Rost, P., et al. Mobile network architecture evolution toward 5G, in *IEEE communications magazine, 54(5), May 2016, pp. 84-91*

DOI: https://doi.org/10.1109/MCOM.2016.7470940

Mobile Network Architecture Evolution towards 5G

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Abstract: As a chain is as strong as its weakest element, so as the efficiency, flexibility, and robustness of a mobile network, which relies on a range of different functional elements and mechanisms.. Indeed, the mobile network architecture needs particular attention when discussing the evolution of 3GPP EPS because it is the architecture which integrates the many different future technologies into one mobile network. This article discusses 3GPP EPS mobile network evolution as a whole, analyzing specific architecture properties which are critical in future 3GPP EPS releases. In particular, this article discusses the evolution towards a "network of functions," networking slicing, and software-defined mobile network control, management, and orchestration. Furthermore, the roadmap for the future evolution of 3GPP EPS and its technology components is detailed and relevant standards defining organizations are listed.

Index Terms—*3GPP EPS, mobile network architecture, network slicing, network functions virtualization, software defined mobile networks*

I. INTRODUCTION

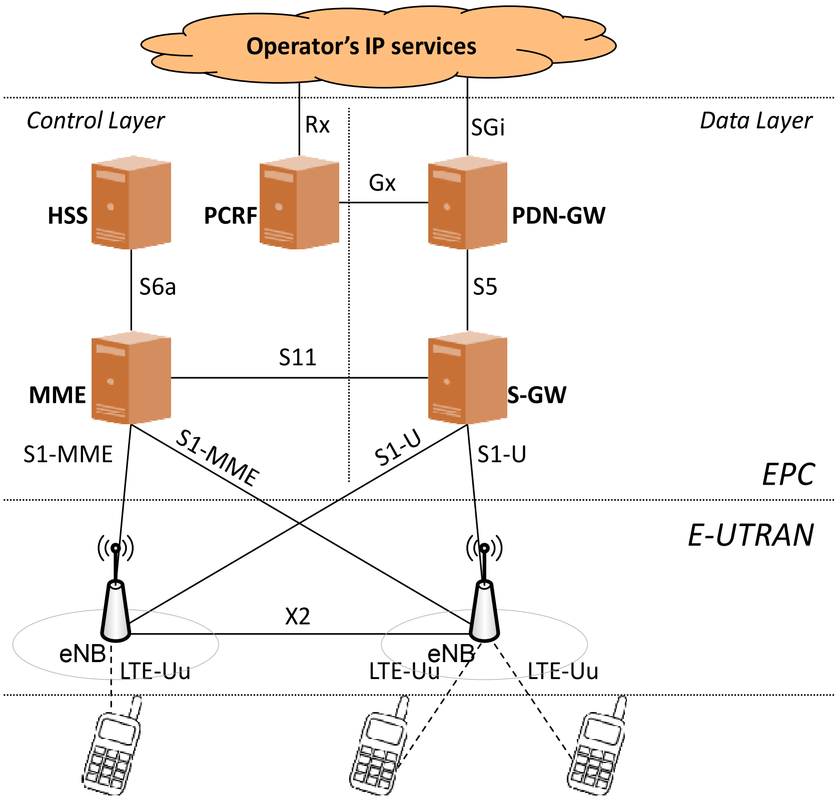

Figure 1: The (basic) 3GPP Evolved Packet System

The 3GPP evolved packet system (EPS) of LTE refers to the logical architecture, which is composed by the radio access network (RAN), called evolved universal terrestrial radio access network (E-UTRAN) in case of LTE, and the evolved packet core (EPC) as defined in [1], [2] and illustrated in Figure 1. The objective of this logical architecture is to enable a flat IP-based network and provide a standardized set of network elements and network interfaces. Standardized elements and interfaces enable operators to integrate equipment and implementations from different vendors into a single system, while ensuring interoperability. The design of a logical architecture satisfies requirements originating from use cases that are expected to be of particular interest for 3GPP EPS. So far, the aim of 3GPP EPS has been mainly the provision of mobile broadband service, for which the system makes very efficient use of available spectrum.

So far past releases, i.e. Rel-11, Re-12, and Rel-13, studied and specified how to integrate further services such as small data services as well as machine type communication (MTC) services. Meanwhile, cloud-computing technologies and cloud concepts gained momentum not only from the information technology (IT) perspective, but also within the telecom world. Integrating cloud concepts into 3GPP EPS allows for supporting novel and emerging services. On the other hand, it requires novel architectural concepts, which natively support cloud technologies. However, the static assignment of functionality to network elements and the strong functional dependencies within each network element make it difficult to support the required flexibility of future 3GPP EPS deployments.

