This is a postprint version of the following published document:

Sayadi B. et al. (2016) SDN for 5G Mobile Networks: NORMA Perspective, In: *Cognitive Radio Oriented Wireless Networks. CrownCom 2016. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 172. Springer, Cham*

DOI: https://doi.org/10.1007/978-3-319-40352-6_61

SDN for 5G Mobile Networks: NORMA perspective

Bessem Sayadi, Marco Gramaglia, Vasilis Friderikos, Dirk von Hugo, Paul Arnold, Marie-Line Alberi-Morel, Miguel A. Puente, Vincenzo Sciancalepore, Ignacio Digon and Marcos Rates Crippa

bessem.sayadi@nokia.com, mgramagl@it.uc3m.es, vasilis.friderikos@kcl.ac.uk, Dirk.von-Hugo@telekom.de, Paul.Arnold@telekom.de, marie_line.alberi-morel@nokia.com, miguelangel.puente@atos.net, vincenzo.sciancalepore@neclab.eu, ignacio.digonescudero@telefonica.com, crippa@eit.uni-kl.de

Abstract. To build a flexible and an adaptable architecture network supporting variety of services and their respective requirements, 5G NORMA introduced a network of functions based architecture breaking the major design principles followed in the current network of entities based architecture. This revolution exploits the advantages of the new technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV) in conjunction with the network slicing and multi-tenancy concepts. In this paper we focus on the concept of Software Defined for Mobile Network Control (SDM-C) network: its definition, its role in controlling the intra network slices resources, its specificity to be QoE aware thanks to the QoE/QoS monitoring and modeling component and its complementarity with the orchestration component called SDM-O. To operate multiple network slices on the same infrastructure efficiently through controlling resources and network functions sharing among instantiated network slices, a common entity named SDM-X is introduced. The proposed design brings a set of new capabilities to make the network energy efficient, a feature that is discussed through some use cases.

Keywords: 5G Architecture, SDN, NFV, QoE, Energy Efficiency, Network Slicing.

1 Introduction

By just observing our daily routines we understand the impact that mobile connectivity has on our lives. This trend will be even clearer when new services that are envisioned in these days will come to market: self-driving vehicles or the Internet of Things (IoT) will further increase the need for expanded and faster network connectivity and increases the requirements on a mobile network. This goal cannot be achieved by just extending the current 4G architecture: a complete re-thinking of the mobile network system towards the 5G networking is needed.

The 5G NORMA[1] project aims at providing such a new architecture. Its main characteristics will be flexibility and adaptability required to match the available network resources with the fluctuating demand which is the utmost requirement to maintain the economic viability of future networks. Due to steadily rising energy costs a strongly related important key performance indicator addressed by the players in 5G is the energy efficiency as outlined in [1].

Driven by the rising of new technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV), flexibility and adaptability can be achieved by

[1] http://5gnorma.5g-pppp.eu/

using a virtualized infrastructure in which Network Function are allocated on demand by a centralized controller.

To provide the needed performance several levels of infrastructure may be deployed, ranging from the closest to the antenna (called *Edge Clouds*) to the most centralized (called *Central Cloud*). Network functions can be allocated at different levels according to the needed performance. This infrastructure is eventually shared among different *tenants* to provide different services, using *the network slicing* concept.

The network is sliced into many dedicated end-to-end virtual networks, each one handling a business case or a service while sharing the same network infrastructure. Based on customized SLAs, the owner of the network infrastructure should be able to allocate (or to sell) the required resources to each network slice. 5G NORMA leverages network softwarization and virtualization to implement a dynamic and a personalized network infrastructure resources allocation. In the 5G NORMA architecture the management of the network slices, running on the infrastructure, is in charge of a centralized controller. In this paper we describe how a network slice is controlled in order to achieve the target performance level for each business case or a service. In Section 2 we describe the 5G NORMA architecture, and then we focus on the Network Slice controller in Section 3. Section 4 describes the issues related to the coordination of different slices, while Section 5 shows the benefits of this architecture in terms of cost reduction and energy efficiency. Finally, section 6 concludes the paper.

