Towards Scalable and Cost-efficient Software-Defined 5G Core Network

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Abstract

Network and network functions virtualization (NFV) promise a number of attractive benefits and thus have driven mobile network operators to transform their previously static networks to more dynamic and software-defined networks. In this article, we share a mobile network operator's view based on implementation and deployment experiences in the wild during the past few years towards a software-defined 5G core network. More specifically, we present a practical point of view from mobile network operators and elaborate on why some of the virtualization benefits such as total cost of ownership (TCO) reduction are not easily realized as initially intended. Then, we describe 5G visions, services, and their requirements commonly agreed across mobile operators globally. Given the requirements, we then introduce desirable characteristics of 5G mobile core network and its key enabling technologies.

I. INTRODUCTION

Mobile networks have been rapidly evolving, especially during the past few years with the commercialization of network functions virtualization (NFV) [1] and software defined networking (SDN) [2] in the existing 4G mobile network. These virtualization techniques promise many desirable benefits, including agility (e.g., time-to-market reduction), flexibility (e.g., dynamic lifecycle management of a given network function), network operation intelligence (e.g., automated end-to-end quality-of-service management), and total-cost-of-ownership (TCO) reduction. For example, NFV eliminates hardware dependency of a given network function by decoupling the software function from the underlying physical hardware infrastructure. This leads to cost savings mainly in three different aspects. First, the servers used to build virtualization infrastructure mostly consist of simple and commercial off-the-shelf (COTS) hardware, which are usually less costly, compared to the previous dedicated and proprietary hardware. Second, when additional functions are needed, only the decoupled software functions may be purchased without the costly dedicated hardware. Third, the network resources no longer need to be over-provisioned. The resources are allocated dynamically and more efficiently during runtime as needed, rather than statically being over-provisioned for the peak usage and not used most of the time.

Given these claims on the benefits of the new virtualization techniques, there has been a substantial progress towards virtualizing the existing network functions and deploying the virtualized network functions in the production mobile networks, paving the way towards the software-defined 5th generation (5G) mobile network. Yet, there are also many questions raised during the implementation and deployment phase of the transformation process, regarding the benefits of NFV and SDN that were initially claimed. For example, operators often make an observation that, unlike the initial claims from NFV pioneers, the cost of the decoupled software without the dedicated hardware, is not as attractive as initially expected. This is the case even when other circumstances are considered, including that the technology is still in its early phase.

In this article, we provide an overview of various visions, services, and requirements of the next generation

5G mobile network and motivate the transformation of the mobile network towards software-defined network. More specifically, we describe key enabling technologies of 5G mobile core network that are commonly agreed amongst various stakeholders. It is worth noting that currently new 5G core architecture is being discussed in 3GPP and scheduled to be completed in the next few years. Therefore, we intentionally limit the discussion scope to key enabling technologies that are likely to be included in the new architecture and also a desirable evolution path towards the new 5G core architecture.

This article is organized as follows. In Section II, we introduce 5G, potential services, and architectural challenges. In Section III, we describe a cost-efficient and scalable 5G software-defined mobile core network, designed with a practical NFV and SDN deployment experiences, addressing the challenges described in Section II. In Section IV, we discuss remaining issues and conclude.

II. 5G MOBILE NETWORK AND CHALLENGES

1. Introduction on 5G, Services, and Requirements

Over the past few years, one of the key buzzwords in the mobile network industry has definitely been 5G. An increasing number of mobile network operators, equipment manufacturers, research organizations and governments [5]-[9] are actively engaged in discussions on 5G and its key enabling technologies. In 2012, International Telecommunication Union (ITU) coined the term IMT-2020 to tentatively describe 5G and announced its plan towards 5G. To be more specific, ITU plans to define 5G visions and requirements by 2015 and 2017 respectively. Then, suggestions on key enabling technologies and architecture which satisfy the defined IMT- 2020 requirements will be gathered and evaluated by the second half of 2017. Based on the suggestions and evaluation results, the goal is to complete the 5G standardization by 2020. In accordance with this timeline, many countries and regions around the world have established organizations tasked to better define 5G services and infrastructure, while exchanging their intermediate views and technologies. In this section, we introduce three representative service types (STs) which are commonly discussed. Then, we induce six high-level technical requirements for 5G system based on the introduced three service types.

There exist slight naming differences across different organizations. However at a high level, the service types are more or less equivalent. For example, 3GPP SMARTER TR has four categories of services types (i.e., enhanced mobile broadband, massive IoT, Critical Communications, and enhanced V2X).

