Software Defined Networking (SDN) and Network Function Virtualization (NFV) for C-RAN systems

Massimo Condoluci[1], Toktam Mahmoodi[1], Giuseppe Araniti[2]

[1]King's College London, UK
[2]University Mediterranea of Reggio Calabria, Italy

1. Introduction

The availability of wireless connections is changing the way people interact and communicate and this has brought a drastic growth in the number of wireless devices as well as to the introduction of a vast amount of applications covering heterogeneous areas, from smart cities to smart office, from advertisement to industrial automation and so on. Such applications have led to an increasing demand for more bandwidth and have dictated the need for more powerful and faster networks. As a consequence, network operators need novel solutions to enhance the traditional architecture and coverage paradigms which are becoming increasingly overwhelmed. To this aim, *cell densification*, where small (e.g., pico and femto) cells are deployed to increase the coverage of existing macro cells, is a viable solution to effectively handle the extremely huge traffic load of future mobile networks (Andrews, Claussen, Dohler, Rangan, & Reed 2012). Nevertheless, denser deployments open new challenges (for instance, in terms of interference management, inter-cell coordination, spectrum allocation, control and data planes management) which thus ask for the adoption of more efficient approaches in the network design to guarantee high reliability, flexibility and low latency.

In this scenario, *Cloud/Centralized Radio Access Network (C-RAN)* is considered as a promising solution to boost and optimize the network performance (Dawson, Marina, & Garcia, 2014). C-RAN is based on the idea of decoupling the baseband processing from the radio units thus allowing the processing power to be pooled at a central location; this allows to replace the traditional cells with more generic and simpler nodes carrying out minimal tasks (such as RF operations) and to move other computationally intensive tasks (such as resource allocation, baseband processing, etc.) to a centralized location. C-RAN allows to reduce the total cost of ownership (especially, capital and operating expenditures) thanks to the shared use of storage/computing/network/radio resources. Therefore, common repositories for networking functionality may be used to avoid multiple deployment of the same component (e.g., macro and small cells which use shared resources). C-RAN may come in help in several scenarios: *(i) cell configuration*, *resource assignment* and *traffic distribution* to the cells; *(ii) activation of the appropriate volume/type of functional/software components* needed to handle a given network situation; *(iii) allocation of functional components to the physical elements*. Nevertheless, effective solutions to guarantee deployment and to efficiently run the C-RAN architecture are needed. In this regard, further steps are needed in decoupling **data delivery from management & control** and decoupling **functionalities from the underlying hardware.**

This chapter discusses two enabling technologies for C-RAN that allow decoupling beyond baseband and radio, i.e., Software Defined Networking (SDN) and Network Function Virtualization (NFV). SDN is an emerging network architecture based on the idea of decoupling the control and data planes; SDN exploits a logically centralized network controller, which works in the control plane, handling the allocation of traffic to network elements in an isolated data plane. Moreover NFV foresees to implement the network function of a network device in a software package running in virtual container(s), e.g. virtual machine(s), to allow for network functions being decoupled from the hardware. The NFV introduces flexibility and allows quick installation/re-configuration of network functions by simply installing/upgrading software package(s). While picture of C-RAN system through SDN and NFV will be depicted, the pros and cons of these enabling technologies will also be thoroughly discussed in this chapter.

2. Software Defined Networking (SDN)

In traditional IP networks, the control and data planes are tightly coupled, i.e., control and data planes functionalities run on the same networking devices; this aspect is highlighted in Fig. 1. This was considered important for the design of the Internet in the early days: it seemed the best way to guarantee network resilience, which was a crucial design goal.

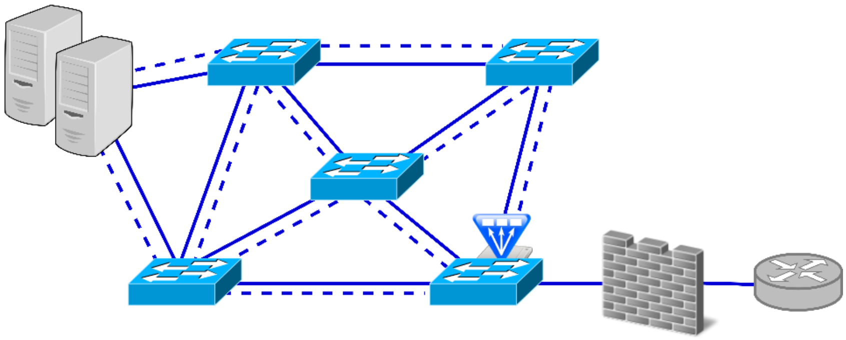

Figure 1. Conventional networking with coupled control\data planes

The main drawback of this coupled paradigm is a very complex and relatively static architecture as, for instance, addressed by Kim & Feamster (2013). A further issue is related to the network management, which is typically handled through a large number of proprietary solutions with their own specialized hardware, operating systems, and control programs. This involves high OPEX/CAPEX as operators have to acquire and maintain different management solutions and the corresponding specialized teams and this further involves long return on investment cycles and limits the introduction of innovation.

The *softwarisation* paradigm is useful to overcome above limitations as it introduces the following features:

- **Decoupling of control and data planes.** This means that control functionalities will be no longer handled by network devices that will act only as packet-forwarding units.
- **Per flow-based forwarding.** This means that all packets belonging to the same flow (identified through the sender/receiver addresses) receive identical service policies at the forwarding devices, instead of having per-packet routing decisions based only on the packet destination address.
- **Network Controller.** Control logic is moved to an external controller, which is a software platform that runs on commodity server technology and provides the essential resources and abstractions to facilitate the programming of forwarding devices based on a logically centralized, abstract network view. This allows to control the network by taking into consideration the whole state of the network.
- **Software-based network management.** The network is programmable through software applications running on top of the network controller that interacts with the underlying data plane devices. This allows a quick network reconfiguration and innovation.

The new network vision based on SDN, whose high-level architecture is depicted in Fig. 4, will allow to program in an easier way novel network functionalities as well as to optimize the network balancing as all applications can take advantage of the same network information (i.e., global network view). The switches in Fig. 4 are SDN network elements running OpenFlow and this allows them to receive information by the SDN controller to configure link parameters (bandwidth, queues, meters, etc.) as well as intra-network paths. As a consequence, Fig. 2 highlights that data and control planes are now decoupled as the control plane is removed from the physical links between the switches and it is instead managed by the SDN controller.