2 Slicing Enabled 5G NORMA Architecture

5G architecture should bring the required flexibility to support many services with different stringent requirements in terms of latency, throughput and availability. This requires rethinking the current mobile network architecture to move from current *network of entities* architecture to a *network of functions* architecture. 5G NORMA introduces an architecture leveraging the network slicing and multi-tenancy concepts allowing to deploy different network slices instances running on the same network infrastructure. Each one is tailored to the corresponding service and business needs.

2.1 Design Principles

The future mobile network architecture will be designed by the following the above principles which play an important role to fulfill the flexibility, scalability, context and security requirements:

- **Multi-tenancy** allows for several service providers operating on top of a shared infrastructure. The range of tenants is diverse, ranging from mobile network operators (MNOs) via over-the-top (OTT) service providers to companies from vertical industries. This also results in varying levels (depths) of service and resource control to be exposed to tenants.
- **A shared infrastructure** leverages the economies of scale to be expected when hosting multiple logical mobile networks. The infrastructure consists of heterogeneous hardware resources (general-purpose as well as dedicated,

special-purpose hardware) and necessary software for hosting mobile network functions. The infrastructure as a whole is provided by several infrastructure providers, e.g., MNOs or 3rd party providers.

- **Efficient control frameworks** allow for a sufficient abstraction of controllable resources and functions and expose uniform control APIs on different abstraction and architectural levels. Thus, they allow for, e.g., cross-domain orchestration of network functions and services, flexibility in function decomposition and placement, and customized business service composition.
- **The fragmentation of administrative domains** increases complexity. Vertically, at least business service providers, network service providers and infrastructure providers have to be differentiated. Depending on the type of tenant, some or even all can collapse into one. Horizontally, multiple providers of each type co-exist.

2.2 Building Blocks Overview

The concept of network slicing is paramount within the 5G NORMA architecture. Therefore, the main 5G NORMA building blocks are related to this concept. More specifically, three families are envisioned (see Fig. 1): i) related to the network slice life cycle and the interactions among different network slice instances, ii) related to the management functions within a slice, and iii) the mobility management module. In the sequel, each block will be introduced.

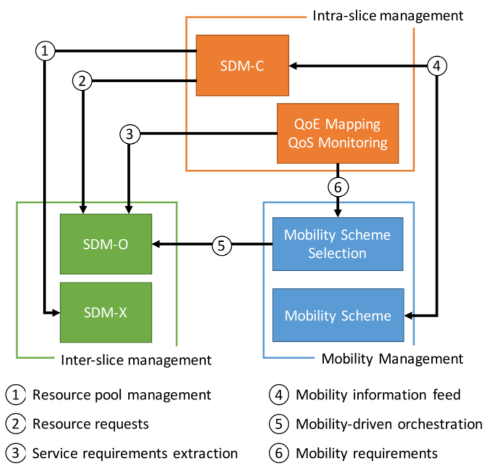

Fig. 1 The 5G NORMA connectivity and QoE/QoS management building blocks.

The Software Defined for Mobile Network Orchestrator (SDM-O) interfaces the network slices infrastructure to the business domain. The handling of slice creation requests (e.g., vehicular, IoT, possibly belonging to different tenants) is managed here. Requests come mapped to a set of KPIs according to the requested service: e.g., a vehicular and a HD video slice requests will be associated to low latency and high bandwidth KPIs, respectively. These abstract requirements are translated to real network requirements that are used to build the chain of virtual Network Functions (vNF) and

