Contents

Acronyms

AN Access Network. 7

BH Backthaul. 3

CP Control Plane. 7

E2E End to End. 3

eMBB enhanced mobile broadband. 14

FH Fronthaul. 3

IaaS Infrastructure-as-a-Service. 4

MANO Management and Orchestration. 6

mMTC massive machine-type communications. 14

MNO Mobile Network Operators. 3

MTA Multi-Tenancy Application. 7

NBI Northbound Interface. 6

NF Network Functions. 7

NFV Network Functions Virtualization. 7

NGMN Next Generation Mobile Networks. 3

NS Network Services. 4

NSIL Network Service Instance Layer. 3

SBI Southbound Interface. 7

SDN Software Defined Network. 4

SIL Service Instance Layer. 3

UP User Plane. 7

URLLC ultra-reliable low-latency communications. 14

VI Virtual Infrastructures. 4

VNF Virtual Network Functions. 4

1 Introduction

Mobile networks are a key element of today's society, enabling communication, access and information sharing. Moreover, traffic forecasts predict that the demand for capacity will grow exponentially over the next years, mainly due to video services. However, as cellular networks move from being voice-centric to data-centric, operators' revenues are not able to keep pace with the predicted increase in traffic volume. Such pressure on operators' return on investment has pushed research efforts toward designing for 5G novel mobile network solutions able to open the door for new revenue sources. In this context, the network slicing paradigm has emerged as a key 5G disruptive technology addressing this challenge. Network slicing for 5G allows Mobile Network Operators (MNO) to open their physical network infrastructure platform to the concurrent deployment of multiple logical self-contained networks, orchestrated in different ways according to their specific service requirements; such network slices are then (temporarily) owned by tenants. The availability of this vertical market multiplies the monetization opportunities of the network infrastructure as new players may come into play (e.g., automotive industry, e-health) and an higher infrastructure capacity utilization can be achieved by admitting network slice requests and exploiting multiplexing gains. With network slicing for 5G networks, different services (e.g., automotive, mobile broadband, or haptic Internet) can be provided by different network slice instances. Each of these instances consists of a set of virtual network functions that run on the same infrastructure with a tailored orchestration. In this way, very heterogeneous requirements can be provided on the same infrastructure, as different network slice instances can be orchestrated and configured separately according to their specific requirements. Additionally, this is performed in a cost-efficient manner as the different network slice tenants share the same physical infrastructure. A network slice is defined by Next Generation Mobile Networks (NGMN) as "a set of network functions, and resources to run these network functions, forming a complete instantiated logical network to meet certain network characteristics required by the Service Instance(s)." According to NGMN, the concept of network slicing involves three layers, namely, (i) service instance layer, (ii) network slice instance layer, and (iii) resource layer. The Service Instance Layer (SIL) represents the end user and/or business services provided by the operator or the third-party service providers, which are supported by the Network Service Instance Layer (NSIL). The NISL is in turn supported by the resource layer, which may consist of the organic resources such as compute, network, memory, storage, etc., or it may be more comprehensive as being a network infrastructure, or it may be more complex as network functions. Figure 1 depicts this concept where the resources at the resource layer are dimensioned to create several sub network instances, and network slice instances are formed that may use none, one, or multiple sub network instances. The end goal of network slicing in 5G mobile networks is to be able to realize End to End (E2E) network slices starting from the mobile edge, continuing through the mobile transport (Fronthaul (FH) /Backthaul

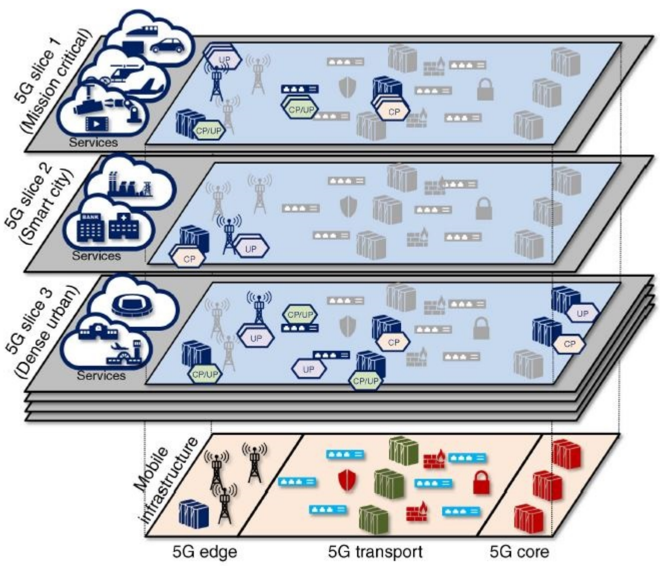

Figure 1: Example of network slicing in 5G.

(BH)), and up until the core network (CN). The allocation of a slice involves the selection of the required functions, their constrained placement, the composition of the underlying infrastructure, and the allocation of the resources to fulfill the services' requirements, for example, bandwidth, latency, processing, resiliency. We consider two main network slicing services that enable different degrees of explicit control and are characterized by different levels of automation of the mobile network slices management: 1) The provision of Virtual Infrastructures (VI) under the control and operation of different tenants-in line with an Infrastructure-as-a-Service (IaaS) model[1], that is, creation of a network slice instance. 2) The provision of tenant's owned Network Services (NS), that is, creation of a service instance. In the former service, the deployment of a mobile network deals with the allocation and deallocation of VIs. The logical entities within a VI encompassing a set of compute and storage resources are interconnected by a virtual, logical network (i.e., virtual nodes are interconnected by virtual links over the substrate network). The Vis can be operated by the tenant via different Software Defined Network (SDN) control models. In the latter, NS are instantiated directly over a shared infrastructure, and as a set of interrelated Virtual Network Functions (VNF) connected through one or more VNF forwarding graphs. Multi-tenancy is an characteristic that can be applied to both kinds of services, guaranteeing separation, isolation, and independence between different slices coupled with the efficient sharing of the underlying resources for both VI and NS concepts. In this context, a tenant is a logical

[1] form of cloud computing that provides virtualized computing resources over the internet

entity owning and operating either one or more VIs or one or more network services. A tenant can be associated with an administrative entity (e.g., mobile virtual network operators) or user of a given service (e.g., over-the-top service providers).