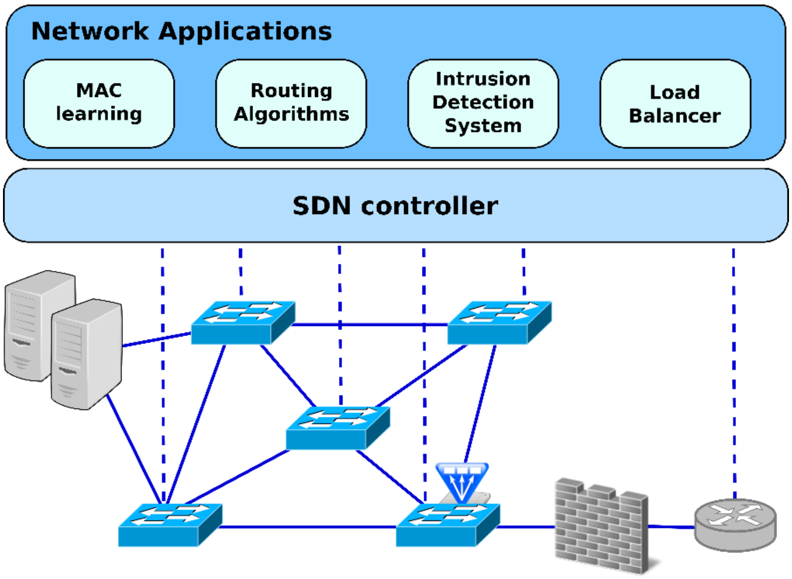

Figure 2. Software-defined networking with decoupled control\data planes

2.1 The SDN architecture

The SDN architecture is depicted in Fig. 3. Different components may be envisioned, which are presented in more detail in (Kreutz, Ramos, Esteves Verissimo, Esteve Rothenberg, Azodolmolky & Uhlig, 2015). In the remainder of this Section, we will provide a global overview of the SDN architecture.

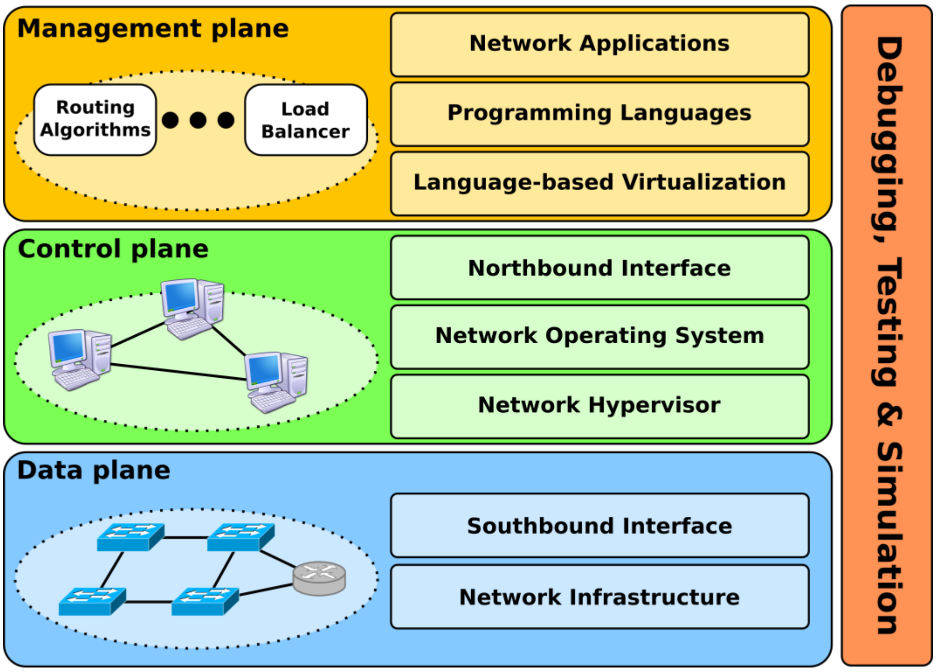

Figure 3. The SDN architecture with the related planes, layers and main entities

Entities. An SDN architecture is composed of two main elements, i.e., *forwarding devices* and *controllers*. The formers are hardware- or software-based elements handling packet forwarding, while a controller is a software stack running on a commodity hardware platform.

Planes. An SDN network is composed of three different planes. The *data plane (DP)* refers to the plane where devices are interconnected through wireless radio channels or wired cables. The *control plane (CP)* can be considered as the “network brain”, as all control logic rests in the applications and controllers, which form the control plane. Finally, the *management plane (MP)* deals with the set of applications that leverage functions such as routing, firewalls, load balancers, monitoring, and so on. Essentially, a management application defines the policies, which are ultimately translated to southbound-specific instructions that program the behavior of the forwarding devices.

Interfaces. SDN introduces the concept of *southbound interface (SI)*, which defines: *(i)* the communication protocol and APIs between forwarding devices and control plane elements and *(ii)* the interaction between control and data planes. Actually, OpenFlow is the most widely accepted and deployed open southbound standard for SDN; other solutions are gaining ground as alternative SI, such as ForCES, OVSDB, POF, OpFlex, OpenState, Revised Open-Flow Library (ROFL), Hardware Abstraction Layer (HAL), and Programmable Abstraction of Datapath (PAD). The *northbound interface (NI)* is a common interface exploited to develop applications, i.e., the NI abstracts the low-level instruction sets used by SIs to program forwarding devices. A common NI is still an open issue; it may still be a bit too early to define a standard NI, as use-cases are still being worked out.

2.2 Standardization Activities

The standardization landscape in SDN is already wide. The *Open Networking Foundation (ONF)* is considered as the member-driven organization aiming at promoting the adoption of SDN; the main contribution has been the development of the OpenFlow protocol. The *Internet Research Task Force (IRTF)*, has created the Software Defined Networking Research Group (SDNRG) that is currently investigating SDN in both short- and long-term activities, i.e., aiming at identifying the approaches that can be defined, deployed and used in the near term, as well as identifying future research challenges. Similarly, the *International Telecommunications Union's Telecommunication sector (ITU-T)* has already started to develop recommendations for SDN. The *Institute of Electrical and Electronics Engineers (IEEE)*, has started some activities to standardize SDN capabilities on access networks based on IEEE 802 infrastructure, for both wired and wireless technologies to embrace new control interfaces.

The *European Telecommunication Standards Institute (ETSI)* is working on the *virtualization* of SDN. ETSI considers softwarisation and virtualization as complementary features, as both share the goal of accelerating innovation inside the network through the introduction of programmability. Similarly, the 3rd Generation Partnership Project (3GPP) is studying the management of virtualized networks. The main aspects of network virtualization will be treated in the next Section.