The following sections detail concepts that could contribute to the evolution of 3GPP EPS in order to provide the required flexibility for supporting network services with diverse requirements, for enabling diverse mobile networks deployments, and for providing a higher degree of context awareness. Specifically, Section II introduces relevant concepts such as flexible function composition (detailed in Section III), network slicing (detailed in Section IV), and software-defined network control (detailed in Section V). In Section VI, we provide an overview on the standardization roadmap, and the article concludes in Section VII.

II. MOBILE NETWORK EVOLUTION

In order to support diverse services such as eHealth, IoT (Internet of Things), and V2X (vehicular-to-everything) in future mobile networks, we see a need for enhancing the EPS towards a flexible mobile network accommodating novel architectural principles, while maintaining backward compatibility. Such an evolved EPS architecture must support legacy radio technologies as well as novel radio access interfaces such as mm-wave or cm-wave transmission. It should accommodate emerging processing paradigms such as mobile edge computing (MEC) and Cloud-RAN (C-RAN), while enabling flexible deployment patterns based on small, micro, and macro cells and allowing programmability to support very different requirements in terms of latency, robustness, and throughput.

Based on this, we see two main objectives that must be addressed by an evolved 3GPP EPS architecture:

- **Multi-service and context-aware adaptation** of the mobile network, which implies that the mobile network needs to adopt its operation based on the actual service requirements and the related context. The context includes deployment properties, transport network properties, service properties, as well as available radio access network technologies.
- **Mobile network multi-tenancy,** which aims to reduce capital and operational costs by allowing infrastructure providers to make best use of available resources, including spectrum and infrastructure. Hence, multiple tenants may share resources within the mobile network while offering diverse services.

In order to achieve these objectives, the following main functionalities should be supported and will be further detailed in the following sections:

- **Network of functions**: Traditionally, mobile network functions are readily grouped into network entities, each responsible for a pre-defined set of functions, and interfaces connecting these entities. Using flexible “network of functions” allows to adapt to diverse services, and to optimize using different software rather than using different parameterizations. Each block may be replaceable and could be individually instantiated for each logical network running on the same infrastructure. However, it must not imply a multitude of interfaces as detailed later.
- **Network-slicing** allows for using the same mobile network infrastructure by multiple different operators, including vertical market players, each implementing its own logical network, e.g. a logical network for mobile broadband with very high throughput, a logical network connecting massive amount of sensor nodes (incl. indoors), or a logical network providing critical infrastructure connectivity for traffic management or energy control. Hence, each network slice fulfills different requirements and serves very different purposes.
- **Software-defined mobile network control** is required to flexibly control both a flexible network of functions as well as a set of network slices. This control must be programmable in order to adapt the network behavior to the current requirements. This functionality goes beyond the separation of control and data plane including the control of radio access network functionality as well as the mobile network control plane.

III. NETWORK OF FUNCTIONS

The objective of a mobile network architecture is to allow for integrating different technologies and enabling different use cases. Due to the partly conflicting requirements, it is necessary to use the right functionality at the right place and time within the network. In order to provide this flexibility, it has recently been discussed whether the network functions virtualization (NFV) paradigm should be adopted in the mobile access network domain, i.e. enabling mobile network functionality to be decomposed into smaller function blocks, which are flexibly instantiated.

So far, the degrees of freedom for assigning network functionality to network entities is very limited. For instance, it is possible to collocate EPC elements, such as gateways, with a base station in 3GPP EPS. However, it is not possible to only place *parts* of the functionality of a gateway or mobility management entity (MME) with a base station. Similarly, it is possible to fully centralize radio access network functionality using the common public radio interface (CPRI) and central baseband units. However, such deployments use non-virtualized baseband units at the central location, hence, it is rather re-locating functionality which does not exploit all characteristics of cloud-computing. It is further not possible to only move parts of the RAN functionality except in a proprietary way [3].