physical Network Functions (pNF) by using a template library. This process is similar to the one under investigation by the IETF Service Function Chaining (SFC) WG[2]. The needed vNFs are finally orchestrated by SDM-O, which has a complete view of the network: the optimal set of resources to be used and their location in the infrastructure is decided here.
On the other hand, the Software Defined for Mobile Network Control (SDM-C) directly manages the resources assigned to a network slice (there is a SDM-C in every network slice allocated by the SDM-O): it builds the forwarding path used to realize an SFC (Service Function Path, SFP, in the IETF SFC WG) while fulfilling the constraints and requirements defined by the SDM-O.
The information used to define those constraints is gathered from the QoE/QoS Mapping module, which also continuously analyzes the performance of a network slice and reports to the SDM-C. The configuration of a network slice may then be changed based on the QoS reporting. The re-configuration may happen at either vNF level or by reconfiguring forwarding paths by using an SDN interface. If the reconfiguration performed within a slice is not enough to fulfill the requirements assigned to a network slice, the SDM-C requests for more resources to the SDM-O.
Besides the Mapping & Monitoring module, also the Mobility Management module, in charge of selecting the right mobility scheme (e.g. Client based mobility, such as MIPv6, Network-based mobility, such as Proxy Mobile IPv6…) according to the service/user, reports to the SDM-C. The information exchanged through this interface is the one regarding the mobility of users, and it is used by SDM-C to deal with mobility-related aspects within the slice. The functional mobility of vNF between edge clouds is also managed by this module exploiting an interface with the SDM-O, which executes the migration.
The last major operation affecting a network slice is its reshaping (i.e., scale-in and scale-out operation). As mentioned above, these requests are managed by the SDM-O if they are related to computational resources. Otherwise, requests for shared resources (e.g., radio resources) are managed by the Software-Defined Mobile Network Coordinator named SDM-X.

2.3 5G NORMA Architecture

Fig. 2 shows the architecture as specified so far in 5G NORMA [2]. The architecture differentiates between service layer functions which e.g. consider constraints and requirements related to demanded service and the policies applicable to the customer. The service layer itself is generally out of scope here. Major focus here is on the MANO (MANagement and Orchestration) layer mainly responsible for long-term allocation of resources for virtual network functions. The depicted architecture indicates at which functional entities the building blocks shown in Fig. 2 are logically located. Further details of the functional entities characteristics and features are described in [2]. The exact functionality is still for further specification within the 5G NORMA project. A typical example for newly defined entity in 5G NORMA is the SDM-C. The latter has two interfaces. The southbound interface (SBI) connects to all (dedicated) pNFs and vNFs. The northbound interface connects to the 5G NORMA-MANO components. For

[2] https://datatracker.ietf.org/wg/sfc/

sharing pNFs and vNFs across multiple slices instances, a common entity named SDM-X is introduced as detailed in section 4.

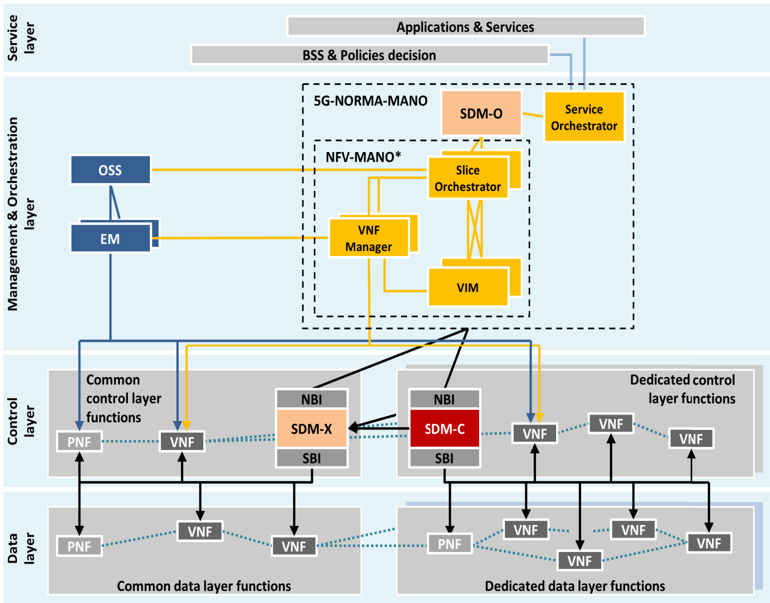

Fig. 2 5G NORMA functional reference architecture

Another example for instantiation is the multipath feature of 5G which enables a device to be connected via multiple radio links and transport paths to enhance reliability, improve handover performance and save resources by efficient usage of different radio sites and/or technologies matching to the actual session demands. This functionality included in mobility management is realized at different vNFs in the Control Plane under control of one or multiple SDM-Cs resulting in new challenges for efficient operation.