ST1. Enhanced Mobile Broadband (eMBB): The overall amount of multimedia contents over the current 4G mobile broadband already takes a significant portion (e.g., more than 60% of overall mobile traffic) and is still growing. It is projected that this trend continues in the upcoming years, as the user mobile devices will continue to become increasingly powerful to provide users with more vivid and immersive experiences (e.g., 3-dimensional ultra-high definition video, augmented reality, virtual reality, etc.). 5G is expected to further enhance the overall user experience of immersive multimedia applications already exist today.

ST2. Massive Machine Type Communication (mMTC): As the wireless and mobile technologies become mature and start to become available at low cost, increasing number of devices and things connected to provide rich information about individual users as well as the surroundings without human intervention. Although the data being sent and received by the individual devices belong to this category is expected to be best-effort basis and relatively small amount, this service requires the underlying future 5G communication system to be capable of handling massive number of potentially simultaneous connectivity.

ST3. Ultra-Low Latency and Reliable Communications (ULLRC): As the technologies that implement mobile networks and how the networks are managed for high performance, reliability, and availability are better understood over time, various mission critical services (e.g., remote machinery/vehicle/drone controlling, public safety networks, etc.) start to be implemented on top of the mobile networks. The capability to send and receive data and control information without any wires across a large metro area reliably with minimal end-to-end latency makes the future mobile network an ideal solution, and this demand seems to increase in 5G. These services require the underlying communication system to be highly reliable and available even in the case of large scale natural disasters.

In the rest of this sub-section, we describe six high-level technical requirements (HRs) which are typically mentioned in order to support the above-mentioned three service types in 5G.

HR1. Increased Bandwidth: 5G promises from tens to thousand times improvement in the overall bandwidth, and this increase is measured from the view point of individual users, as opposed to the best possible peak data rate measured from the network perspective. In 5G, there will be sufficient bandwidth to guarantee consistent user-experience, served at Gbps-level on the average anywhere and anytime. Recently, ITU-R defined 20 Gbps as the minimal peak data rate supported per cell and UE.

HR2. Reduced End-to-End Latency: The emergence of various remote controlled devices (e.g., drones, robots, sensors, etc.) will eventually lead to the necessity of a highly reliable communication channel with a very low delay. Currently the de-facto radio and end-to-end latency expected to be supported by 5G is 1ms and 10ms respectively.

HR3. Massive Connectivity: Increased number of devices (e.g., sensors, meters, etc.) will be connected simultaneously, and this number is expected to increase at a very fast rate. Although the amount of data being communicated by these devices in the data-plane is sporadic and much smaller than high quality multimedia contents, these devices tend to trigger frequent control-plane messages in bursts.

HR4. Guaranteed Quality of Experience (QoE): The massive number of devices connected to the network leads to very rich set of information (e.g., time, location, and context) which may be used to offer personalized services. Operator may use the information to best utilize and enhance quality of experience, taking the full advantage of dynamic and programmable network infrastructure and real-time data analytics. At the same time, a subset of gathered information will be exposed externally potentially to the application and service providers, such that the overall service performance may be optimized based on the information provided by the network (e.g., network load, and congestions).

HR5. High(er) Availability: One of the representative 5G use-case belonging to ULLRC is public safety. As such, 5G is designed to be highly available and reliable with zero-perceived service downtime to support various mission critical services.

HR6. High(er) Efficiency: One of the key enablers for high throughput in 5G is densely-deployed massive-scale small cells. Therefore, 5G network shall be a lot more efficient in cost and energy usage, given that the massive deployment of infrastructure, devices, and the overall cost should be efficiently managed in a scalable manner. From the view point of mobile operators, the reduction in the total cost of ownership (TCO) is especially important.

To summarize the technical requirements mentioned so far in this Section, 5G is user-centric, as opposed to being network-centric in the past, and disruptive in nature, integrating different industries to create enabling services with enhanced overall service experience of the end-users.

2. Architectural Challenges

The future 5G services pose a wide variety of highly stringent requirements on the network functions, underlying infrastructure, and the interworking of the two. In this section, we elaborate on the architectural challenges (AC) for each of the high-level technical requirements described in the previous section.