2.3 Data and Control decoupling in the Mobile Network

It is also interesting to see the transition from fully coupled data and management/control plane in the mobile network to a relatively decoupled architecture. The LTE core network, i.e. the EPC, for the first time has a clear split into: *(i)* a packet-only data-plane, comprised of eNodeB, S-GW and PDNGW, and *(ii)* a management plane to manage mobility, policies and charging rules, comprised of MME, PCRF and HSS. Although the LTE architecture yields to easier management, it is still not as evolvable, flexible and programmable as can be. Furthermore and as mentioned before, the LTE design enforce significant increase to the backhaul load and to the signalling message, as discussed by Nokia Siemens (2012).

Introducing SDN in the mobile core network has been so far discussed through integration of software agents (possibly OpenVSwitch[1]), installed in all devices, that can be controlled by a SDN controller; examples can be found in (Amani, Mahmoodi, Tatipamula, & Aghvami, 2014) and (Errani, Mao, & Rexford, 2012). Introduction of these agents is

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[1] OpenVSwitch: An Open Virtual Switch, http://openvswitch.org.

mainly to maintain the logically centralized nature of the SDN-controller, with the distributed solution, inline with the today's mobile architecture design. Considering 2G, 3G and 4G networks are all simultaneously active in today's mobile network, a clean slate approach is not justifiable. To this end, introducing SDN within the existing operational mobile network is discussed by Mahmoodi & Seetharaman (2014), where management plane is retained and significant flexibility and programmability are introduced through a newly introduced control plane. Since the management plane could also potentially be software-defined, the control plane may, in the long term, subsume the functions offered by the management plane.

3. Network Function Virtualization (NFV)

The proprietary nature of existing hardware appliances as well as the cost of offering the space and energy for a variety of middle-boxes limits the time to market of new services into today's networks. The Network Function Virtualization (NFV) is a radical shift in the way network operators design and deploy their infrastructure which deals with the separation of software instances from hardware platform. The main idea behind the virtualization is that virtualized network functions (VNFs) are implemented through software virtualization techniques and run on commodity hardware (i.e., industry standard servers, storage, and switches), as shown in Fig. 4.

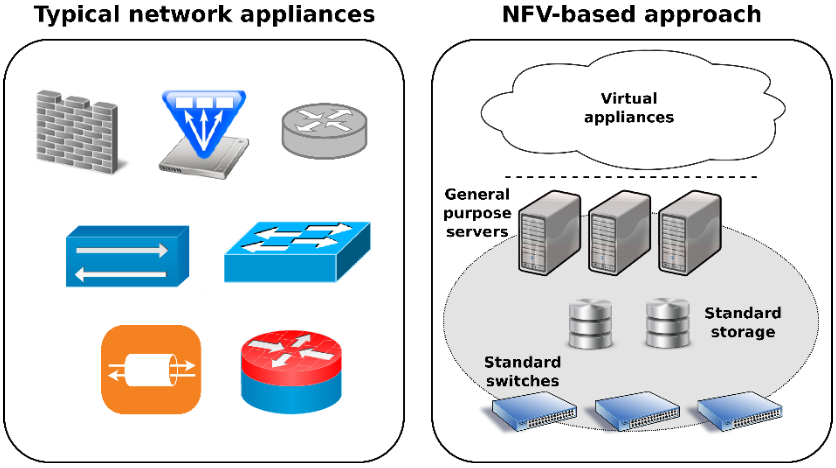

Figure 4. The network virtualization paradigm

The virtualization concept is expected to introduce a large set of benefits for telco operators: *(i)* capital investment reduction; *(ii)* energy savings by consolidating networking appliances; *(iii)* reduction in the time to market of a new services thanks to use of software-based service deployment; *(iv)* introduction of services tailored to the customer needs. Furthermore, the concept of virtualization and softwarisation are mutually beneficial and highly complementary to each other. For example, SDN can support network virtualization to enhance its performance and simplify the compatibility with legacy deployments.

3.1 Architecture

The NFV architecture, shown in Fig. 5, highlights the two major enablers of NFV, i.e., *industry-standard servers* and *technologies developed for cloud computing*. Being general-purpose servers, industry-standard servers have the key feature of a competitive price, compared to network appliances based on bespoke application-specific integrated circuits (ASICs). Using these servers may come in handy to extend the life cycle of hardware when technologies evolve (this is achieved by running different software versions on the same platform). Cloud computing solutions, such as various hypervisors, OpenStack, and Open vSwitch, enable the automatic instantiation and migration of VMs running specific network services.

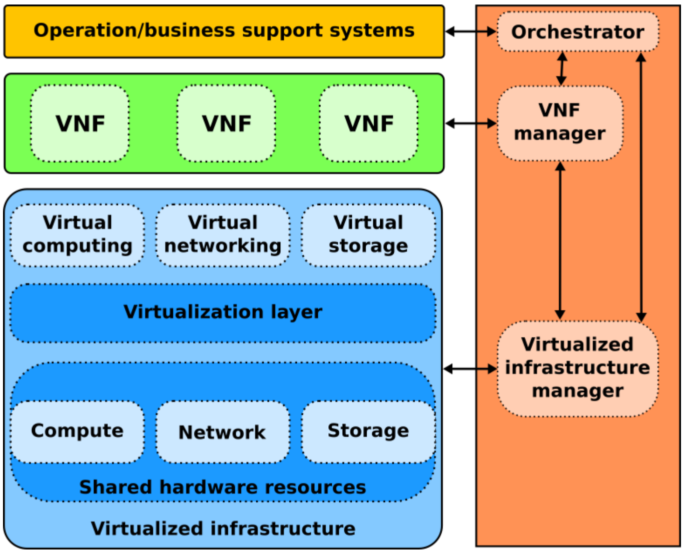

Figure 5. The NFV architecture

The NFV architecture is mainly composed of four different units. The first one is the *orchestrator*, which is responsible for the management and orchestration of software resources and the virtualized hardware infrastructure to realize networking services. The *VNF manager* has the following tasks: instantiation, scaling, termination, updating events during the life cycle of a VNF, supporting zero-touch automation. The *virtualization layer* is in charge for abstracting the physical resources and anchoring the VNFs to the virtualized infrastructure. The virtualization layer has the key role to ensure that the life cycle of VNFs is independent of the underlying hardware platforms: this is achieved through the use of virtual machines (VMs) and their hypervisors. Finally, the *virtualized infrastructure manager* has the role of virtualizing and managing the configurable computing, networking, and storage resources, and control their interaction with VNFs.

More details on the architecture of NFV can be found in (Han, Gopalakrishnan, Lusheng Ji, & Lee, 2015).