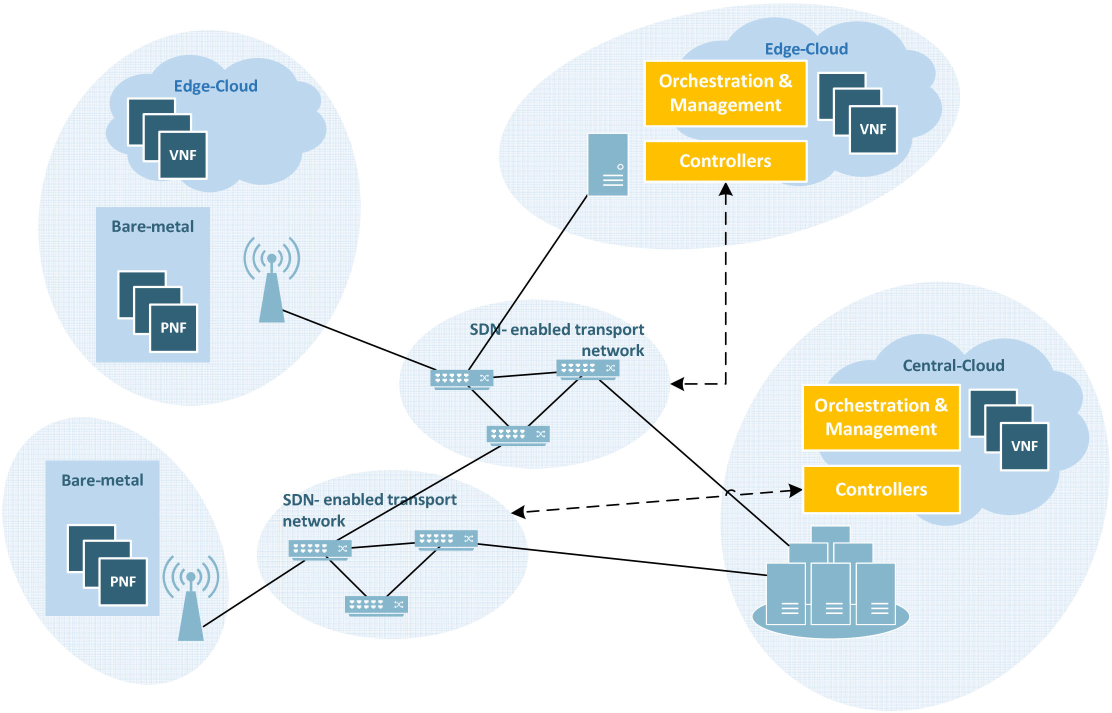

Figure 2: Relationship of functional assignment and physical architecture

The decomposition of the mobile network functionality would imply a stronger decoupling of logical and physical architecture than in 3GPP EPS as illustrated in Figure 2, i.e. physical network functions (PNFs) may be executed on bare metal, while virtual network functions (VNFs) may be executed on local or remote data centers (referred to as edge and central cloud in Figure 2). Bare metal refers in this case to the non-virtualized access to radio access resources, e.g. through DSPs, compared to the execution on cloud-computing platforms. Hence, depending on the use case, requirements, and the physical properties of the existing deployment, mobile network functionality is executed at different entities within the network. This imposes a number of challenges, e.g. the system itself must not become more complex and the introduction of new interfaces should be avoided as much as possible. Hence, the VNF assignment should exploit an efficient control and orchestration plane as further described in Section V. Furthermore, the coexistence of different use cases and services would imply the need of using different VNF allocations within the network. This is further elaborated in Section IV using the network slicing model. The challenge of avoiding many additional interfaces may be addressed by a flexible container protocol on user [4] and control plane. The mobile network must further integrate also legacy technologies to guarantee that it can operate with existing networks.

Network Functions	Relevant parameters
Cell discovery	Highly depends on carrier frequency, e.g. sub-6 GHz or mm-wave, MIMO technologies, e.g., beamforming.
Mobility	Mobility may not be required by some services (metering), or only very locally (enterprises), in groups (trains), or at very high speed (cars).

Carrier Aggregation	Carrier aggregation may not be needed in each scenario as it also impacts battery consumption; it could further include very distinct spectrum.
Multi-Connectivity	Multi-connectivity could include different network layers (micro/macro), different technologies (Wi-Fi/LTE), and different spectrum (sub-6 GHz/mm-wave). It may further be implemented at very different layers, e.g. among others depending on deployments.
Connectivity model	The actual connectivity may be based on bearers (high throughput) or connection-less (IoT). In the connection-less case, many non-access stratum (NAS) functions are not needed.
Coding	Coding techniques may vary depending on the use case, e.g. block-codes for short (sensor) transmissions or turbo-codes for high throughput.
Multi-Cell Cooperation	Depending on the current load, deployment, and channels, tighter cooperation (joint Tx/Rx) or looser cooperation (ICIC) is possible.
Spectrum Access	Depending on the use case requirements and available spectrum, possibly different spectrum access strategies may be required, e.g. licensed, unlicensed, license-assisted.
Authentication, Authorization, Accounting (AAA)	Depending on the applicable access control and accounting/charging policies, AAA functionality is differently and may be placed/instantiated in different locations.
Parental Control	Depending on the user context (children) and the requested service, the parental control function becomes part of the service chain for according service flows.

Table 1: Examples for functional optimization

The main benefit of the described architecture is the possibility to exploit centralization gains where possible, to optimize the network operation to the actual network topology and its structural properties, and to use algorithms optimized for particular services, i.e. optimize through dedicated implementations instead of parameters.