AC1. Increased Bandwidth: Increased amount of bandwidth poses architectural challenges on both radio access network, transport, as well as core network. So far, one of viable approaches in increasing the peak bandwidth has been aggregating multiple carriers together and using them simultaneously to send or receive data which belong to a single flow. Today, the peak bandwidth of Long-Term-Evolution (LTE), achieved by aggregating three different carriers, is 450 Mbps. Note that this is the best-case peak bandwidth, which is very different than Gbps-level bandwidth on average at any location, including near the cell edges. Because it is practically infeasible to achieve such a high data rate based on how today's infrastructure is designed, it is suggested that a new radio carrier at a much higher frequency band (e.g., above 6 GHz) to be considered. In addition to the radio access network challenges, the core network also needs to be re-designed to remove any potential traffic bottlenecks because the network nodes are currently structured in a hierarchical manner, where all user traffic traverse through a series of serving gateways (S-GWs) and packet gateways (P-GWs). In order to handle the data-plane traffic more efficiently, the network shall become flatter and more distributed to avoid the user traffic from unnecessarily reaching the network nodes located remotely in the center of the network.

AC2. Reduced End-to-End Latency: Today with LTE, it typically takes about several tens of milliseconds for a given IP packet sent from an application running inside a device to traverse up and down the LTE protocol stack before finally received by the receiving application. This delay is mostly due to how LTE (e.g., Transmission Time Interval, etc.) is initially designed. To minimize the overall delay (e.g., to be less than 10ms), the entire system should be redesigned and optimized with a holistic view to guarantee such low latency requirement. All of these architecture redesign and optimization eventually increase the overall cost of network functions, infrastructure, and management.

AC3. Massive Connectivity: The existing 4G mobile network is designed and optimized mostly for data-plane traffic. That is, the system is more efficient in handling data-plane traffic than the control-plane traffic. Recently and in the upcoming years, different communication pattern is observed for machine type of traffic. These machines (or devices) make very frequent and sporadic attempts to transmit small amount of data, leading to huge amount of overall and simultaneous control-plane signaling traffic and small amount of overall user plane traffic. To avoid having a potential network collapse caused by the massive simultaneous control-plane signaling traffic, the control-plane of the future mobile system shall be optimized to efficiently handle such traffic generated by machine type communication.

AC4. Guaranteed Quality of Experience (QoE): Recently, there have been a lot of efforts to make the Telco network flexible and programmable. At the same time, techniques on collecting huge amount of network data and analyzing the collected data in real-time also have been maturing. Taking the full advantage of the flexible and programmable network, it becomes feasible to configure and optimize the network performance on-demand in real-time. Some of the examples are ETSI NFV Management and Orchestration (MANO) and NETCONF [3].

AC5. High(er) Availability: Virtualizing and decoupling core software functions from the underlying hardware yields several benefits. One of the main benefits is high availability where the function can be migrated and replicated flexibly for high availability.

AC6. High(er) Efficiency: The next generation mobile network is expected to provide a highly dense coverage, which eventually leads to a higher overall deployment cost. Furthermore, 5G services and use-cases pose extremely stringent technical requirements, which may potentially raise the cost of individual network functions to be deployed. Therefore, individual network functions and the overall infrastructure have to be highly efficient in cost. Fortunately, the industry has diligently worked on addressing each of the above challenges individually. On the other hand, a practical question on how these solutions can be applied to make up the overall 5G system in a cost-efficient manner still remains; applying the related and inter-dependent technologies altogether on a single 5G system may potentially lead to a highly complex and cost-prohibitive system.

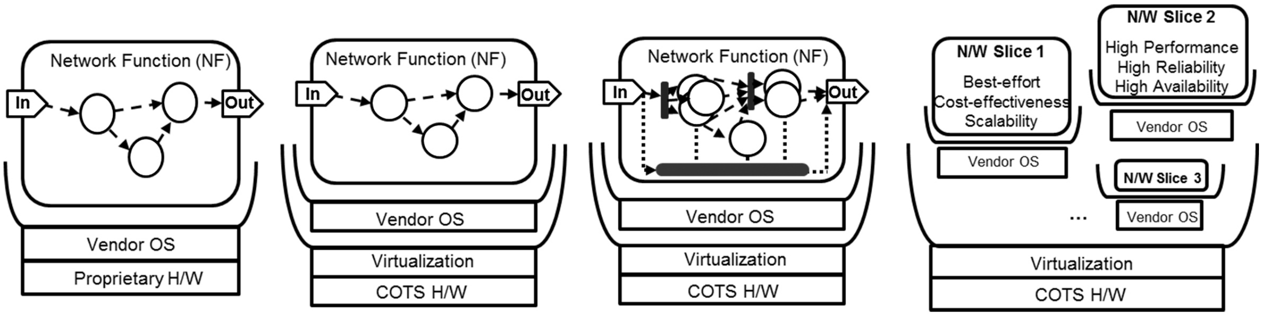

Fig. 1. Virtualized Network Function (VNF) Design Evolution

In the following section, we introduce a scalable and cost–efficient approach towards 5G core network architecture which addresses the above–mentioned challenges in a scalable and cost–efficient manner.