3.2 Reception by industries

Service providers have shown keen interest in NFV and this pushed IT companies to investigate different aspects of NFV realization. Leading vendors like Ericsson, Nokia, Alcatel-Lucent, and Huawei have already started to adopt and upgrade their equipment to support NFV (an example can be found in Ericsson, 2014). In addition, companies like HP have been working closely with Intel to optimize their software on Intel processors in order to achieve higher packet processing computations that enable softwarisation and virtualization on commercial off-the-shelf (COTS) platforms. To this aim, Intel has released the Data Plane Development Kit (DPDK) and has scheduled the release of a signal processing development kit in its software development roadmap.

4. The role of C-RAN in 5G systems

The traffic in mobile networks continues to grow and 5G systems need to face with unprecedented challenges in terms of *capacity*, i.e., simultaneous support of high-data rate traffic and very huge amount of devices. Indeed, according to Cisco (2014), a data traffic of about 24.3 exabytes per month is expected from high-end devices (e.g., smartphones, tablets) by 2019, while Ericsson (2011) predicts 50 billion of connected (machine and human) devices by 2020.

To cope with the above mentioned challenges, cell densification is attracting the interest of mobile network provider to offload data from the creaking traditional network and to extend the coverage (Andrews, Claussen, Dohler, Rangan, & Reed 2012). Nevertheless, the densification of coverage cells eases congestion in the radio access network (RAN) due to the larger number of BSs to be managed in a restricted area (Bhushan, Malladi, Gilmore, Brenner, Damnjanovic, Sukhavasi, Patel, & Geirhofer, 2014). Consequently, denser deployments bring new challenges in interference management and inter-cell coordination that dictate new approaches to properly manage such aspects.

The C-RAN has come to the fore as one of the key architecture concept for future 5G networks and beyond (Boccardi, Heath, Lozano, Marzetta, & Popovski, 2014). C-RAN represents a cost effective approach for addressing the increased density in the RAN.

4.1 C-RAN architecture

The main idea behind C-RAN is the *replacement of self-contained base stations* at each radio mast with shared/cloud-based processing and distributed radio elements. The C-RAN architecture is depicted in Fig. 6 and the related main components are:

- **Baseband processing units (BBUs)**, i.e., the pool of computing resources to provide the signal processing and coordination functionality required by all cells within the area;
- **Fronthaul**, i.e., optical fibre/wireless links carrying digitized representations of the baseband data ready for transmission in the RAN;
- **Remote Radio Heads (RRHs)**, i.e., light weight radio units and antennas that user equipment connects to via the RAN. RRHs can be used in place of any size of cell from macro down to femto and pico.

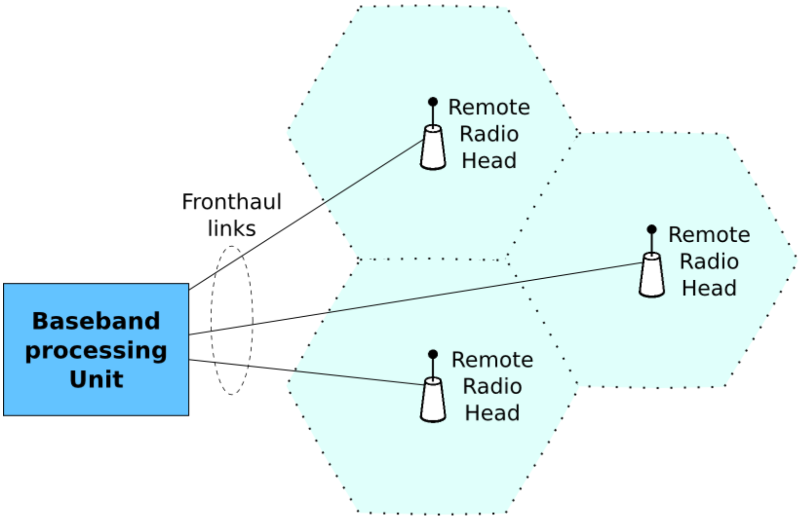

Figure 6. The C-RAN architecture with centralized baseband processing and remote radio heads

In this architecture, RRHs, potentially smaller in size compared to traditional base stations, can be located almost anywhere and not necessarily on a dedicated tower. The RRHs, therefore, need only the space for the antenna and access to any fronthaul link.

One of the key goals of the C-RAN architecture is achieving significantly easier inter-cell coordination given that management of RRHs in a given area is handled by a single BS pool, and communications occur directly within the pool.

4.2 Challenges, limitations and enabling technologies

The C-RAN paradigm offers lower costs and easier deployment of macro/small cells while it also enables simultaneous management of huge heterogeneity in the RAN. Nevertheless, the network's overall operation efficiency will continue to be limited by the signaling load between the radio access and the Evolved Packet Core (EPC) segments of the network.

The EPC, depicted in Fig. 7 and defined by 3GPP (2015), is entirely packet switched with all data sent using IP and is composed of the following entities:

- **Mobility Management Entity (MME)**, which handles mobility-related signaling;
- **Home Subscriber Server (HSS)**, which contains all information related to users and subscribers and provides supporting functionalities to the MME;
- **Policy and Charging Rules Function (PCRF)**, which decides the policies and charges each service/user flow;
- **Serving Gateway (SGW)**, which forwards/receives data to/from BSs and, in case of inter-BS handover, it acts as mobility anchor;
- **Packet Data Network Gateway (PDN-GW)**, which connects the EPC to external networks.

The EPC is currently facing a significant challenge in terms of signaling load when considering the deployment of small cells. Compared to 2G and 3G/HSPA, the 4G Long Term Evolution (LTE) results in a significantly higher signaling requirement per subscriber up to 42% compared to HSPA, according to Nokia Siemens (2012). Although a portion of this new signaling is required for new services and new types of devices, over 50% of the signaling is related to mobility and paging, due to the greater node density.