2 Architecture for Network Slicing

The necessary architecture involves the aspects of modularization resource virtualization, virtual infrastructure, and network service management. The design

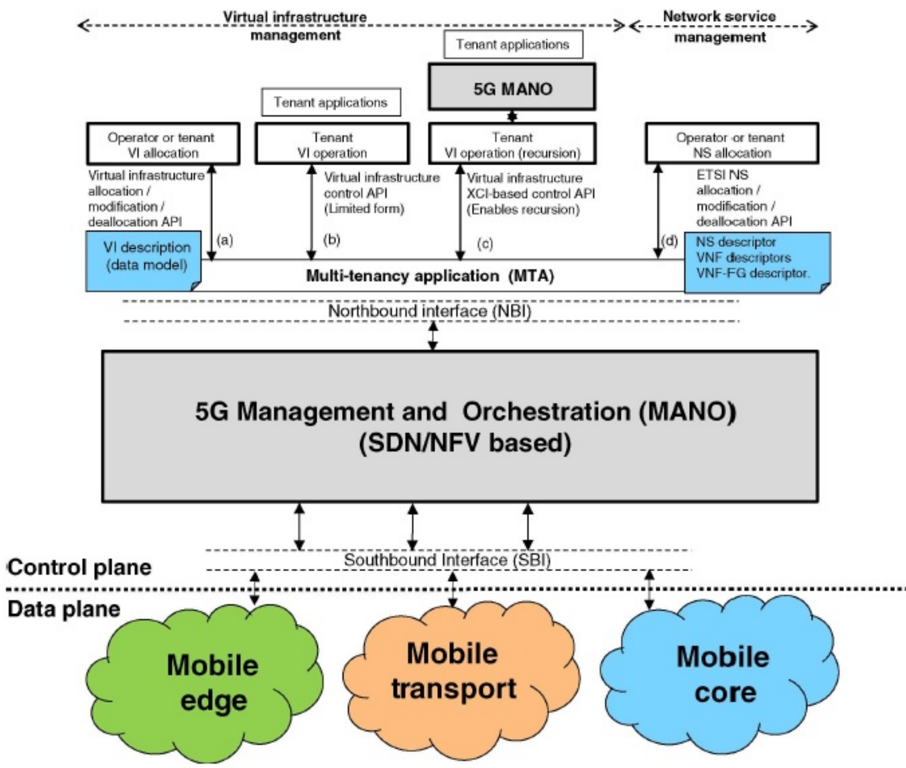

Figure 2: Architecture for network slicing.

proposed in Fig. 2 follows the SDN principles of (i) data and control plane fully decoupled, (ii) control logically centralized, and (iii) applications having an abstracted view of resources and states. The data plane is the resource layer which includes mobile edge, mobile transport, and core. The infrastructure is composed of links, forwarding nodes (e.g., switches and routers), cloud nodes (e.g., data centers), and so on, comprising a set of network, computing, and storage resources. The control plane is divided into two layers: an application layer at the top and the 5G Management and Orchestration (MANO) platform below. The design of the MANO is based on the ETSI management and network orchestration framework with integrated SDN-based control. The MANO provides an abstracted view of available resources and states and control, and management functions to an ecosystem of applications, via a Northbound Interface (NBI). On the other hand, the MANO is connected to the data plane elements via a

Southbound Interface (SBI) to execute control and management functions (e.g., OpenFlow, SNMP, OVSDB) on the actual hardware components. With respect to the Multi-Tenancy Application (MTA), it implements the multi-tenancy support by coordinating and managing tenants access to a shared infrastructure, performing resource isolation between instances assigned to different tenants, and delivering multi-tenancy-related services, such as the allocation and operation of VIs, by means of dedicated APIs in cooperation with the data plane, enforcing this logical separation. As shown in Fig. 2 such APIs depend on the actual service: for the control of a VI or NS lifetime, instantiation, modification, and deletion.

2.1 Enablers and Design Principles

Future 5G networks will be built on novel concepts that were not envisioned by the previous generation network architectures. The revolution provided by the introduction of software-defined networking and Network Functions Virtualization (NFV)[2]) opens the door to a large list of possible applications recalling that the latter focuses primarily on optimization of the network services, instead the former to separate the control and forwarding plane for a centralized view of the network. The fundamental parts involved in the network slicing realization for the future 5G networks are now discussed.