III. EVOLUTION TOWARDS SOFTWARE–DEFINED AND SERVICE–ORIENTED 5G MOBILE NETWORK

With the advent of virtualization technologies such as NFV and SDN, there has been a quiet, yet intense battle between physical and virtual equipment vendors. The virtualized equipment vendors had to show and verify that the benefits it initially claimed are true. On the other hand, the physical equipment vendors had to show that they are still necessary and competent. Although the virtualized equipment vendors have been very aggressively trying to increase their market share, the rate of penetration is not as fast as initially anticipated. There are mainly two reasons for this slow penetration rate. First, many technology forerunners who are willing to adopt new technologies have just finished making huge amount of investments for 4G LTE technology, and therefore, strategically decided to postpone another big investment of transforming the network to a software–defined cloud–based network until certain level of Return–of–Investment (ROI) for the LTE investments is achieved. Second and more importantly, the cost of virtualized equipment is not sufficiently attractive, as the price of physical equipment has been rapidly dropping. The flexibility and agility alone without the cost reduction are not enough to justify for another big investments. Worse, it is not clear whether or not the cost of the virtualized infrastructure can go down, since the future mobile networks pose a lot more stringent requirements; these challenging requirements are likely to add extra costs on the top of already quite expensive prices.

Given the observation, we deem it necessary that the future mobile architecture must not only satisfy the technical requirements posed by various future mobile services, but also be realized in a highly cost–efficient manner. In the following two sub–sections, we introduce fundamental building blocks for an architecture that satisfies the 5G requirements in a cost–efficient manner. We first introduce cloud–aware and service–aware virtualized network functions (ca–VNF, sa–VNF), as an evolutionary path towards modularized and service–oriented virtualized network functions. Using sa–VNF as cost–efficient building blocks, we then describe service–aware micro Clouds (micro Clouds), as a network architecture to realize a wide variety of network services in a cost efficient manner.

1. Towards Modular Virtualized Network Function (VNF) Design

Virtualized Network Function (VNF) design evolution in the mobile network has seen three phases so far: (1) simple porting, (2) cloud–aware virtualized network function (ca–VNF), and (3) service–aware virtualized network function (sa-VNF) as illustrated in 〈Figure 1〉. The overall evolution path is that the VNFs become increasingly cloud and service-aware to better implement the intended network services with a minimal cost. Each of the three phases is described in this subsection.

1st Phase - Simple Porting: Simple porting takes the existing network functions, such as mobility management entity (MME) and serving/packet gateways (S/P-GW) running on physical servers, and simply migrates them to run in virtualized environments via simply porting the software. Given that the virtualized infrastructures (e.g., Hypervisors) today readily embrace various flavors and versions of guest operating systems, simple porting is relatively quick and easy approach to immediately enable a subset of virtualization benefits such as on-demand instantiation, migration, and termination. On the other hand, this approach may not be efficient in a longer term, due to the following two reasons. First, hardware specific and unnecessary portions of implementation may have been ported together, which brings unnecessary complexity in the implementation that eventually results in extra cost. Second, this approach does not take the full advantage of benefits offered by virtualization technology such as dynamic scaling and high availability, etc.

2nd Phase - Cloud-aware Virtualized Network Functions (ca-VNF): A VNF running on cloud environments is expected to be cloud-aware, meaning that it takes a full advantage of a set of additional capabilities provided by the cloud environment. More specifically, a VNF running in a Cloud is designed initially to run optimally on a cloud environment.

One such design paradigm is decomposed and stateless virtualized network functions. Given that a virtualized network function may dynamically and frequently scale in and out based on the actual demand during run-time, it shall be decomposed to the smallest unit possible to allow efficient scaling at a finer granularity. One example of this VNF decomposition is UP (User Plane) / CP (Control Plane) separation. Since data plane traffic typically grow at a much faster rate than that of control plane, upscaling the user plane functions only without control plane function upscaling makes much more sense.