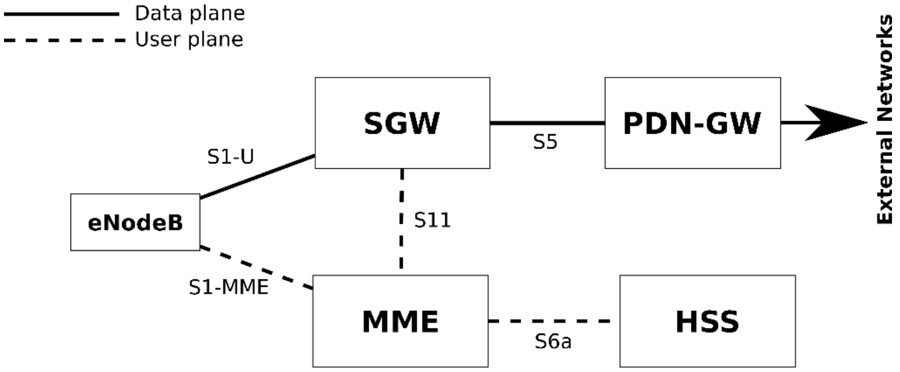

Figure 7. The existing 4G EPC architecture

To address the above considered issues, *softwarisation* and *virtualization* are gaining ground in the mobile networking ecosystem, particularly in conjunction with C-RAN (Chiosi, Clarke, Willis, Reid, Feger, Bugenhagen, & Sen, 2012). These two paradigms aim at introducing programmability in the mobile core with the main benefit in decoupling of the network control and management function from data forwarding, which takes place in the hardware (Granelli, Gebremariam, Usman, Cugini, Stamati, Alitska, & Chatzimisios, 2015). In this direction, significant works have gone to softwarise radio access functionalities and to allow their implementation in software packages running on generic processing hardware: this introduces the opportunity of saving cost and time during the re-configuration tasks of the network (Ganqiang, Caixia, Lingshu, & Quan, 2015). An example can be found in (Riggio, Marina, & Rasheed, 2014), where authors presented a software defined RAN (SDRAN) controller, where a Python SDK provides a framework to access to network resource information and scheduling transmissions independent of access technology.

In the remainder of this Chapter, we will focus on the main features of a software-based virtualized core network, by highlighting their role in introducing flexibility in the design of 5G systems.

5. The role of SDN and NFV for C-RAN deployments

The virtualization and softwarisation paradigms are gaining ground in the mobile networking ecosystem, particularly in conjunction with C-RAN (for instance, refer to Chiosi, Clarke, Willis, Reid, Feger, Bugenhagen, & Sen, 2012). In this field, great effort has gone into virtualizing radio access technology as this enables the virtualization of edge functions of the core network without incurring additional hardware costs. In the remainder of this Section, we will focus on the recent advances in the virtualization of mobile networks, with particular attention to C-RAN deployments.

5.1 Softwarization in the radio access

Sofwarization represents an important enhancement in the process towards effective C-RAN deployments by exploiting the novel features of SDN paradigm.

As for instance discussed by Arslan, M., Sundaresan, K., Rangarajan, S. (2015), the programmability of the SDN architecture allows the data plane to only deal with fast rule lookups and executes forwarding at fine timescales, whereas new rules can be pushed into longer timescales due to the latency involved in communicating with the controller. In this sense, a C-RAN architecture can be seen as a direct extension of SDN's control/data plane separation principle to the RAN where the C-RAN and SDN complements each other. As an example, Zaidi, Z., Friderikos, V., & Imran, M. A., (2015) proposed to handle control plane tasks such as radio resource management (RRM) or interference coordination logic in an SDN controller implemented in the C-RAN architecture in order to orchestrate the parameters of RRHs (data plane): in this case, SDN brings some benefits in terms of distributing the control information triggered by the C-RAN to the involved network entities. Another example is for instance the activation/de-activation of RRHs which is decided by the C-RAN according to network load and interference level; in this case, SDN updates the path configuration in order to guarantee reliable communication for the new activated RRHs or to optimize data paths when some RRHs are switched off.

Among aspect that needs to be properly highlighted is the role of SDN in managing the fronthaul link of C-RANs. Zaidi, Z., Friderikos, V., & Imran, M. A., (2015) investigated the benefits of SDN in providing APIs to the RRHs as well as to the core network. When considering in detail how to manage the fronthaul links, it is worth highlight that the C-RAN decouples the BBUs from the RRHs in terms of physical placement, but there is a one-to-one logical mapping between BBUs and RRHs. As analyzed by Sundaresan, K., Arslan, M., Y., Singh, S., Rangarajan, S., & Krishnamurthy, S. V. (2013), this notion of fixed one-to-one mapping can potentially limit the performance of C-RANs. For instance, mobile users require handovers when moving from one RRH to another one and in this scenario a one-to-many mapping on the fronthaul link could reduce the overhead and optimize network performance. : Another aspect to be taken into consideration is that, with the one-to-one mapping, several BBUs are active and generate frames (and thus consume energy in the BBU pool) even if an enhanced capacity may not be needed in all parts of the network or at all times. As an example, when the traffic load is low in a region (e.g., coverage area of multiple small cell RRHs), a single BBU may be enough to serve the offered load. The SDN paradigm may come in handy to introduce this flexibility in the fronthaul management by treating fronthaul links as network links. Sundaresan, K., Arslan, M., Y., Singh, S., Rangarajan, S., & Krishnamurthy, S. V. (2013) proposed a flexible C-RAN system for RRHs that is based on the introduction of an intelligent controller in the BBU pool that, similarly to an SDN controller, dynamically re-configures the fronthaul (at coarse time scales) based on network feedback to cater effectively to both heterogeneous user and traffic profiles. As a consequence, the amount of traffic demand satisfied on the RAN is maximized for both static and mobile users, while at the same time the compute resource usage in the BBU pool is optimized.

5.2 Virtualization in the radio access

The interest of service providers in virtualizing mobile base stations is growing as this allows to consolidate as many network functions as possible in a standard hardware: this introduces the opportunity of handling different mobile network technologies with a single virtualized base station.

The main challenge in the virtualization of mobile networks is related to the physical layer functionalities of the base stations. Consequently, virtualization is first considered for implementation in the higher network stack layers. As an example, ETSI (2013) is considering to introduce virtualization in the layer 3 and then in layer 2 of the base stations: layer 3 hosts the functionalities of the control and data plane that connect to the mobile core network while layer 2 hosts the packet data convergence protocol (PDCP), radio link control (RLC), and media access control (MAC) network functions.

The virtualization of layers 2 (which hosts the packet data convergence protocol, PDCP, radio link control, RLC, and media access control, MAC) and 3 (which implements the functionalities of control and data planes) provides the opportunity to offer a centralized computing infrastructure for multiple base stations. Finally, some effort to centralize the functionalities of layer 1 of several base stations are currently in progress aiming at supporting multiple telecommunications technologies and adapting them for new releases. This may allow the effective deployment of C-RAN networks as service providers will benefit from sharing their remote base station infrastructure to achieve better area coverage with minimum CAPEX and OPEX investment. A more detailed overview on the state of the art in the virtualization of mobile network can be found in (Hawilo, Shami, Mirahmadi, Asal, 2014).