3 Software Defined for Mobile Network Control Design for a Network Slice

Along the lines of SDN, 5G NORMA architecture incorporates the Software-Defined Mobile Network Control and Orchestration (SDM-C and SDM-O) concept which includes functions relevant for radio access and mobile core network. Starting by introducing the SDN concept, we describe in section 3.2, our approach SDM-C highlighting the similarities and the new proposed features.

3.1 SDN Overview

The well-known approach of SDN has been recently introduced by researchers and data center architects in order to decouple the signaling layer (controller) from the physical resources. This directly implies a functional split between C-plane and U-plane. The

Open Networking Foundation (ONF) focuses its activities on the adoption of the SDN paradigm in the standard network deployments. In particular, they aim at providing open interfaces for simplifying the development of novel software that is used to directly control the network. In addition, open interfaces between functions should be defined to allow multi-vendor access technology to be readily integrated into the network. Therefore, the SDN approach can be envisaged as the key-enabler for having software-based programmability of network functions (NFs) and network capabilities.
On the one hand, the network is based on a set of physical network elements (NE) forming sub-networks within the network control domain of a SDN controller. The network intelligence is located in the SDN controller, which takes care of managing the physical network elements, seen as abstract resources. Each NE contains a controller which instantiates an agent as well as a virtualizer to supporting the agent. The agent represents dedicated resources which will be assigned to a particular service. Hence, the resources assigned to the agent are mapped onto the hardware abstraction layer of the single NE.
On the other hand, the network elements are controlled by a SDN controller, placed on different platforms. The SDN controller includes a coordinator and a data plane control function (DPCF). Another agent with virtualizer may be instantiated in the SDN controller to directly support applications on upper layers.
In Fig. 3, we show the ONF-SDN architecture, where NFs are properly managed by the applications.

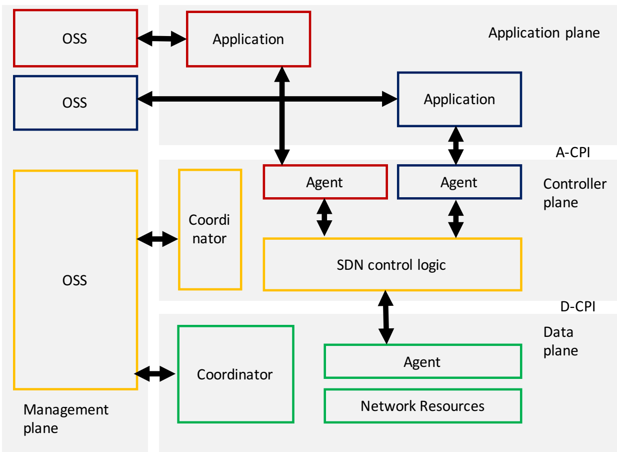

Fig. 3. The ONF-SDN Architecture [4]

We can easily identify three different layers in the SDN architecture: (*i*) the data plane, wherein network entities expose their capabilities through D-CPI interface, (*ii*) the controller plane, the intermediate layer which maps the applications requirements onto physical resource requests while it feedbacks the infrastructure status to the application layer by means of A-CPI interfaces and, (*iii*) the application plane, where SDN-capable applications are developed.
It is clear that the current SDN architecture is well realized for fixed/transport network. For that, further modifications are needed to support RAN part of the network and forthcoming 5G features and to coordinate with legacy network controller to guarantee a smooth transition to the novel SDN paradigm.