2.1.1 Modularization

The evolution of mobile communication systems towards 5G was intentionally aiming at achieving architecture flexibility, heterogeneous accesses and vertical business integration, leveraging on NFV and SDN. To enable the design of logical architectures tailored to performance and functional requirements of different use cases, the principle of architecture modularization and network function decomposition was proposed at the earliest 5G research stages.
Network Functions (NF)s are functional blocks that provide specific network capabilities to support and realize the particular service(s) demanded. Generally implemented as software instances running on infrastructure resources, NFs can be physical (a combination of vendor-specific hardware and software, defining a traditional purpose-built physical appliance) and/or virtualized (network function software is decoupled from the hardware it runs on). In particular, conventionally monolithic network functions are proposed to be split into basic modules, both for the Control Plane (CP) and User Plane (UP), thus allowing the definition of different logical architectures via the interconnection of different subsets of CP and UP NFs. In the process of decomposing the NFs into basic modules, the distinction between NFs relating to the Access Network (AN) and core network emerged. To minimize the dependency of the 5G core on the

[2]Although NFV and VNF are often used interchangeably, for the sake of clarity NFV is an overarching concept, while a VNF is building block of a NFV framework.

access (and vice versa), and achieve the definition of a convergent network[3], providing connectivity via a multitude of accesses not only including cellular radio, a different AN/CN functional split and an interface model are necessary. Besides flexibility, the architecture modularization provides the essentials to support network slicing, as a network slice can be defined as an independent logical network shaped by the interconnection of a subset of NFs, composing both CP and UP, and which can be independently instantiated and operated over physical or virtual infrastructure.

2.1.2 Virtualization

Virtualization is a key process for network slicing as it enables effective resource sharing among slices. Virtualization is the abstraction of resources using appropriate techniques. Resource abstraction is the representation of a resource in terms of attributes that match predefined selection criteria while hiding or ignoring aspects which are irrelevant to such criteria, in an attempt to simplify the use and management of that resource in some useful way. The resources to be virtualized can be physical or already virtualized, supporting a recursive pattern with different abstraction layers. Just as server virtualization makes virtual machines (VMs) independent of the underlying physical hardware, network virtualization enables the creation of multiple isolated virtual networks that are completely decoupled from the underlying physical network and can safely run on top of it. The framework consists of three kinds of actors:

- Infrastructure provider (InP): owns and manages a given physical network and its constituent resources. Such resources, in the form of WANs and/or data centers (DCs), are virtualized and then offered through programming interfaces to a single or multiple tenants.
- Tenant: leases virtual resources from one or more InPs in the form of a virtual network, where the tenant can realize, manage, and provide network services to its users. A network service is a composition of NFs, and it is defined in terms of the individual NFs and the mechanism used to connect them.
- End user: consumes (part of) the services supplied by the tenant, without providing them to other business actors.

2.1.3 Orchestration

Orchestration is also a key process for network slicing. In its general sense, orchestration can be defined as the art of both bringing together and coordinating disparate things into a coherent whole. In a slicing environment, where the players involved are so diverse, an orchestrator is needed to coordinate seemingly disparate network processes for creating, managing, and delivering services. According to the ONF, orchestration is defined as the continuing process of selecting resources to fulfill client service demands in an optimal manner. The idea

[3]Network convergence is the efficient coexistence of telephone, video and data communication within a single network.

of optimal refers to the optimization policy that governs orchestrator behavior, which is expected to meet all the specific policies and service level agreements (SLAs) associated with clients (e.g., tenants or end users) that request services. The term continuing means that available resources, service demands, and optimization criteria may change in time. Interestingly, orchestration is also referred to as the defining characteristic of an SDN controller. Note that client is a term used in the SDN context. The ONF states that the orchestrator functions include client-specific service demand validation, resource configuration, and event notification. However, in network slicing, orchestration cannot be performed by a single centralized entity, not only because of the complexity and broad scope of orchestration tasks, but also because it is necessary to preserve management independence and support the possibility of recursion. In our view, a framework in which each virtualization actor has an entity performing orchestration functions seems more suitable to satisfy the above requirements. The entities should exchange information and delegate functionalities between them to ensure that the services delivered at a certain abstraction layer satisfy the required performance levels with optimal resource utilization.

2.1.3.1 Isolation Strong isolation is a major requirement that must be satisfied to operate parallel slices on a common shared underlying substrate. The isolation must be understood in terms of:

• Performance: Each slice is defined to meet particular service requirements, usually expressed in the form of key performance indicators (KPIs). Performance isolation is an E2E issue, and has to ensure that service-specific performance requirements are always met on each slice, regardless of the congestion and performance levels of other slices.

• Security and privacy: Attacks or faults occurring in one slice must not have an impact on other slices. Moreover, each slice must have independent security functions that prevent unauthorized entities to have read or write access to slice-specific configuration/management/accounting information, and be able to record any of these attempts, whether authorized or not.

• Management: Each slice must be independently managed as a separate network. To achieve isolation, a set of appropriate, consistent policies and mechanisms have to be defined at each virtualization level, following the recursion principle introduced earlier. The policies contain lists of rules that describe how different manageable entities must be properly isolated, without delving into how this can be achieved. To fully realize the required isolation level, the interplay of both virtualization and orchestration is needed.

2.1.4 SDN: Software-Defined Network

In a software-defined network, a network engineer or administrator can shape traffic from a centralized control console without having to touch individual switches in the network. The centralized SDN controller directs the switches to deliver network services wherever they're needed, regardless of the specific connections between a server and devices. This process is a move away from traditional network architecture, in which individual network devices make traffic decisions based on their configured routing tables.

The SDN architecture comprises an intermediate control plane that dynamically configures and abstracts the underlying forwarding plane resources so as to deliver tailored services to clients located in the application plane. This is well aligned with the requirements of 5G network slicing, which needs to satisfy a wide range of service demands. Thus, the SDN architecture is an appropriate tool for supporting the key principles of slicing.