The increases in signaling and more stringent latency requirements for inter cell cooperation are placing pressure on network providers which need to properly manage such issues, especially in the context of C-RAN in order to achieve the expected benefits of this technology. To this aim, Dawson, Marina, & Garcia (2014) proposed to isolate the EPC from the RAN in order to reduce both radio/core loads. Indeed, considering the legacy 4G deployments, all signaling information of a given flow is passed to the EPC and this presents a significant load if, for instance, a given user regularly moves between small cells or requires enhanced transmission schemes, such as Coordinated Multi-Point (CoMP) transmission, to improve its coverage at the cell edge. A possible solution to reduce this signaling is to allow integration at BS, in order to group several small cells. The idea proposed by Dawson, Marina, & Garcia (2014) is to exploit the C-RAN approach where macro BS are visible to the EPC whilst small cells are visible only to the BS. This approach is named *C-RAN BS*. In this way, mobility signaling due to transitions between the macro and small cells is handled at the BS; simultaneously, the EPC still maintains overall vision of user mobility.

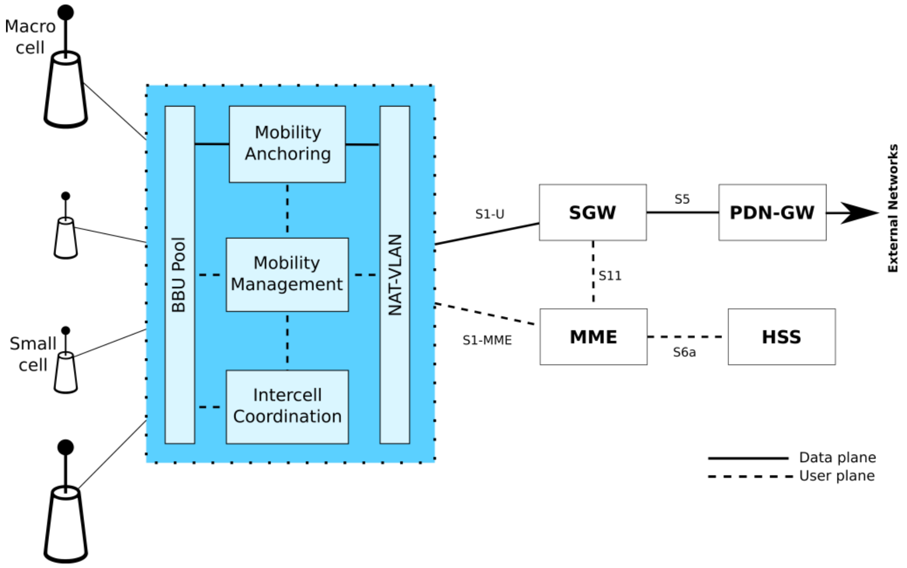

Figure 8. Virtualization in the C-RAN BS

The architecture enabling virtualization in the C-RAN is depicted in Fig. 8. The idea at the basis of the architecture proposed by Dawson, Marina, & Garcia (2014) is to extend the concepts of virtual local area networks (V-LANs) and network address translation (NAT), which have long been accepted features of the modern internet, to mobile networks. On the EPC side of the C-RAN BS, authors introduced two entities: *(i)* a VLAN controller that is responsible for grouping cells together as virtual cells; *(ii)* a NAT that will represent the virtual cells to the EPC as a single macro cell. The C-RAN BS will be in charge of performing different functions. It will act as a *mobility anchor*, in a similar way as the SGW acts in the EPC, to provide a static endpoint for communications as well as handovers between cells belonging to the same virtual cell. To further reduce the signaling with the use of C-RAN BS, it is also expected to have completely new user-centric protocols aiming at redefining the mobility management. In this scenario, the VLAN allows the EPC to continue to function without requiring knowledge of RAN changes due to user mobility.

Another element introduced in this architecture is an SD-RAN controller, which describes and provides the methods for polling all available resources available at connected cells. So doing, the C-RAN BS can ensure that only the minimum required resources are active at any time in the whole VLAN, instead of activating the minimum required resources in each cell. The SD-RAN controller would also provide slicing of the network resources to allow for RAN sharing between operators, in order to deploy and support multi-tenancy deployments which are attracting the interest of 5G research community as outlined for instance by Condoluci, Sardis, & Mahmoodi (2015).

5.3 Softwarization & virtualization in the mobile core

The mobile core network is the most important part of the network, and for this reason the virtualization of the mobile core represents the most investigated field in introducing virtualization and softwarisation in 5G.

The most recent core network is the evolved packet core (EPC), defined by 3GPP (2015) and discussed in Sec. 2.2 and 3.3. The EPC is a flat all-IP architecture designed to permit mobile broadband services and to support a variety of access technologies. To introduce virtualization in the mobile core, Hawilo, Shami, Mirahmadi, & Asal (2014) proposed to group the EPC's entities into different segments to achieve less control signaling traffic and less congestion in the data plane. In the first segment, the MME is migrated with the HSS front-end (HSS FE), which is an application that implements all the logical functionality of the HSS but does not contain the user information database. In particular, the HSS FE requests the user information from the user data repository (UDR, the central user information database) and stores these data temporarily in cache memory. This allows to run authentication and authorization processes internally, without any data transactions through the network but in a similar way as if the MME was accessing the complete HSS database. In the second segment, PDN-GW is migrated with the SGW with the aim to minimize the number of nodes processing data plane. Implementing both PDN-GW and SGW in one VM or VNF will benefit from centralized processing in the data plane. Finally, another segment is composed of the UDR, online charging system (OCS), and offline charging system (OFCS) which are migrated in the PCRF. The idea behind this migration is that the PCRF requests user information to generate the required policies for each established bearer; in this way, information exchange is no longer necessary and this minimizes the latency of policy function generation.

The benefits of grouping network entities are in terms of reduced amount of transactions among network entities. A numerical example is listed in Tab. I, which highlights the meaningful reductions in terms of transactions per second offered by the solution proposed by Hawilo, Shami, Mirahmadi, & Asal (2014) compared to legacy 4G deployments (as discussed by Nokia Siemens, 2012), while introduced benefits are listed in Tab. II.