3.2 Intra Network Slice Control

The inter-slice control comprises two main blocks. The first one is the SDM-C which is slightly different from SDN, introduced in section 3.1, in case of mobile network through the co-existing of data and control plane. The second block is the QoE awareness which play an innovative role in 5G architecture design introduced by 5G NORMA.

3.2.1 Software Defined for Mobile Network Control

The Software Defined for Mobile Network Control (SDM-C) is a key function of the 5G NORMA architecture. It is assumed to have an SDM-C instance per network slice. It controls all of the network slice's dedicated pNFs, vNFs and associated resources (network, radio). The SDM-C allows for a fast reconfiguration (the right order will be assessed through the course of the project), to dynamically influence and optimize the performance of its network slice within the given amount of resources assigned to its network slice, i.e. at the time of the last (re-)orchestration made by SDM-O. The (re-)configuration occurs after (re-)instantiation and can be considered to take place at a different time scale (with extents in the order of several seconds).

Following the SDN spirit, the SDM-C also exposes a Northbound Interface (NBI) towards the 5G NORMA-MANO functions, whose scope is two-fold. The 5G NORMA-MANO to SDM-C direction is used to define all the QoE / QoS constraints that have to be fulfilled for a given traffic identifier, that may range from a single flow to an entire network slice. The granularity of this API (that goes beyond the simple network function re-configuration) will be determined during the project, but we can provide some examples of its envisioned operation. For instance, the UL/DL scheduler can be dynamically configured by the SDM-C to provide the needed QoE-related KPIs to HD Video Users flows, while maintaining resources for Best Effort user flows. The network capacity may be another KPI that the SDM-C must fulfill, taking decisions about network function reconfiguration and routing.

In the case that the given QoE/QoS targets of the service(s) provided by its network slice cannot be met, the SDM-C may request re-orchestration. For that purpose, it uses the SDM-C to 5G NORMA-MANO interface to trigger a re-instantiation request (both of computational capabilities or shared resources such as frequencies or other shared network function).

3.2.2 QoE awareness in 5G for energy efficiency

Quality of Experience (QoE), which is lately becoming the ultimate item to be delivered to end-users, is defined as "the degree of delight or annoyance of a person whose experiencing involves an application, service, or system" [3]. This contrasts with Quality of Service (QoS), which concerns objective and technical metrics at network (delay, jitter, packet loss, etc.) and application level (frame rate, resolution, etc.).

QoE-awareness refers to the ability of knowing about and react according to the user perceived quality (QoE) of a certain service. The 5G-NORMA network architecture will allow the development of QoE-aware mechanisms, being one of their main goals energy efficiency (see Section 5).

A key aspect to achieve QoE-awareness is the proper monitoring of the QoS factors. Conventionally, legacy and 4G mobile networks employ QoS measures based on objective system-centric metrics at network (such as delay, jitter or packet loss, etc.) and application level (frame rate, resolution, etc.). In 5G-NORMA the QoE will be then derived from these QoS metrics through a QoE/QoS mapping process using appropriate mathematical functions. Furthermore, the QoE model shall include the complete end-to-end objective system factors (network, application/service and terminal) and the subjective human influencing factors (expectations, likings, etc.) along with information about the user's context and business factors (Fig. 4).

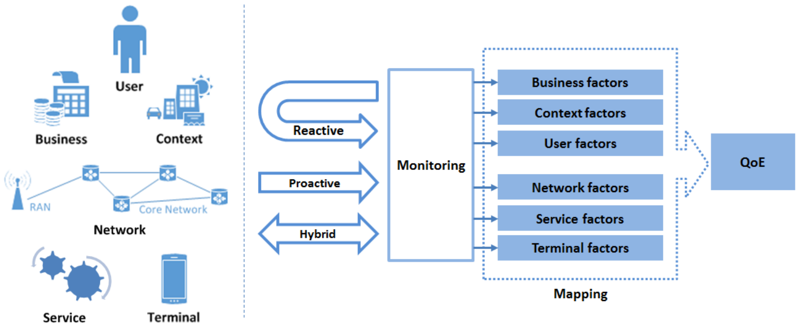

Fig. 4. Monitoring and mapping of the QoE influencing factors

QoE/QoS mapping and monitoring is strongly architecturally related to the SDM-C. The QoE engine described in Fig. 4 will be an application running in the Northbound of the SDM-C.