The major SDN components are resources and controllers. For SDN, a resource is anything that can be utilized to provide services in response to client requests. This includes infrastructure resources[4] and NFs, but also network services, in application of the recursion principle described earlier. A controller is a logically centralized entity instantiated in the control plane which operates SDN resources at runtime to deliver services in an optimal way. Therefore, it mediates between clients and resources, acting simultaneously as server and client via client and server contexts, respectively. Both contexts are conceptual components of an SDN controller enabling the server-client relationships:

• Client context: Represents all the information the controller needs to support and communicate with a given client. It comprises a Resource Group and a Client support function. The Resource Group contains an abstract, customized view of all the resources that the controller, through one of its northbound interfaces, offers to the client, in order to deliver on its service demands and facilitate its interaction with the controller. Client support contains all that is necessary to support client operations, including policies on what the client is allowed to see and do and service-related information to map actions between the client and the controller.

• Server context: Represents all the information the controller needs to interact with a set of underlying resources, assembled in a Resource Group, through one of its southbound interfaces. The process of transforming the set of Resource Groups accessed through server contexts to those defined in separate client contexts is not straightforward, and it requires the SDN controller to perform virtualization and orchestration functions. When performing the virtualization function, the SDN controller carries out the abstraction and the aggregation/partitioning of the underlying resources. Thanks to virtualization, each client context provides a specific Resource Group that can be used by the client associated with that context to realize its service(s). Through orchestration, the SDN controller optimally dispatches the selected resources to such separate Resource Groups. The interplay of both controller functions enables the fulfillment of the diverging service demands from all clients while preserving the isolation among them. The SDN architecture also includes an administrator. Its tasks consist of instantiating and configuring the entire controller, including the creation of both server and client contexts and the installation of their associated policies. The SDN architecture naturally supports slicing, as

[4] Heterogeneous hardware and necessary software for hosting and connecting NFs. They include computing hardware, storage capacity, networking resources (e.g., links and switching/routing devices enabling network connectivity), and physical assets for radio access.

the client context provides the complete abstract set of resources (as a Resource Group) and the supporting control logic that constitute a slice, including the complete collection of related client service attributes. Another key functional aspect that makes SDN architecture ideal to embrace 5G slicing is recursion. Because of the different abstraction layers that the recursion principle enables, the SDN control plane can involve multiple hierarchically arranged controllers that extend the client-server relationships at several levels. According to these premises, it is evident that SDN can support a recursive composition of slices. This implies that the resources (i.e., Resource Group) a given controller delivers to one of its clients in the form of a dedicated slice (i.e., client context) can, in turn, be virtualized and orchestrated by such a client in the case of being an SDN controller. In this way, the new controller can utilize the resource(s) it accesses via its server context(s) to define, scale, and deliver new resources (and hence new slices) to its own clients, which might also be SDN controllers.

2.1.5 NFV: Network Functions Virtualization

Although the SDN architecture described above gives a comprehensive view of the control plane functionalities enabling slicing, it lacks capabilities that are vital to efficiently manage the life cycle of network slices and its constituent resources. In this respect, the NFV architecture is ideal to play this role, as it manages the infrastructure resources and orchestrates the allocation of such resources needed to realize VNFs and network services. VNFs, generally speaking, are virtualized tasks formerly carried out by proprietary, dedicated hardware. VNFs move individual network functions out of dedicated hardware devices into software that runs on commodity hardware. These tasks, used by both network service providers and businesses, include firewalls, domain name system (DNS), caching or network address translation (NAT) and can run as virtual machines. In this respect, the NFV architecture is ideal to play this role, as it manages the infrastructure resources and orchestrates the allocation of such resources needed to realize VNFs and network services. To benefit from the management and orchestration functionalities of NFV, appropriate cooperation between SDN and NFV is required. However, embracing SDN and NFV architectures into a common reference framework is not an easy task. ETSI presents a framework to integrate SDN within the reference NFV architecture. This framework incorporates two SDN controllers, one logically placed at the tenant and another at the InP level. The NFV architecture comprises the following entities:
• Network Functions Virtualization Infrastructure (NFVI): A collection of resources used to host and connect the VNFs. While the broad scope of SDN makes resource a generic concept, the current resource definition in the NFV framework comprises only the infrastructure resources.
• VNFs: Software-based implementations of NFs that run over the NFVI.
• Management and Orchestration (MANO): Performs all the virtualization-specific management, coordination, and automation tasks in the NFV architecture. The MANO framework comprises three functional blocks:
• • Virtualized infrastructure manager (VIM): responsible for controlling and

managing the NFVI resources.
• • VNF manager (VNFM): performs configuration and life cycle management of the VNF(s) on its domain.
• • Orchestrator: According to ETSI, it has two set of functions performed by the Resource Orchestrator (RO) and Network Service Orchestrator (NSO), respectively. The RO orchestrates the NFVI resources across (potentially different) VIMs. The NSO performs the life cycle management of network services using the capabilities provided by the RO and the (potentially different) VNFMs.
• Network Management System (NMS): Framework performing the general network management tasks. Although its functions are orthogonal to those defined in MANO, NMS is expected to interact with MANO entities by means of a clear separation of roles. NMS comprises:
• • Element management (EM): anchor point responsible for the fault, configuration, accounting, performance, and security (FCAPS) of a VNF.
• • Operation/business support system (OSS/ BSS): a collection of systems and manage- ment applications that network service providers use to provision and operate their network services. In terms of the roles we considered earlier, tenants would run these applications. The ETSI proposal includes two SDN controllers in the architecture. Each controller centralizes the control plane functionalities and provides an abstract view of all the connectivity-related components it manages. These controllers are:
• Infrastructure SDN controller (IC): Sets up and manages the underlying networking resources to provide the required connectivity for communicating the VNFs. Managed by the VIM, this controller may change infrastructure behavior on demand according to VIM specifications adapted from tenant requests.
• Tenant SDN controller (TC): instantiated in the tenant domain as one of the VNFs or as part of the NMS, this second controller dynamically manages the pertinent VNFs used to realize the tenant's network service(s). These VNFs are the underlying forwarding plane resources of the TC. The operation and management tasks that the TC carries out are triggered by the applications running on top of it (e.g., the OSS).
Both controllers manage and control their underlying resources via programmable southbound interfaces, implementing protocols like OpenFlow, NETCONF, and I2RS. However, each controller provides a different level of abstraction. While the IC provides an underlay to support the deployment and connectivity of VNFs, the TC provides an overlay comprising tenant VNFs that, properly composed, define the network service(s) such a tenant independently manages on its slice(s). These different resource views each controller offers through its interfaces have repercussions on the way they operate. On one side, the IC is not aware of the number of slices that utilize the VNFs it connects, nor the tenant(s) which operate(s) such slices. On the other side, for the TC the network is abstracted in terms of VNFs, without notions of how those VNFs are physically deployed. Despite their different abstraction levels, both controllers have to coordinate and synchronize their actions. Note that the service and tenant concept mentioned here can be extended to higher abstraction layers by simply