Table 1 lists examples where the operation may be optimized through different VNFs. For instance, it may be possible to use a flexible air interface numerology and depending on the network terminal different coding strategies, MIMO modes, and framing structures are employed, which are optimized for throughput, delay, or reliability. However, the upper layer packetization may still be the same for all use cases, which allows for reusing the same software implementation. Another example includes cooperative transmission, where gains are highly dependent on the environment, e.g., if the system is not operating at full load cooperative scheduling may perform as efficiently as cooperative multi-point transmission; at full load the gains depend highly on the number of interferers and channel knowledge.

IV. NETWORK SLICING

Network slicing is centered on the concept of deploying multiple dedicated logical mobile networks with varying levels of mutual isolation on top of the same infrastructure. A network slice is a collection of mobile network functions (or groups of functions) and a specific set of radio access technologies (RATs) (or specific RAT configurations) necessary to operate an end-to-end (self-contained) logical mobile network. This set of network functions and configurations may be combined such that slice-specific data and control plane functionality is tailored to the requirements of considerably different use cases, network customers, or business models. Consequently, network slicing is a technology that enables both multi-tenancy and service-tailored composition of mobile networks.

Network slicing leverages the economies of scale to be expected when running multiple logical mobile networks on top of a common infrastructure. In this sense, network slicing is an evolution of network sharing, which has been a key business model for mobile network operators to reduce deployment and operational costs. In 3GPP, the working group System Architecture 1 (WG SA1) conducted a study on actively sharing RAN resources while maintaining sharing policies and providing flexibility for on-demand resource sharing within shorter time periods [5]. Architecture and operations that enable different mobile operators with a separate core network (multi-operator core network, MOCN) to share the RAN are specified by the WG SA2 [6]. In general, sharing of resources can be divided into three categories: static [13], dynamic (e.g. spectrum sharing [7]), and mixed resource allocation (spectrum sharing and virtualized resource block sharing [8]). While passive and active sharing solutions, e.g., for network elements or MAC (medium access control) schedulers, are partially used and standardized today, these sharing concepts are based on fixed contractual agreements with mobile virtual network operators (MVNOs) on a coarse granularity basis (monthly/yearly) [9].

NFV, and software-defined mobile network control and orchestration enable a new level of sharing by decoupling infrastructure resources from application software, and by a split of control and data plane. This significantly simplifies the partitioning of network infrastructure resources among different operators (or tenants). Further, slices can be isolated from each other to allow for an adaptation of security measures according to service-specific requirements (flexible security) and for securing parallel operation of multiple services or tenants. While isolation between network slices is highly important, it finds its limits where available resources need a common control (e.g., the radio scheduler): If the required isolation level cannot be preserved, a security weakness in one slice can be exploited to attack another slice. Strong security measures to maintain the isolation between multiple services and tenants operating on a shared infrastructure platform must be mandatory for all services and tenants.

Mobile core network elements rapidly evolve towards “cloud readiness”, i.e., deployed in data center environments. Consequently, each network slice can be composed from dedicated, customized instances of required network functions (NFs) and elements (NEs). Alternatively, slices can share function instances in particular cases, e.g., for storage-intensive components like subscriber databases. In the RAN domain, extended sharing concepts facilitate the exploitation and management of radio resources offered by the owner of the network infrastructure to tenants. In this multi-tenant ecosystem, classic tenants such as mobile network operators (MNOs) and MVNOs coexist with vertical businesses, e.g. utility companies, automotive and manufacturing companies, and over the top (OTT) service providers such as YouTube and Netflix. These tenants relate to network slicing in the sense that a tenant may instantiate and make use of one or more slices. Figure 3 shows how the different NFs may be instantiated on different network elements depending on the network slice (service), i.e. physical NFs would be deployed on non-virtualized hardware, different levels of edge cloud instances would provide virtualized resources (for instance closer to the access point or exploiting points of presence), and a central cloud . It further shows the Virtualization Layer which is responsible for multiplexing requests from different slices operating on virtualized resources towards physical resources.