4 Software Defined for Mobile Network Control Design For a Set of Network Slices

To optimize the infrastructure usage and support different business cases or services, it is expected that many network slices will be instantiated on the same infrastructure. According to NGMN, a set of network slices could share one or many network functions or network capabilities. One can cite, the scheduling function deployed to share the same spectrum among network slices. Thus, two network functions categories could be defined: dedicated or common ones, invoking different manner of control. For that purpose, our 5G NORMA design introduces a new component called SDM-X developed in the following section.

4.1 SDN Hierarchy Overview

In [4], the ONF provides its perspective on the relationship between SDN and NFV. According to the report, a SDN controller virtualizes resources under its control, and then orchestrates their shared use to satisfy the user requests. VNFs are among the resources available for a SDN controller, which brings together SDN and NFV. The goal is to structure the resources as an end-to-end service. This process is recursive, as SDN controllers at a higher hierarchical level can see lower level controllers as resources as well. One illustrative example is given in Fig. 5, showing a SDN hierarchy where the Green controller has a global perspective, while the Blue, Gold and Violet controllers have a local view of their sub-domains.

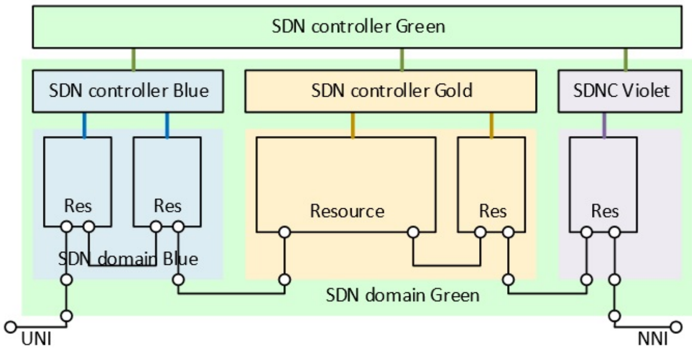

Fig. 5. SDN hierarchy example [4]

The Green controllers orchestrates the resources offered by its subordinate SDN domains to offer a service for some given user-network interface (UNI) to some network-network interface (NNI), as well as coordinates the handoff between domains (alignment of physical port, protocol stack, security, etc...), which requires alignment between Green and the neighboring domains. Alignment may be achieved by provisioning, discovery, or negotiation.

Local SDN controllers will recursively operate in the same way with the resources in their domain (orchestrating, interconnecting and provisioning resource instances).

A similar dynamic occurs in 5G NORMA, where the Software-Defined for Mobile Network Coordination (SDM-X) manages network functions or resources shared among selected network slices. Those resources can be physical or virtual network functions, or wireless resources, like spectrum. The SDM-O decides which functions will be shared among network slices and provides the SDM-X with the relevant service policy. The SDM-X combines this policy with the received network MANO requirements and decides whether to modify or not a network slice capabilities, in order to fulfill the agreed Service Level Agreement (SLA) for the given tenant.

4.2 Software Defined for Mobile Network Coordination for common functions control

5G NORMA defines Software Defined for Mobile Network Coordination (SDM-X) in order to control resources and vNFs sharing among instantiated network slices [5]. Based on service policies defined by the SDM-O (orchestrator) it can provide short term modifications to fulfill the SLA of a given tenant. Due to the decomposition and virtualization of core and RAN related NFs [2] the SDM-X controls and reacts on data flow requirements if the network slices share their allocated resources. The SDM-X coordinates the resources (e.g. computing power or radio resources), vNF and pNFs shared by network slices and decides, e.g. which network function, such as scheduling or ICIC schemes have to be used to avoid conflicts. It needs to tightly interact with all affected SDM-Cs which have access to the same PNFs and VNFs.