In addition, separating database from a VNF is also being considered to make the VNF stateless, as stateless VNFs may have a significantly improved availability. When VNFCs are stateless, temporal redundancy by placing VNFCs across different physical locations becomes feasible, as the VNFs become relatively light without cumbersome databases to carry. For Example in 〈Figure 1(c)〉, load balancers are placed in front of stateless computing modules (e.g., VNFCs). This allows the computing module to scale-in/out at smaller granularity, independently from other computing modules within the same VNF. Other examples of cloud-aware features include high availability, and geographical and hardware affinity via monitoring agents inside the given VNF as also shown in 〈Figure 1(c)〉.

3rd Phase - Service-aware Virtualized Network Functions (sa-VNF): A VNF is expected to provide differentiated capabilities depending on the intended service as shown in 〈Figure 1(d)〉. In certain cases, a VNF must offer various complicated and expensive capabilities such as high performance (e.g., real-time multimedia content delivery service, Tactile Internet, etc.) and availability (e.g., public safety network). Obviously, the VNFs offering these costly capabilities (i.e., high-end VNFs) are expected to be expensive in cost. On the other hand, there are other categories of services which pose much lower level of technical requirements (thus less expensive), such as massive machine type communication (mMTC). Therefore, it would be more economical to design, implement, and configure a given VNF with the intended service in mind from the very beginning.

As the number of flavors and cost of VNFs varies widely, it will also become important for an operator to wisely select the appropriate VNFs when implementing a given network service. For example, it is obviously more scalable and cost-efficient to implement MTC service using low-end VNFs which may not have fancy technical capabilities but still sufficient enough to satisfy the MTC service requirements.