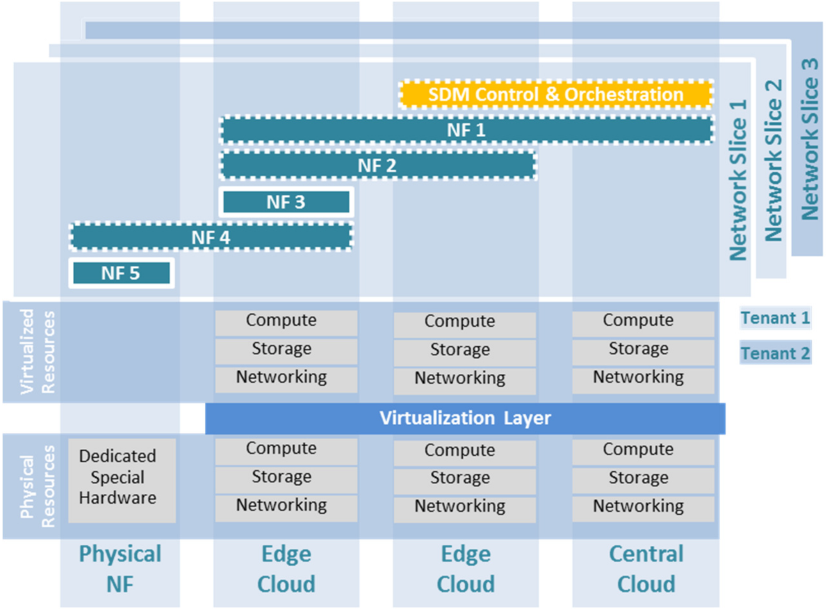

Figure 3: Network slicing concept

Beyond multi-tenancy, network slicing additionally serves as a means to deploy multiple service-tailored mobile network instances within a single MNO, each addressing a particular use case with a specific set of requirements, e.g., mobile broadband or IoT. In that context, the aforementioned "network of functions" concept enables the joint optimization of mobile access and core network functions. Each network slice is composed of functions according to service needs, e.g. low latency services require the allocation of most network functions at the edge.

V. ORCHESTRATION AND MANAGEMENT

As mentioned before, an essential component of the mobile network is the efficient orchestration and management of mobile network functions through a low-complex interface. In that context, the software-defined network (SDN) functionality has recently gained momentum as a new approach for performing network operations. With traditional SDN, control functions are decoupled from the data plane through a well-defined interface and are implemented in software. This simplifies networking, provides a higher degree of flexibility and an enhanced scalability, while reducing cost. Indeed, by simply modifying the software of the control functions, SDN allows to flexibly change the behavior of the network, considering specific services and applications.

Following the paradigm of SDN, the control of the mobile network architecture adopts the software-defined mobile network control (SDMC) concept focusing on wireless-specific functions. Our SDMC approach resembles SDN by splitting wireless functionality into (i) those functions that are being 'controlled' and remain relatively stable; and (ii) those functions that 'control' the overall network and are executed at the controller. However, our SDMC concept is specifically devised to control wireless functionality, and it is not limited to data plane functions, but includes control plane functions of the mobile network, both of which can be placed arbitrarily in the edge cloud or the central cloud as shown in Figure 2.

To enable the SDMC paradigm within 3GPP EPS, where wireless functionality is controlled centrally, we collocate the SDMC within the 3GPP network management system. This takes advantage of the legacy performance monitoring forming a logical global RAN information base, which can be used by the SDMC to control various network functions. The control of wireless networks comprises among others: channel selection, scheduling, modulation and coding scheme selection and power control. Figure 4 illustrates the SDMC architecture showing the main functional features and operations. With a software-defined approach, all these functions could be performed by a programmable Software Defined Mobile Controller, which provides very important *benefits* for the operation of the mobile network.

However, it is essential to enhance the current 3GPP Type 2 interfaces (Itf-N) between the network management system and the network equipment to allow the SDMC to provide network programmability and support for multi-tenancy. Those enhancements should reflect SDN capabilities such as network abstraction and control providing sufficient network management flexibility. Interfacing the SDMC with the network management system in such a manner can also enable multi-tenancy support and network programmability taking advantage of the 3GPP Type 5 interface. This allows to receive network sharing requests from MVNOs [11] and offering the means of network resource acquisition to OTT providers and verticals via the SDMC northbound API. In addition, the northbound interface offers the capability for flexible provision of the so-called SDMC Apps. To accommodate the related service requirements of multi-tenancy and SDMC Apps, the Infrastructure Provider Network Manager needs to interact with 3GPP policies, i.e. the policy and charging rules function (PCRF), via a new network interface called *Itf-Policy*, to enable a flexible policy provision for multiple tenants and network innovation.

