access links, the wireless fronthaul/backhaul links, and cloud computational resources make network slicing over UDN very challenging. Therefore, the integrated access and fronthaul/backhaul design should be considered for UDN slicing. Moreover, the UDN may be deployed by third party micro operators. More work on end-to-end network slicing by orchestrating local UDN resources of micro operators and wide area network resources of PLMN operators is needed.

Network Slicing Security

Network slicing brings many unprecedented security challenges [11] which include inter-slice security threats and the issues of resource harmonization between inter-domain slice segments. Moreover, 3GPP has identified many 5G network slicing related security risks [12]. First, security and performance isolation between different slices is critical and challenging because the virtual network functions (VNF) of network slice instances are deployed on shared cloud-based infrastructures. Since physical isolation is not always feasible, attackers may abuse the capacity elasticity of one slice to consume the resources of another target slice, which makes the target slice out of service. Furthermore, according to 5G architecture, certain control plane functions, such as NSSF, are common to multiple slices, which makes it possible for attackers to eavesdrop on the data of the target slice by accessing the common functions from another slice illegally.

From the UE perspective, it is agreed that a UE can simultaneously access more than one network slice. Therefore, it is possible that a UE can be misused as the bridge to initiate a security attack from one slice to another. So far, several candidate solutions to the aforementioned security risks have been identified [12], but there is no agreement in 3GPP 5G Phase I.

Industry Research and Practice

Many industry programs have been launched to facilitate the development of 5G network slicing from concept to management and verification. Under the European Union's framework program Horizon 2020 (H2020), the 5G PPP project METIS-II studies 5G RAN slicing and architecture. The 5G-PPP Phase II project SLICENET focuses on end-to-end slice management across multiple domains to achieve a cognitive and integrated 5G slice management framework. SLICENET will design, prototype and demonstrate a QoE-driven 5G network slicing framework oriented to verticals. Another 5G-PPP Phase II project MoNArch is pushing the network slicing concept developed in the 5G-PPP Phase I project NORMA into practice. MoNArch aims to develop and implement dedicated slices with specific requirements from vertical use cases and perform proof-of-concept. Moreover, the EU-Japan joint project PAGODA intends to develop a scalable 5G slicing architecture to support dynamic creation and management of network slices through a federated 5G testbed.

The METIS-II project has evaluated network slicing performance from the scheduler dimensioning and RRM functionalities placement perspectives [13]. For Ultra-reliable MTC (uMTC) slice, spectrum efficiency more than 1bps/Hz may be acceptable while latency is more stringent. For eMBB slice, more than 2.5bps/Hz spectrum efficiency is required. Therefore, the level of centralization can be determined by considering these requirements and interference levels. The radio resource scheduler dimensioning and placement of RRM functionalities for different network slices are evaluated, as illustrated in the Fig. 5. For the uMTC slice, the distributed RRM is used to reduce latency unless the users are near the cell edge. On the other hand, the more centralized RRM can be used for higher spectrum efficiency as required by the eMBB slice. However, the study is limited to RAN. More work is need to study end-to-end slice performance.

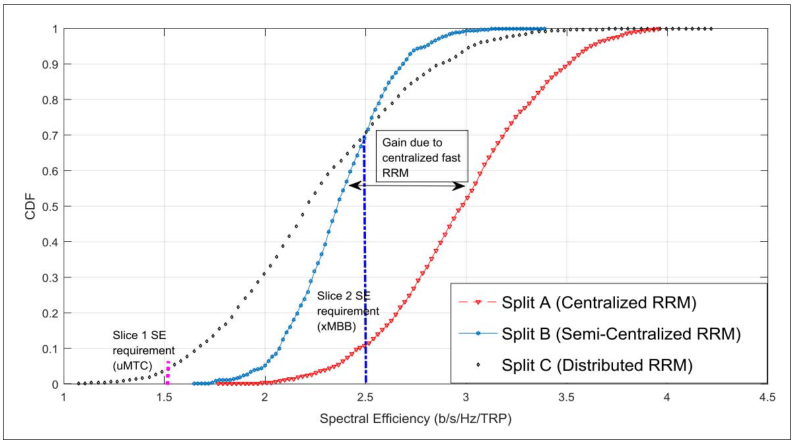

FIGURE 5. Spectrum efficiency of different slices [13].