applying the recursion principle. Finally an overall description of the system is given by Fig. 3.

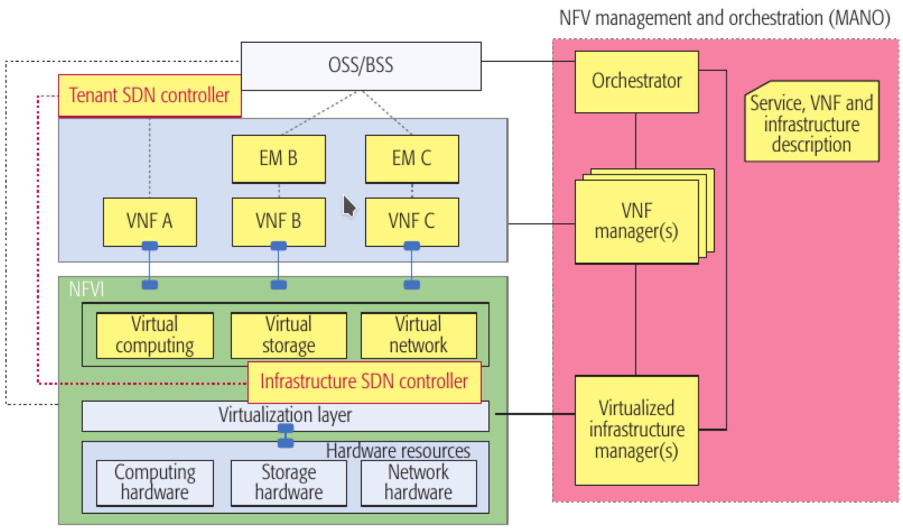

Figure 3: Integrating SDN controllers into the reference NFV architectural framework.

3 Network Slicing

In order to create tenant or service-specific networks, NGMN has proposed the concept of network slicing. While legacy systems host multiple telecommunication services, such as mobile broadband, voice, SMS, on the same mobile network architecture, for instance composed of Long Term Evolution (LTE) radio access and the Evolved Packet Core (EPC), future 5G networks should also support shared or dedicated logical architectures customized to the respective telco or vertical services, such as enhanced mobile broadband (eMBB), vehicular communications, ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). These services need very different KPIs that are hard to be fulfilled by legacy systems, as they are characterized by monolithic network elements that have tightly coupled hardware, software, and functionality. Future architectures, as already explained, leverages the decoupling of software-based network functions from the underlying infrastructure resources by means of utilizing different resource abstraction technologies. Furthermore, exploiting modularization, well-known resource sharing technologies such as multiplexing and multitasking, e.g., wavelength division multiplexing (WDM) or radio scheduling, can be advantageously complemented by softwarization techniques. Multitasking and multiplexing allow sharing physical infrastructure that is not virtualized. NFV and SDN allow different tenants to share the same general-purpose hardware.

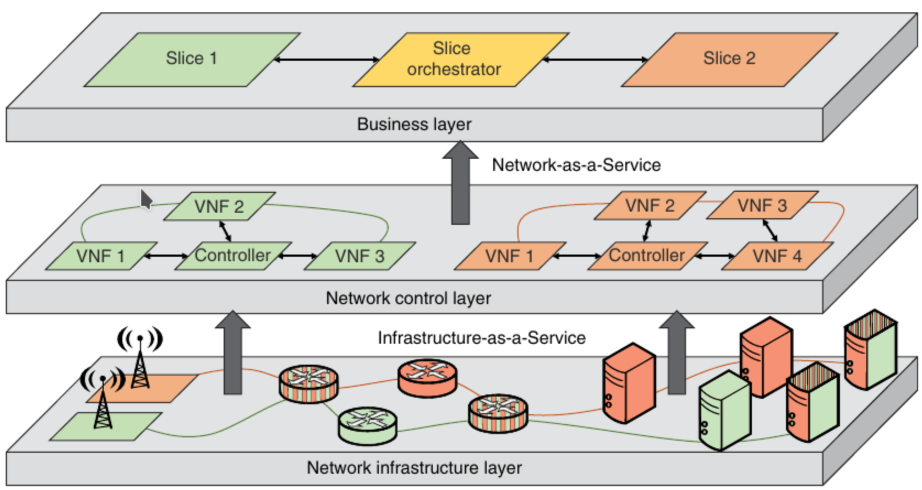

Figure 4: An example of a network-sliced architecture.