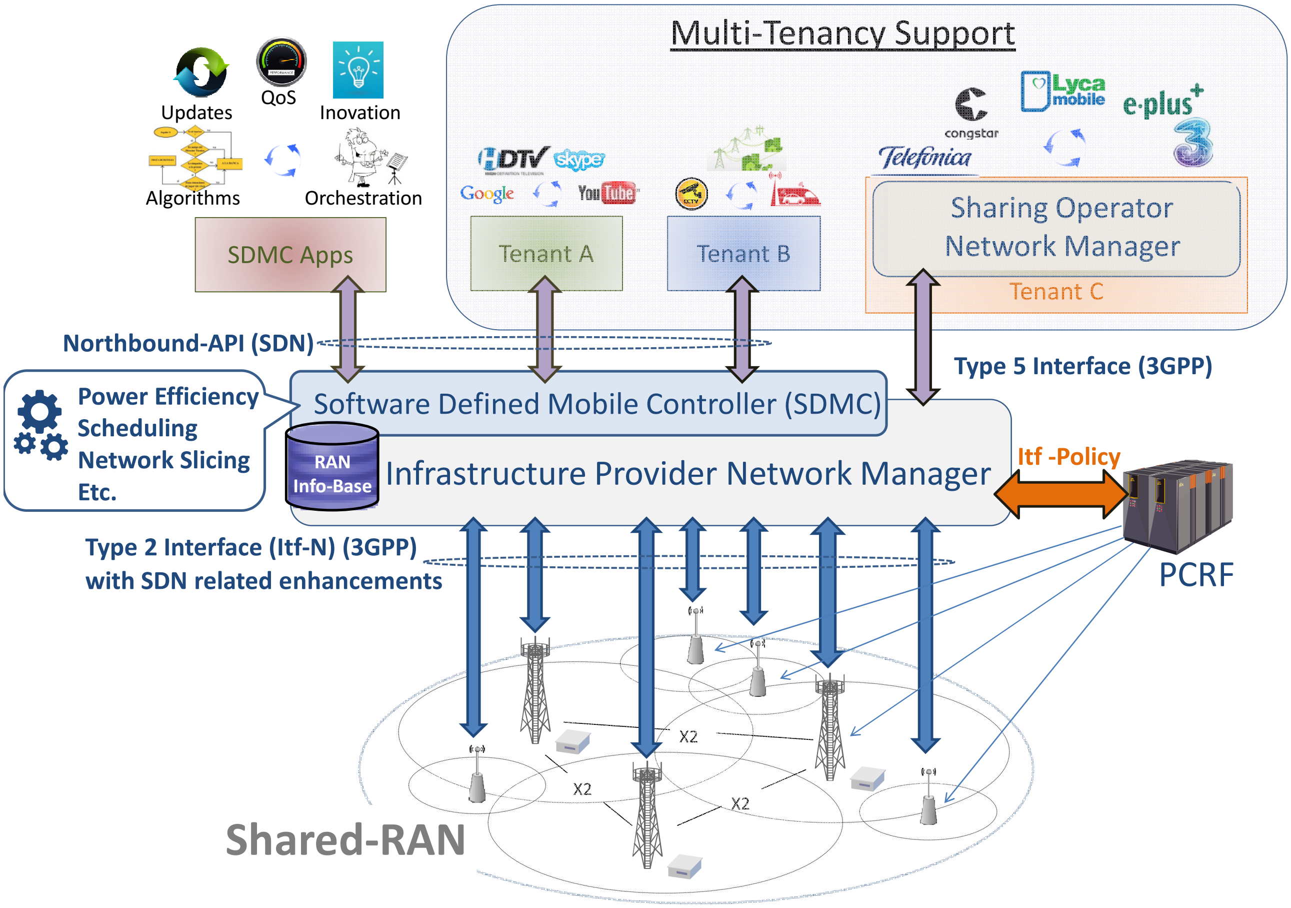

Figure 4: SDMC architecture and operations

The key advantages resulting from the proposed approach include the following:

- **Flexibility**: One of the problems that network operators are facing today is that while wireless equipment is quite expensive, this is very rigid and does not adapt to their needs. By using SDMC, operators would be able to fit the equipment to their needs through simply re-programming the controller and thus reducing costs, while being able to scale up and down virtual functions, enhancing also reliability.

- **Unified management**: Adopting a logically centralized control unifies heterogeneous network technologies and provides an efficient network control of heterogeneously deployed networks. In particular, the network control must consider evolving traffic demands, enhanced mobility management and dynamic radio characteristics.
- **Simplified operation of the wireless network**: With SDMC, network operators only need to control a set of logically centralized entities that run the entire network, which, depending on actual latency requirements, possibly includes heterogeneous radio technologies.
- **Enabling network innovation**: By modifying the controller functions, i.e. SDMC Apps, many new services that were not included in the initial architecture design can be enabled by modifying the network behavior to introduce service-specific enhancements within a few hours instead of weeks [15].
- **Programmability**: By adapting the functions such as scheduling or channel selection to the specific needs of the applications or the scenario, significant performance gains can be achieved. For instance, the controller has a global view of the network, which allows for optimizing the resource allocation and scheduling across multiple BSs.
- **Inter-slice resource control**: Following the network slice concept described in Section IV, infrastructure domain-hosted SDMC allows the infrastructure provider to assign not utilized resources to support third party services. Hence, the SDMC can allocate a network slice with a specified network capacity, a particular split of the control/data-plane and a selection of virtual network functions.