	Signalling (transactions per second)	
Transactions between core elements	**Before grouping**	**After grouping**
MME, eNBs , and S-GW	175,322	175,332
S-GW and P-GW	56,559	0
MME and HSS	1,039,430	173,239
PCRF and P-GW	37,706	37,706
PCRF and UDR	18,853	0
PCRF and OCS	30,164	0
Total Traffic	1,358,044	386,277

Table I. Benefits of virtualization in terms of number of transactions

Entities	Benefits
• HSS FORNT END (HSS FE) • Mobility Management Entity (MME)	• Local interactions between HSS and MME • Fewer networking transactions through Vswitches
• Packet data network gateway (PGW) • Policy and charging enforcement function • (PCEF) • Serving gateway (SGW)	• Reduction in the number of nodes processing data plane • Reduction of data-forwarding • Improvements in data monitoring and charging
• User data repository (UDR) • Online charging system (OCS) • Offline charging system (OFCS) • Policy and charging rules function (PCRF)	• Reduced fragmentation • Local interaction between the PCRF and the UDR • Local interaction between OCS and PCRF • Central interaction point for OSS/BSS

Table II. Benefits introduced by virtualizing network entities

When considering the integration of C-RANs in the mobile core, Yang, C., Chen, Z., Xia B., & Wang, J., (2015) have analyzed the benefits offered by the joint use of virtualization and SDN by focusing on different aspects. As a first benefit, the authors have considered the traffic offload which can be beneficial to relief the load of the core network. In this scenario, virtualization is exploited to instantiate network functionalities such as PDN-GW in the C-RAN while SDN triggers path re-configuration of data traffic. Another example always focusing on how to relief the core network load is related to the caching (that can be in general both data and control functionalities caching) in the C-RAN. In this case, SDN can be useful to analyze the utilization of data links as well as to analyze the end-to-end paths while virtualization is useful to move the content from the PDN-GW to the C-RAN.

5.4 Major Research challenges

The design and the deployment of a software-based virtualized C-RAN architecture are still under investigation. The related challenges have been investigated in (Arslan, Sundaresan, Rangarajan, 2015), and are now summarized here:

- **Latency.** The main task of the fronthaul network is to deliver highly delay-sensitive signals to the RRHs. If we consider the LTE frame, novel signals need to be delivered to the RRHs every 1ms (i.e., the LTE's subframe duration); this becomes more challenging in 5G deployments expected to operate also with shorter subframes. This introduces latency challenges in the fronthaul network, especially in terms of switching procedures.
- **Communication protocol.** C-RANs are still evolving and there is no consensus on open APIs to send\receive data to\from the RRHs. An admissible trend should be the exploitation of protocols such as the Common Public Radio Interface (CPRI), commonly used to carry signals between the indoor and outdoor units of traditional base stations and tailored to be extended for the fronthaul network. However, integrating such protocols with switch operations and catering to low latencies is still a big challenge to be adequately investigated.

- **Electrical vs. optical switching.** The design and the deployment of proper switching solutions represent a key aspect to be taken into consideration as proper switching procedures involve several benefits in the whole C-RAN network. Optical switches may incur a longer reconfiguration time than electrical switches but are advantageous in terms of cost, power consumption, and being data rate agnostic (Farrington, Porter, Radhakrishnan, Bazzaz, Subramanya, Fainman, Papen, & Vahdat, 2010). These and other trade-offs such as operational cost and reliability need to be carefully evaluated before deciding on a particular technology.
- **Heterogeneity.** This challenged is due to the fact that the fronthaul interfaces may be composed of a mix of fiber, wireless, and copper links. This thus introduces the need of efficient integration strategies using the bandwidth from the available forms of physical fronthaul to support the logical configurations made by the controller.
- **Security.** SND/NFV-based systems should obtain a security level close to that of a proprietary hosting environment for network functions. Nevertheless, security attacks are expected to increase when implementing network functions in a virtualized environment. In addition to the hypervisor, which should be protected to prevent any unauthorized access or data leakage, other processes such as data communication and VM migration should run in a secure environment. Finally, the exploitation of APIs, exploited to provide programmable orchestration and interaction with its infrastructure, introduce a higher security threat to VNFs, as considered in (Cloud Security Alliance, 2013).
- **Reliability and stability.** Reliability is an important requirement for network operators as they need to guarantee the service reliability and service level agreements; this should not be affected when considering SND/NFV deployments. The challenges deal with the fact that the flexibility of service provisioning may require the consolidation and migration of VNFs according to the traffic load as well as the user demand and this may involve reliability degradations. Furthermore, network operators should be able to move VNF components from one hardware platform onto a different platform, which consequently may introduce delays, while still satisfying the service continuity requirement.
- **SDN controller.** The exploitation of SDN in wireless networks introduces new challenges for the SDN controller that needs to orchestrate and manage the control plane of the network by taking into account a radio access system composed of several base stations; this exacerbates the issues in terms of load balancing and traffic/mobility management.

6. Conclusions

In this Chapter, we highlighted how current trends in the development of the RAN cannot be supported by the existing 4G core infrastructure. We further illustrated that the deployment of C-RAN still needs to handle several challenges, such as high signalling overhead and increasing demands for low latency which still affect the network in case of centralized intelligence.

We have discussed the benefits introduced by virtualization and softwarisation paradigms in the network design of next-to-come 5G systems, and we discussed about the role of these two novel paradigms as enablers for the deployment of C-RAN. We summarized the state of the art in exploiting virtualization and softwarisation for C-RAN and, finally, we provided the related research challenges and outlined the future research trends.

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Reference

3GPP, (2015). Network Architecture. Technical Specification 23.002.

Amani, M., Mahmoodi, T., Tatipamula, M., & Aghvami, H. (June 2014). *Programmable policies for Data Offloading in LTE Network*. Paper presented at the IEEE International Conference on Communications, Sydney, Australia.

Andrews, J.G., Claussen, H., Dohler, M., Rangan, S., & Reed, M.C. (2012). Femtocells: Past, Present, and Future. *IEEE Journal on Selected Areas in Communications,* 30(3), 497-508. doi: 10.1109/JSAC.2012.120401

Arslan, M., Sundaresan, K., Rangarajan, S. (2015). Software-defined networking in cellular radio access networks: potential and challenges. *IEEE Communications Magazine*, 53(1), 150-156. doi: 10.1109/MCOM.2015.7010528

Bhushan, N.J. Li, Malladi, D., Gilmore, R., Brenner, D., Damnjanovic, A., Sukhavasi, R., Patel, C., & Geirhofer, S (2014). Network densification: the dominant theme for wireless evolution into 5G. *IEEE Communications Magazine*, 52(2), 82–89. doi: 10.1109/MCOM.2014.6736747

Boccardi, F., Heath, R., Lozano, A., Marzetta, T., & Popovski, P. (2014). Five disruptive technology directions for 5G. *IEEE Communications Magazine*, 52(2), 74–80. doi: 10.1109/MCOM.2014.6736746

Chiosi, M., Clarke, D., Willis, P., Reid, A., Feger, J., Bugenhagen, M., & Sen, P. (October 2012). *Network functions virtualisation: An introduction, benefits, enablers, challenges and call for action*. Paper presented at the SDN and OpenFlow World Congress, Darmstadt, Germany.