In combination, these technologies allow building fully decoupled E2E networks on top of a common, shared infrastructure. Consequently, multiplexing will not happen on the network level anymore, but on the infrastructure level, as depicted in Fig. 4, yielding better quality of service (QoS) or quality of experience (QoE) for the subscriber (as different slices will have tailored orchestration for a given service) as well as improved levels of network operability for the mobile service provider or mobile network operator. In principle, a network slice is a logical network that provides specific network capabilities and network characteristics and comprises NFs, computing and networking resources to meet the performance requirements of the tenants, for instance verticals. This comprises both radio access network (RAN) and CN NFs and, depending on the degree of freedom that a tenant may have, also the management and orchestration (MANO) components. A network slice may be dedicated to a specific tenant or partially shared by several tenants that have the same performance requirements but different security or policy settings. The decoupling between the virtualized and the physical infrastructure allows for the efficient scaling in, out, up or down of the slices, hence suggesting the economic viability of this approach that can adapt the used resources on demand. The 5G atom proposed in Fig. 5 summarizes the 5G discussion: use cases are in the center; the layers, from the center out, represent the requirements of the 5G use cases, the concepts that will allow network operators to satisfy the requirements, the technologies that enable the implementation of the concepts, and the novelties, that is, technologies that can be easily implemented due to softwarization and virtualization techniques.

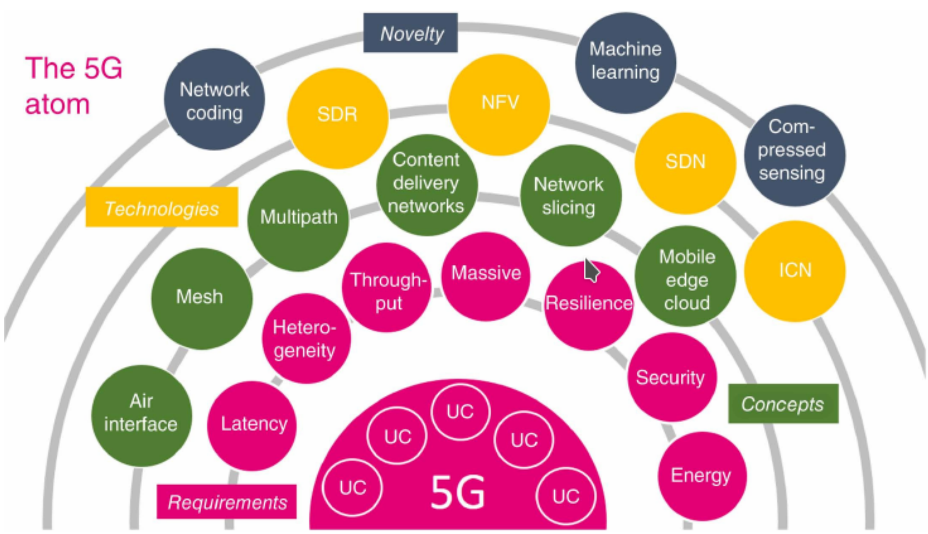

Figure 5: 5G atom representation.

3.1 Main Services Types

The main 5G service types typically considered are: • • Enhanced mobile broadband (eMBB): related to human-centric and enhanced access to multimedia content, services and data with improved performance and increasingly seamless user experience. This service type, which can be seen as an evolution of the services nowadays provided by 4G networks, covers UCs with very different requirements, e.g. ranging from hotspot UCs characterized by a high user density, very high traffic capacity and low user mobility, to wide area coverage cases with medium to high user mobility, but the need for seamless radio coverage practically anywhere and anytime with visibly improved user data rates compared to today; • • Ultra-reliable and low-latency communications (URLLC): related to UCs with stringent requirements for capabilities such as latency, reliability and availability. Examples include the wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc. It is expected that URLLC services will provide a main part of the fundament for the 4th industrial revolution (often referred to as Industry 4.0) and have a substantial impact on industries far beyond the information and communication technology industry; • • Massive machine-type communications (mMTC): capturing services that are characterized by a very large number of connected devices typically transmitting a relatively low volume of non delay-sensitive data. However, the key challenge is here that devices are usually required to be low-cost, and have a very long battery lifetime. Key examples for this service type would be logistics applications (e.g., involving the tracking of tagged objects), smart metering, or for instance agricultural applications where small, low-cost and low-power sensors are sprinkled over large areas to measure ground humidity, fertility, etc. The concept of network slicing will be implemented at the beginning of the 5G era in order to realize these main services as slices, furthermore some QoS parameter that regulates them are presented in one the last specifications. The 8 most important KPI are the following: • • Peak data rate, referring to the maximum achievable data rate under ideal conditions per user or device in bits per second. The minimum 5G requirements for peak data rate are 20 Gbps in the downlink (DL) and 10 Gbps in the uplink (UL); • • User experienced data rate, referring to the achievable data rate that is available ubiquitously across the coverage area to a mobile user or device in bits per second. This KPI corresponds to the 5% point of the cumulative distribution function (CDF) of the user throughput, and represents a kind of minimum user experience in the coverage area. This requirement is set by ITU-R to 100 Mbps in the DL and 50 Mbps in the UL;