It is of paramount importance to have a common entity among network slices which provides scheduling decisions for efficient usage of wireless physical resources, such as frequency, time and transmission points. It has to coordinate and control the access of single network slice related SDM-Cs on common pNFs and vNFs to prevent conflicting decisions.

Based on [6], Fig. 6 shows an example, how the SDM-X needs to control inter-slice related radio resource allocation and RAN related network functions. Focus of the example is on RAN related aspects, while the core related functions are excluded for simplicity here. Fig. 6 illustrates three instantiated slices A (green), B (magenta) and C (blue). Within each network slice A and C one data flow is given, while in network slice B, two data flows are concurrently served. Dependent on QoS requirements of the data flows and network slice related policies the SDM-X needs to decide which set of RAN related network functions the data flows need to have when network slices are allowed to use the same physical radio resources. Slice A and B use the same time, frequency grid while slice C dedicated resources are allocated based on the defined network slice C policy in time and frequency domain. Thus for these exclusively assigned resources the slice (C) specific SDM-C can decide autonomously on how to map radio resources to the flows and packets. However, slice C might use the same Tx points as slice A and B. Therefore the SDM-X needs to resolve upcoming conflicting requests of the slice individual SDM-Cs.

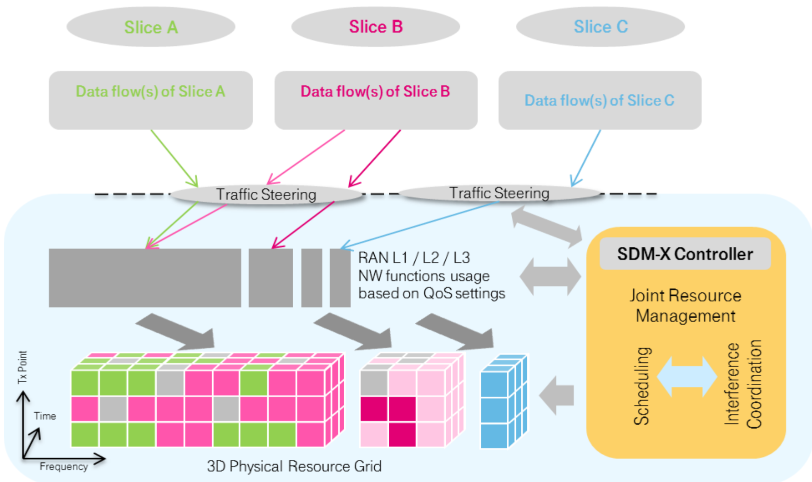

Fig. 6. SDM-X control of radio resources and RAN network functions

5 Energy Efficiency Impact

The proposed 5G NORMA architecture leveraging NFV and SDN approaches can provide energy proportionality by gracefully adjusting the network resource to the current demand, to improve inter alia energy consumption.

SDM-O can allocate network functions at selected geographical locations exploiting the energy saving benefits of centralized scenarios, e.g. in terms of the power amplifier, air-condition, etc., and distributed environments, e.g. allocating network functions and content at the edge of the network, closer to the end user, can save energy for the mobile backhaul and core network. In addition, SDN enables a split of the control and data plane simplifying energy saving management of distributed functions and heterogeneous radio environments, while at the same time creates flexible service chains among virtualized network functions in where energy can be an additional optimization parameter.

To this end, the way that network and node resources are allocated by the SDM-O and controlled via SDM-C/X in a specified network slice has a clear impact on the overall energy consumption. The number of nodes, routing paths and associated virtual machines (VM) that will be allocated, to be active for a specific set of users request will define the energy footprint of the resource allocation. The power consumption of a node can be deemed as load depended and more specifically scales linearly with respect to the CPU usage [7]. To this end, the power consumption can be modeled as shown below based on the CPU utilization U_{cpu}.

$$\boldsymbol{P} = \begin{cases} P_{idle} + (P_{max} - P_{idle}) \times U_{cpu}, & if\ U_{cpu} > 0 \\ 0, & otherwise \end{cases}$$