2. Service-aware micro Clouds (micro-Cloud)

From the 1st generation (1G) analog-based mobile

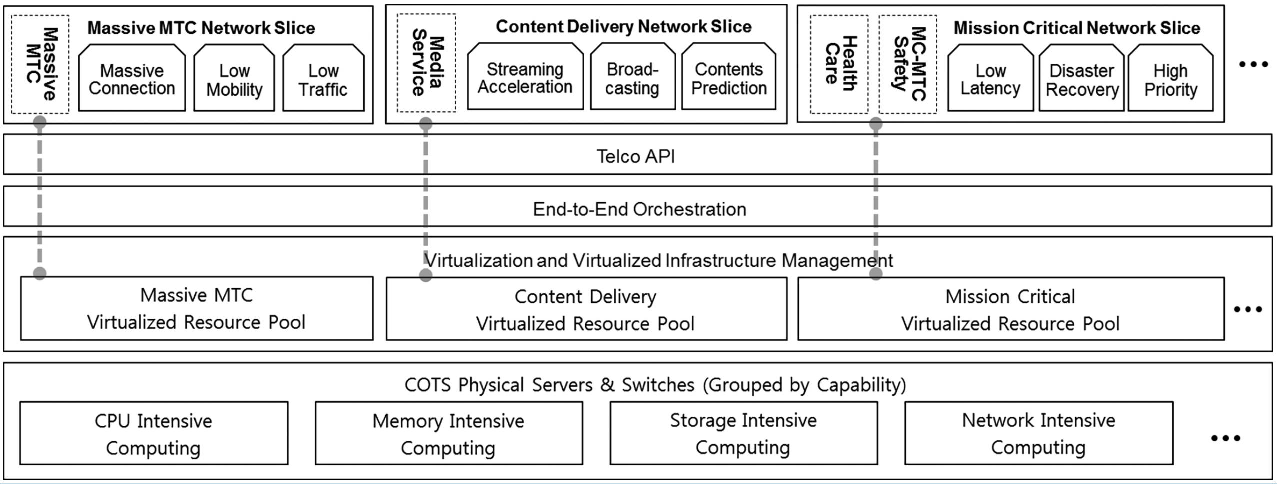

Fig. 2. Logical Architecture of Service-aware 5G Core Network with Micro-Clouds

network to the 3rd generation (3G) mobile network, the main design goal was to implement personal communication services. Starting with the 4th generation (4G) mobile system, the bandwidth supported by the mobile communication system became comparable or even exceeded that of fixed network. Now with 5th generation (5G) mobile networks with abundant bandwidth, reliability and availability, a wide range of services are expected to be introduced. For example, a recently published 5G white paper from next generation mobile network alliance (NGMN) [4], there are a wide set of use-cases (i.e., 25 use-cases spanning across eight different use-case families). As each of the use-case families pose wide variety and sometimes conflicting technical requirements, it becomes impractical and cost-prohibitive to have a single system that can satisfy all of the widely varying technical requirements. The widely varying requirements call for simplification and modularization of the capabilities provided by the underlying virtualized infrastructure. This way, the modularized capabilities at different horizontal layers in the architecture can be picked and chosen based on requirements and corresponding policies of difference services based on the actual need. For example since certain services such as massive MTC do not pose stringent technical requirements, a low-tier and cost-efficient EPC may be chosen. The VNF design evolution path towards modularized sa-VNF discussed in the previous subsection is one example of this trend. We see that the similar trend at the virtualized infrastructure layer is on-going.

Not all network service requires high-end capabilities such as performance accelerations from the virtualized resources. Therefore, it would be more efficient for the virtualized resources to be organized into different groups and will be served accordingly. This is also called network slicing. This modularization and trend towards designing and implementing various independent modules will facilitate the overall ecosystem. It is challenging for the small to medium sized start-ups to enter the existing market, and this is especially true for conservative Telco domain. However, this modularization and trend towards designing and implementing various independent modules will facilitate and foster the overall ecosystem, especially for the start-ups and open source communities, as the market entry for small(er) and simple(r) modules will be relatively easy. Separating and modularizing the key enabling capabilities and features have other additional benefits including, simplified network which is easier to understand and independent evolution of different modules which eventually lead to higher performance and cost reduction via productive competition.

3. Example Use-case

In this subsection, we describe an example use-case elaborating on how ca-VNF, sa-VNF, and micro-Clouds are used to implement a network service. Assume that there are three different network services that a given mobile operator wants to offer to its users as shown in 〈Figure 2〉: 1) massive MTC, 2) high quality multimedia content delivery, 3) mission critical MTC. The service incurring the most investment is mission critical MTC, as it requires the underlying network and network functions to be highly available, reliable, and oftentimes with very low end–to–end network latency. The overall demand for this expensive service is relatively low. On the other hand, the service with the lowest level of technical requirements is massive MTC. In massive MTC, the amount of data being delivered is small and is delivered in best–effort basis. The overall demand for this service may be huge, and the implementation cost of network and network functions for the massive MTC service is low. The operator prepares different groups of virtualized infrastructure.

In 〈Figure 2〉, virtualized resources are grouped based on the capabilities and characteristics. For example, there can be a virtualized resource pool for massive MTC. This virtualized resource pool may consist of best–effort hardware and policies. On the other hand, there may be a virtualized resource pool for mission critical MTC. This virtualized resource pool shall consist of highly reliable hardware, software techniques, and policies that can satisfy the stringent technical requirements. The orchestrator ensures that appropriate type of virtualized resource pools and policies are maps to different services accordingly. As an operator, the goal is satisfy the service requirements for all services with the minimal investments. So in this particular case, it would be wise for the operator to use low–end low–cost network infrastructure and functions to implement a massive MTC network service, and use high–end high–cost network and functions to implement a mission critical MTC only in locations needed to minimize the overall cost. In all cases, resources shall be allocated dynamically and flexibly as needed, without being over–provisioned for the peak usage.

IV. SUMMARY AND FUTURE WORK

In this article, we motivate and justify the mobile network transformation towards software–defined 5G mobile networks. We also share a few years of experiences in the wild on cloudifying our production network using the emerging virtualization techniques such as NFV and SDN, and elaborate the challenges faced during the journey. Last, we introduce and propose a scalable and cost–efficient approach towards the next generation 5G mobile network architecture. The main idea is to first modularize and differentiate the virtualized network functions as well as infrastructure, and then, implement a given network service by selecting appropriate virtualized resources in a cost–efficient manner based on network slicing technology.

We mainly focused on the practical and economical aspect of the architecture. However, there are other important architectural aspects which are not deeply discussed in this article. Security is one of the important aspects. More specifically, the current premise–based security is no longer appropriate, as the virtualized network functions move around in and out of physical locations. Another aspect is policy management, which assigns and manages different provisioning (e.g., description of necessary resources, resource/location affinity, etc.) and run–time (e.g., service quality guarantee, etc.). Real–time operation and network intelligence is another important challenge as one of the requirements for 5G is guaranteed quality of service.

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