• • Average spectral efficiency, also known as spectrum efficiency and defined as the average data throughput per unit of spectrum resource and per cell in bps/Hz/cell. Again, the minimum require- ments depend on the test environments as follows: — Indoor Hotspot: 9 bps/Hz/cell in the DL, 6.75 bps/Hz/cell in the UL; — Dense Urban: 7.8 bps/Hz/cell in the DL, 5.4 bps/Hz/cell in the UL; — Rural: 3.3 bps/Hz/cell in the DL, 1.6 bps/Hz/cell in the UL. • • Area traffic capacity, defined as the total traffic throughput served per geographic area in Mbps/m2. ITU-R has defined this objective only for the indoor hotspot case, with a target of 10 Mbps/m2 for the DL; • • User plane latency, given as the contribution of the radio network to the time from when the source sends a packet to when the destination receives it. The one-way end-to-end (E2E) latency requirement is set to 4 ms for eMBB services and 1 ms for URLLC; • • Connection density, corresponding to the total number of connected and/or accessible devices per unit area. ITU-R has specified a target of 1 000 000 devices per km2 for mMTC services; • • Energy efficiency, on the network side referring to the quantity of information bits transmittedor received from users, per unit of energy consumption of the RAN, and on the device side to the quantity of information bits per unit of energy consumption of the communication module,both cases in bits/Joule. The specification given by ITU-R in this respect is that IMT-2020interfaces must have the capability to support a high sleep ratio and long sleep duration; • • Mobility, here defined as the maximum speed at which a defined quality of service (QoS) and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies can be achieved. For the rural test environment, the normalized traffic channel link data rate at 500 km/h, reflecting the average user spectral efficiency, must be larger than 0.45 bps/Hz in the UL. The following we-spider diagrams in Fig. 6, 7, sum up optimally these capabalities to be achieved and how they have to be split to realize each particular slice

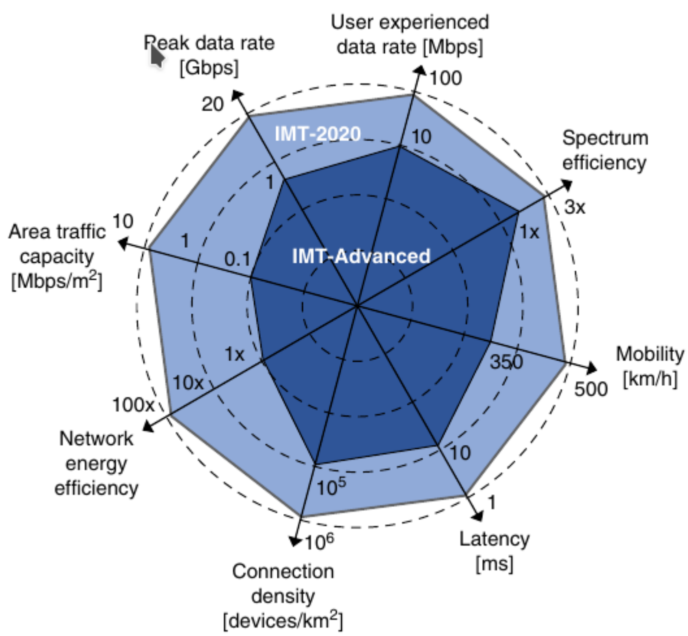

Figure 6: Capabilities to be achieved.

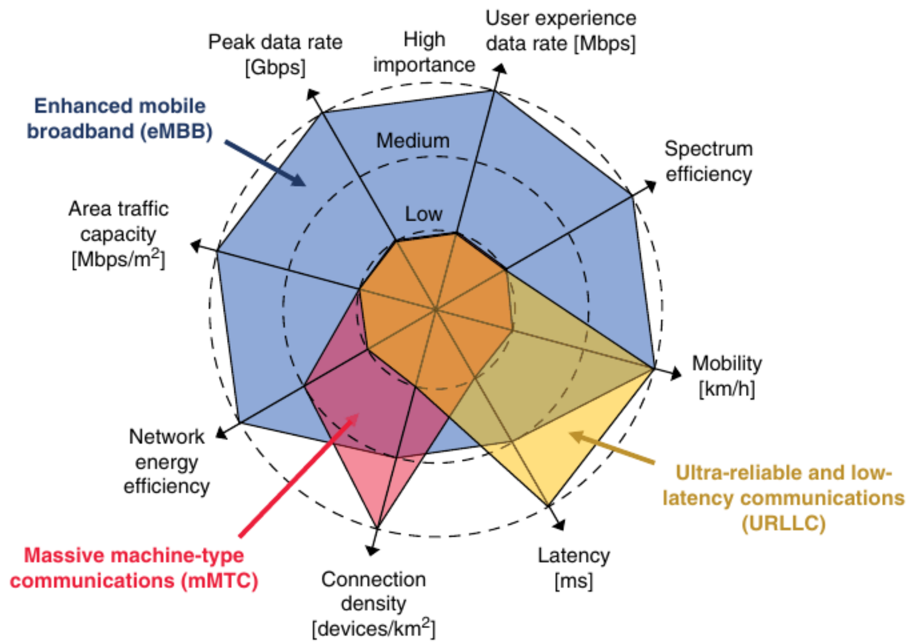

Figure 7: How capabilities are split.

3.2 Example

An illustrative example for deploying multiple network slice instances in a mixed environment consisting of public, i.e. mobile network operator owned, networks and private network infrastructure owned by a vertical enterprise. The infrastructure is used to commission an Internet of Things (IoT) network slice and two eMBB network slices.