Where P_{idle} and P_{max} denote the power consumption of the node in the idle state and the maximum power consumption of the node (i.e., when the node is fully utilized) respectively. Since the utilization is in essence a function of time, i.e., $U_{cpu}(t)$, the total energy consumption can be calculated by integrating the above function over a required time interval. Noting the fixed cost of having elements idle, the resource orchestration should take this into account in order to minimize the number of low utilized nodes. At the same time, care should be taken in high node utilization regimes due to the potential QoS penalties that might incur especially since there is interference between the operations of different VM instances [8]. Besides node perspective, the ability to shift network functions via VM migration between centralized and distribute cloud platforms considering also the fronthaul contribute to energy saving as it is demonstrated in [9].

In addition to, QoE-awareness may have a great impact also on energy efficiency. QoE allows having satisfied users while allocating the minimal amount of resources, thus reducing costs, avoiding churn and increasing energy efficiency. This is particularly interesting in wireless networks, where radio resources are scarce. 5G networks will have to cope with unprecedented densification levels, causing the access network to account for the major energy consumption share [10]. In this scenario a moderate reduction in the data rates can lead to large energy (and therefore costs) savings as it is shown in [11].

6 Conclusions

In this paper we present the 5G NORMA perspective on controlling the network slices. We introduce the concept of Software Defined for Mobile Network Control (SDM-C) putting forward its role in controlling the intra network slices resources and its complementarity with the Orchestration component called SDM-O. We demonstrated the need for another controller named SDM-X in charge of configuring and controlling the common network functions (physical or virtual) between a set of network slices instantiated on the same infrastructure. The energy impact of 5G NORMA design is also discussed showing the direct benefit through the use of our concept SDM-C/X/O.

Acknowledgments. 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.

References

1. NGMN Alliance, NGMN 5G white paper, https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf, Retrieved in December 2015.
2. 5G NORMA, "D3.1: Functional network architecture and security requirements",Available: https://5gnorma.5g-ppp.eu/dissemination/public-deliverables.
3. P. Le Callet, S. Möller and A. Perkis, "Qualinet white paper on definitions of quality of experience", European network on QoE in multimedia systems and services, version 1.2, March 2013.
4. Open Networking Foundation, Technical Report 518, "Relationship of SDN and NFV", issue 1, released October 2015, https://www.opennetworking.org/images/stories/downloads/sdn-resources/technical-reports/onf2015.310_Architectural_comparison.08-2.pdf.
5. Marco Gramaglia, Ignacio Digon, Vasilis Friderikos, Dirk von Hugo, Christian Mannweiler, Miguel A. Puente, Konstantinos Samdanis and Bessem Sayadi, "Flexible Connectivity and QoE/QoS Management for 5G Networks: the 5G NORMA", Submitted to ICC 2016.
6. Deutsche Telekom AG, Deutsche Telekom's view on 5G, Sep 2015, ftp://ftp.3gpp.org/workshop/2015-09-17_18_RAN_5G/Docs/RWS-150033.zip
7. Beloglazov, J. Abawajy, and R. Buyya, "Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing", Future Generation Computer Systems, vol. 28, no. 5, pp. 755–768, 2012.
8. Xing Pu, Ling Liu, Yiduo Mei, Sankaran Sivathanu, Younggyun Koh, Calton Pu, Understanding Performance Interference of I/O Workload in Virtualized Cloud Environments, Proceedings of the 2010 IEEE 3rd International Conference on Cloud Computing, pp.51-58, 2010
9. D. Sabella, et.al., Energy Efficiency benefits of RAN-as-a-Service concept for a cloud-based 5G mobile network infrastructure, IEEE Access, vol.2, Dec. 2014
10. G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume and A. Fehske, How much energy is needed to run a wireless network?, IEEE Wireless Communications, 18, no. 5 (2011): 40-49.
11. J. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. Soong and J. Zhang, What will 5G be?, IEEE Journal on Selected Areas in Communications, 32, no. 6 (2014): 1065-1082.