VI. STANDARDIZATION ROADMAP

The ITU Radio Group (ITU-R) is developing a longer term vision of mobile networks and their evolution towards 2020 and beyond. It provides a framework and overall objectives of the future developments of 5G systems (referred to as IMT-2020) which involves several steps:

- In early 2012, ITU-R embarked on a program to develop “IMT for 2020 and beyond”, setting the stage for 5G research activities that are emerging around the world.
- In 2015, ITU-R has finalized its vision of the “5G” mobile broadband connected society, which will be instrumental in setting the agenda for the World Radiocommunication Conference 2015, where deliberations on additional spectrum will take place in support of the future growth of IMT.
- In the 2016–2017 timeframe, ITU-R will define in detail the performance requirements, evaluation criteria and methodology for the assessment of a new IMT radio interface.
- It is anticipated that the timeframe for proposals will be focused in 2018.
- In 2018–2020 the evaluation by independent external evaluation groups and definition of the new radio interfaces to be included in IMT-2020 will take place.

Similar to previous mobile network generations, 3GPP is expected to be the leading standardization body also for 5G and the corresponding roadmap is shown in Figure 5. 3GPP has started to work on 5G in both the SA and RAN working groups. The current 3GPP Release 13 and the coming 3GPP Release 14 will provide enhancements to LTE-Advanced under the name “LTE-Advanced Pro.” This will become the baseline technology for the evolution from LTE-Advanced to 5G. In parallel, 5G scenarios and requirements will be studied, which likely demand a revolutionary new architecture providing greater flexibility as stated in the previous section. This work is expected to complete by mid of 2017.

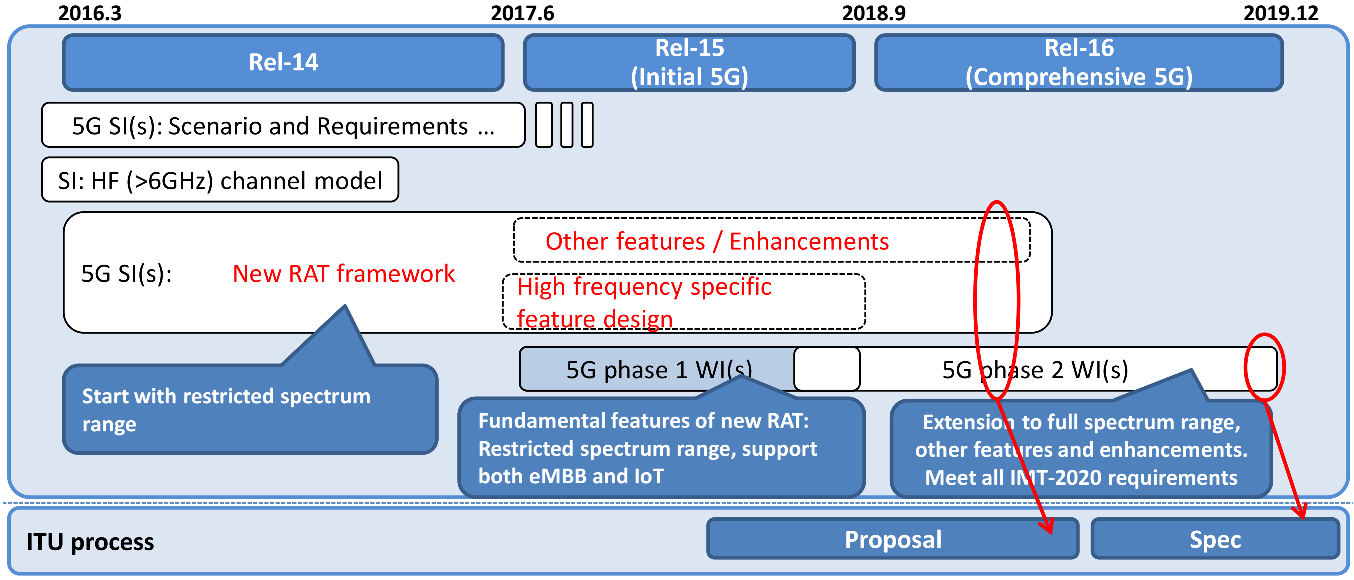

Figure 5: 3GPP LTE standardization roadmap towards 5G

SA1 has been working on a “Study on New Services and Markets Technology Enablers” (SMARTER) since April 2015. As a result, four additional study items are created that include three vertical industries and one horizontal group. The verticals are enhanced mobile broadband (eMBB), critical communications (CriC), and massive IoT (mIoT); the horizontal study is on network operation (NEO). The latter deals, amongst others, with network slicing, interworking and migration, as well as fixed-mobile convergence (FMC). In March 2016, another study item for 5G vehicular-to-anything (V2X) communication may be agreed. SA1 plans to finalize its studies in June 2016 and then start normative work in 3GPP Release 15.