3.2.0.1 5G Services on Factory Premises A process automation use case from industrial manufacturing is considered. Traffic is composed of sensor readings, actuator control signaling, and eMBB services providing access to local as well as remote applications (e.g., augmented reality for machine maintenance). In a process automation environment, IoT devices include actuators, such as pumps, valves, etc., and sensors for capturing heterogeneous physical and logical quantities. The latter may for instance include sensors for supporting maintenance processes or for critical safety applications, aiming to improve the overall operational efficiency and safety of the factory. When connecting such IoT devices, latency and bandwidth requirements can be very diverse. Such a setup requires two types of network slices, one covering machine-type communications for IoT devices and one covering eMBB traffic from smartphones, tablets and similar terminals. Figure 8 shows an example scenario with two E2E network

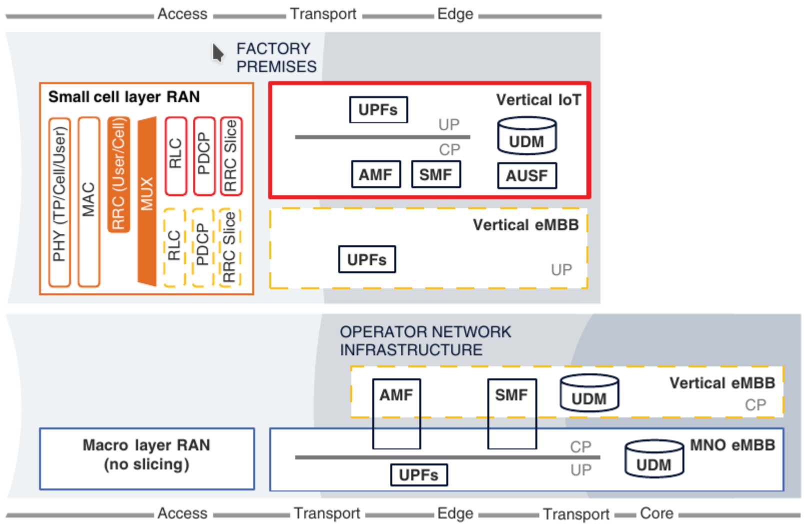

Figure 8: E2E network slice example for 5G services on factory premises.

slices (IoT and vertical eMBB) for the factory owner (also referred to as "vertical") as well as an eMBB network slice for the MNO. The network slices run MNO infrastructure as well as the vertical's telecommunication infrastructure on the factory premises.

3.2.0.2 Ownership of Infrastructure, Spectrum, and Subscriber Data

In the given scenario, the vertical provides the small cell layer RAN equipment for all network slices that require coverage on the factory premises, i.e., both the IoT slice and vertical eMBB slice. Beyond the RAN, this includes the transport network and edge cloud resources, such as general purpose hardware for computing and storage. For operating the small cell layer RAN, the vertical rents dedicated spectrum resources from the MNO, such as higher frequency spectrum (e.g., above 6 GHz) with coverage strictly limited to the factory premises. For the vertical eMBB service, both small cell layer RAN and, if required, the MNO-provided macro layer RAN are utilized. RRM functions for the macro layer strictly remain under control of the MNO, which further owns a 5G-compatible network infrastructure consisting of centralized datacenters and distributed edge clouds comprising general-purpose as well as application-specific hardware. Subscriber information data including long-term security credentials are in possession of the vertical for the IoT devices. This assures full isolation of the vertical's IoT subscriber information from the MNO. For the eMBB subscribers, the MNO holds the corresponding data for own eMBB subscribers as well as vertical eMBB subscribers.

3.2.0.3 Domain-specific Network Slice Deployment

Regarding the deployment of the individual network slices, the IoT network slice deploys all functions in the domain of the vertical, and it is only used by IoT devices that are registered in the vertical's home subscriber system (HSS) or Unified Data Management (UDM) and Authentication Server Functions (AUSF). These devices are mostly stationary and never leave the factory premises. The small cell layer RAN as well as the IoT-specific User Plane Processing Functions (UPFs) and control plane functions, in particular Access and Mobility Management Function (AMF) and Session Management Function (SMF), are operated locally under full control of the vertical. Since also the security mechanisms are strictly realized locally, the entire network slice operates in the shielded factory environment without exposure of any data to the MNO. In contrast, the vertical eMBB slice is deployed in an inter-domain manner: the CN control plane is shared with the MNO eMBB network slice and operated by the MNO outside the factory, including AMF and SMF as well as AUSF and UDM for authentication towards the core network and Non-Access Stratum (NAS) ciphering and integrity protection, respectively. Regarding the transport network, independent slices with guaranteed levels of isolation and security are used by both the vertical and the MNO. In the vertical's small cell layer RAN, on the factory premises, PHY and MAC in the UP and RRC in the CP are shared by both slices. This approach limits the complexity because resource multiplexing is implemented across all network slices on MAC level, forcing each network slice to make use of the same efficient flexible RAN implementation. On the other hand, each network slice may still customize the operation through configuration and parameterization of Radio Link Control (RLC), PDCP, and RRC-Slice functions. RRM for the small cell layer realizes resource allocation according to the defined SLAs for the IoT and eMBB slices of the vertical.

3.3 Actual Implementations

Some early trials have been conducted demonstrating network slicing with cross-industry collaboration among operators, vendors, and vertical industries. Two specific examples are given here. (1) Deutsche Telekom and Huawei demonstration of E2E autonomous network slicing. In this demo, enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable low-latency communication (uRLLC) are envisaged as network classes that could be built as slices. E2E network slicing included not only the core network and RAN, but also interconnecting transport networks. The demo implements E2E network slicing automation based on service oriented network auto creation (SONAC). It uses software-defined topology (SDT), software-defined protocol (SDP), and software-defined resource allocation (SDRA) to ensure the automatic implementation of slice management, service deployment, resource scheduling, and fault recovery. (2) SK Telecom, Deutsche Telekom and Ericsson have jointly built and demonstrated a trial network on federated network slicing for roaming, making SK Telecom and DT network slices available in each operators footprint, connecting South Korea and Germany. The demonstration was hosted at Deutsche Telekom's corporate R&D center in Bonn, Germany and Sk Telecoms 5G testbed at Yeongjongdo (the BMW driving center) in Korea. The demo featured an industrial maintenance use case involving a repair worker communicating via augmented reality with support colleagues in a visited network. The scenario used local breakout and edge cloud to enable the best service experience in terms of latency and throughput for the AR repairman.

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