There have been many implementations to test the feasibility and performance of network slicing. In June 2016, Ericsson and NTT DOCOMO announced a successful proof of concept of dynamic network slicing technology for 5G core networks. In November 2016, Huawei and Deutsche Telecom showed an all cloud based E2E 5G network slicing demo, including RAN, transport and core networks. As part of the MoNArch project, Nokia cooperated with T-Mobile to launch the first 5G network slicing trial in Hamburg Port in 2018. During the second-phase China IMT-2020 5G test in June 2017, Huawei is the first to complete 5G network slicing tests, which verifies that related devices can meet diversified service requirements of three typical scenarios. Given that a large number of different network slice instances across multiple domains may be deployed in commercial 5G system, fully automated network slice management and orchestration are still indispensable to reduce the operation cost and complexity of network slicing.

Open Issues and Research Opportunities

RAN Virtualization and Slicing

RAN virtualization is challenging because many radio resource processing components are still based on dedicated hardware. As an evolution of C-RAN, a 5G base station consists of a CU that may host time-tolerant functions and multiple DUs that may host time-critical functions. The functionalities in the CU are suitable to be virtualized, but the functionalities in the DU are difficult to be virtualized due to the strong dependence on dedicated hardware acceleration [14]. One of the most difficult challenges is the virtualization of the DU and physical channel. In particular, how to ensure good slice isolation in the context of beamforming is to be investigated. Furthermore, it is to be studied whether multiple radio access technologies (RATs) can be virtualized with the same hardware or different types of dedicated hardware.

A recent study [15] shows that a set of new slice-oriented information, configuration descriptors and tailored protocol features need to be

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introduced across Layer 1, Layer 2, and Layer 3 of the 5G radio interface to realize RAN slices. More effort is needed to exploit new virtualization and slice oriented resource scheduling mechanisms to achieve stronger slice isolation without compromising multiplexing gain over shared radio resources. Whether there should be a common RRM for all radio slices or a dedicated RRM for each slice should be investigated further. In the context of distributed multi-vendor hardware components with different functional splits, it is difficult for the centralized RRM to manage them.

Holistic and Intelligent Slice Orchestration

So far, there is not a widely recognized network slice MANO system in the industry. It is far from a holistic end-to-end and orchestration system that could fulfill diverse service requirements while ensuring efficient resource utilization and appropriate isolation. To achieve the target, the orchestration system needs to manage resources efficiently and holistically based on the current state of network slices, underlying resource status and the predicted user demands. Efficient resource scheduling mechanisms need to incorporate optimality techniques, whereby slice instance resources can be dynamically scaled to optimally serve changing tenant demand without negatively impacting the performance of other slice instances. More specifically, one of the most difficult challenges is how to optimally deploy and dynamically adapt network slice stances, given the changing user demand, distributed and dynamic cloud resource status. It is challenging to optimize the placement of network functions of a network slice.

Moreover, a network slice instance may be deployed across multiple network domains even more than one operator. The end-to-end resources include not only the cloud infrastructure but also the radio and transport networks in the administrative domains of different operators. The correlation and coordination among different domains are indispensable and challenging. Artificial intelligence and automatic learning should be considered to realize an intelligent slice orchestration system with self-diagnosis, self-healing, and automatic configuration capability.

Secure Sliced Networks

New actors, for example, cloud infrastructure providers and virtual network providers, have been introduced into virtualized network slices. The new ecosystem changed the existing trust model among users, network operators, and service providers. One of the biggest challenges is trust management between different vendors that provide hardware or software components of an end-to-end network slice instance across administrative domains owned by different operators. Moreover, the VNFs of a network slice may be scaled and migrated flexibly, which means the trust chain is more dynamic. It is quite challenging to manage the dynamic trust chain efficiently and to evaluate the trustiness of the whole sliced network service. Ensuring trust and consistent security policies among slice tenants and providers is still an open issue. Meanwhile, it is a pre-requisite when the network slice is applied to vertical industries with stringent security requirements. Furthermore, instantiating a network slice by orchestration resources across multiple technological domains with their unique security properties will expose the network slice to different intra-slice security and inter-domain security threats. Network slice security policy coordination mechanisms among different domains and operators should be investigated.

Conclusion

Network slicing based on clouding computing and NFV has emerged as a key enabling technology for 5G network operators to provide various customized services on-demand in a sustainable way. However, multiple technical issues still have to be addressed to achieve the ambitious goals of the 5G system. This article investigates related key enabling technologies, including network function virtualization and modularization, dynamic service chaining, management and orchestration. The progress of industry standardization and implementation of 5G network slicing is discussed. By reviewing the progress, we identify potential future research opportunities, including RAN virtualization and slicing, holistic slice orchestration, and secure sliced networks. We hope this review will be helpful for readers to understand the latest developments and perform further studies in the identified directions to realize the vision of network slicing based 5G systems.

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Biographies

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