SA2 targets to finish its “Study on Architecture for Next Generation System” in September 2016. An important topic in this study will be the interface between the LTE-Advanced RAN and a future 5G core network (CN). SA2 has agreed to follow NGMN, in particular Option 3 detailed in [11]. The new 5G CN will be capable to support a new 5G RAT as well as an evolved LTE-Advanced and other RATs such as IEEE 802.11. This enables 5G network terminals to move between 5G and the evolved LTE-Advanced without any interworking between the 5G and the 4G CNs and thus provides a sound migration path from the LTE-based RAN to 5G.

The RAN working groups are targeting the first true 5G features to appear in 3GPP Release 15, i.e., in the second half of 2018. This implies that 3GPP will complete its initial 5G specifications right before the Olympic Winter Games 2018 that will take place in Korea. The focus in this 5G “Phase 1” will be mostly on enabling new spectrum in high frequencies above 6 GHz. More features for implementing architectural enhancements will follow in 5G “Phase 2” with 3GPP Release 16, i.e. by the end of 2019, in time for their submission to the IMT-2020 as well as the Olympic Summer Games 2020 in Japan.

Despite these planned architectural enhancements, further efforts are needed by 3GPP, and other standardization bodies, to accomplish the migration from 3GPP EPS towards a new 5G architecture: A completely new type of interfaces has to be designed and standardized, when the “network of functions” is going to substitute today’s “network of entities” as pointed out in Section III. Furthermore, the use of network slicing for multi-tenancy and multi-service described in Section IV requires a flexible execution environment that is capable of supporting the diversity of network functions in parallel. The application of SDN concepts promising this flexibility to mobile radio networks is however still in an experimental phase, although the C-RAN concept, RAN virtualization, and their expected centralization gains have been discussed for several years.

The mobile network architecture evolution as discussed in this article impacts many different network components. Hence, in addition to 3GPP other standards developing organizations (SDOs) will participate in the definition of the future mobile network architecture. Most notably, the following SDOs will be involved in addition to 3GPP:

- ETSI NFV industry specification group (ISG) has created a framework for virtualization of network functions. This framework has been applied successfully to virtual network functions mostly in the CN. In the RAN, where hardware still plays an important role, implementation of NFV concepts are more difficult [14], e.g. the C-RAN concept with a fully centralized and virtualized RAN has been among the first use cases discussed already in 2012 in ETSI NFV. However, until today, there are no large scale commercial implementations. In order to gain more impact, the ETSI framework must be extended to be applicable not only to virtualized hardware but also to non-virtualized, bare-metal hardware [14].
- ETSI MEC ISG is looking at how to provide IT and cloud-computing capabilities within the RAN in close proximity to mobile subscribers, allowing content, services and applications to be accelerated, and increasing responsiveness from the edge.
- The Open Networking Foundation (ONF) is the leading force in the development of open standards for the adoption of the SDN concept. However, in order to provide the benefits described in Section V, the SDN protocol functionalities developed by ONF, e.g. OpenFlow and OF-Config, need to be extended to cope with 5G requirements and towards 3GPP EPS.
- IETF is also considering the use of Internet protocols, e.g. IPv6 and IP Multicast in 5G networks, although the work required has not a clear scope yet. There are proposals for using IETF developed protocols such as LISP (locator/ID separation protocol), HIP (host identity protocol), and ICN (information centric networking) to address shortcomings of the current 4G core network for the support of additional 5G functionalities, e.g. reducing network latency or supporting new mobility models. IETF is also working on the development of an architecture for service function chaining that includes the necessary protocols or protocol extensions for the nodes that are involved in the implementation of service functions, as well as mechanisms for steering traffic through service functions.

VII. CONCLUSIONS AND FURTHER CHALLENGES

This article discussed the evolution 3GPP EPS mobile network architecture and the need to provide a flexible architecture that integrates different technologies and enables diverse use cases. We introduced and explained various concepts such as the transition from a pre-defined set of functions grouped into network entities to a flexible network of functions, the network slicing concept, and software defined mobile network control, orchestration and management. In addition, the relevance of different standards defining organizations has been outlined and their roadmap has been detailed.

It is in our opinion of high importance to consider the future evolution of 3GPP EPS not only as the introduction of a novel air interface but as the evolution of one mobile network architecture towards a “system of systems” where many different use cases, technologies, and deployments are integrated, and the operation of each system is tailored to its actual purpose.

VIII. ACKNOWLEDGEMENT

This work has been performed in the framework of the H2020-ICT-2014-2 project 5G NORMA. The authors would like to acknowledge the contributions of their colleagues. This information reflects the consortium’s view, but the consortium is not liable for any use that may be made of any of the information contained therein.

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X. BIOGRAPHIES

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