Cisco (2014). Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013-2018. White Paper.

Cloud Security Alliance, (2013). The Notorious Nine Cloud Computing Top Threats in 2013. White paper.

Condoluci, M., Sardis, F., & Mahmoodi, T., (October 2015) *Softwarization and Virtualization in 5GNetworks for Smart Cities*. Paper presented at the EAI International Conference on cyber physical systems, IoT and sensors networks, Rome, Italy.

Dawson, A.W., Marina, M.K., & Garcia, F.J (September 2014). *On the Benefits of RAN Virtualisation in C-RAN Based Mobile Networks*. Paper presented at the Third European Workshop on Software Defined Networks, Budapest, Hungary.

Ericsson (2011). More than 50 billion connected devices. White Paper.

Ericsson (2014). Telefonica and Ericsson Partner to Virtualize Networks. White Paper.

Errani, L., L., Mao, Z., M., & Rexford, J. (October 2012). *Towards Software-Defined Cellular Networks*. Paper presented at the European Workshop on Software Defined Networking, Washington, DC, USA.

ETSI (2013). Network Function Virtualization: Use Cases. White Paper.

Farrington, N., Porter, G., Radhakrishnan, S., Bazzaz, H.H., Subramanya, V., Fainman, Y., Papen, G., & Vahdat, A. (October, 2010). *Helios: a hybrid electrical/optical switch architecture for modular data centers*. Paper presented at the ACM SIGCOMM, New York, NY, USA.

Ganqiang, L., Caixia, L., Lingshu, L., & Quan, Y. (September 2015). *A Dynamic Allocation Algorithm for Physical Carrier Resource in BBU Pool of Virtualized Wireless Network*. Paper presented at the International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery, Xi’an, China.

Granelli, F., Gebremariam, A. A., Usman, M., Cugini, F., Stamati, V., Alitska, M., & Chatzimisios, P. (2015). Software defined and virtualized wireless access in future wireless networks: scenarios and standards. *IEEE Communications Magazine*, 53(6), 26-34. doi: 10.1109/MCOM.2015.7120042

Han, B., Gopalakrishnan, V., Lusheng Ji, L., Lee, S. (2015). Network function virtualization: Challenges and opportunities for innovations. *IEEE Communications Magazine*, 53(2), 90-97. doi: 10.1109/MCOM.2015.7045396

Hawilo, H., Shami, A., Mirahmadi, M., Asal, R. (2014). NFV: state of the art, challenges, and implementation in next generation mobile networks (vEPC). *IEEE Network*, 28(6), 18-26, doi: 10.1109/MNET.2014.6963800

Kim, H., & Feamster, N. (2013). Improving network management with software defined networking. *IEEE Communications Magazine*, 51(2), 114-119. doi: 10.1109/MCOM.2013.6461195

Kreutz, D., Ramos, F.M.V., Esteves Verissimo, P., Esteve Rothenberg, C., Azodolmolky, S., & Uhlig, S. (2015). Software-Defined Networking: A Comprehensive Survey. *Proceedings of the IEEE*, 103(1), 14-76. doi: 10.1109/JPROC.2014.2371999

Mahmoodi, T., & Seetharaman, S. (2014). Traffic Jam: Handling the Increasing Volume of Mobile Data Traffic. *IEEE Vehicular Technology Magazine*, 9(3), 56-62. doi: 10.1109/MVT.2014.2333765

Nokia Siemens (2012). Signalling is growing 50% faster than data traffic. White Paper.

Riggio, R., Marina, M., & Rasheed, T., (September 2014). *Programming software-defined wireless networks*. Paper presented at the ACM Annual International Conference on Mobile Computing and Networking, Hawaii.

Sundaresan, K., Arslan, M., Y., Singh, S., Rangarajan, S., & Krishnamurthy, S. V. (September 2013). *FluidNet: a flexible cloud-based radio access network for small cells*. Paper presented at the 19th annual international conference on Mobile computing & networking, New York, NY, USA.

Yang, C., Chen, Z., Xia B., & Wang, J., (November 2015). When ICN meets C-RAN for HetNets: an SDN approach. *IEEE Communications Magazine*, 53(11), 118-125. doi: 10.1109/MCOM.2015.7321980

Zaidi, Z., Friderikos, V., & Imran, M. A., (March 2015). Future RAN Architecture: SD-RAN Through a General-Purpose Processing Platform. *IEEE Vehicular Technology Magazine*, 10(1), 52-60. doi: 10.1109/MVT.2014.2380632

Authors’ contact information

Massimo Condoluci
Centre for Telecommunications Research
Department of Informatics
King’s College London
Strand Building, Strand Campus, London (UK)
email: massimo.condoluci@kcl.ac.uk

Toktam Mahmoodi
Centre for Telecommunications Research
Department of Informatics
King’s College London
Strand Building, Strand Campus, London (UK)
email: toktam.mahmoodi@kcl.ac.uk

Giuseppe Araniti
DIIES Department - ARTS Laboratory
University Mediterranea of Reggio Calabria
Via Graziella Loc. Feo di Vito, 89100 Reggio Calabria (Italy)
email: araniti@unirc.it

Massimo Condoluci is currently post-doctoral research associate at the Centre for Telecommunications Research, Department of Informatics, King’s College London, UK. He received the M.Sc. degree in Telecommunications Engineering and the Ph.D. in Information Technology in 2011 and 2016, respectively, from the University Mediterranea of Reggio Calabria, Italy. His main current research interests include softwarisation, virtualization, mobility management, group-oriented and machine-type communications over 5G systems.

Toktam Mahmoodi is currently Lecturer in Telecommunications at Department of Informatics, King's College London. She was visiting research scientist with F5 Networks, in San Jose, CA, in 2013, post-doctoral Research Associate in the ISN research group at Electrical and Electronic Engineering department of Imperial College during 2010 and 2011, and Mobile VCE researcher from 2006 to 2009. She worked on European FP7 and EPSRC projects aiming to push the boundaries of the next generation mobile communications forward. She has also worked in mobile and personal communications industry, from 2002-2006, and in an R&D team on developing DECT standard for WLL applications. She has a BSc. degree in Electrical Engineering from Sharif University of Technology, Iran, and a PhD degree in Telecommunications from King's College London, UK.

Giuseppe Araniti is an Assistant Professor of Telecommunications at the University Mediterranea of Reggio Calabria, Italy. From the same University he received the Laurea (2000) and the Ph.D. degree (2004) in Electronic Engineering. His major area of research includes personal communications systems, enhanced wireless and satellite systems, traffic and radio resource management, multicast and broadcast services, device-to-device and machine-type communications over 4G/5G cellular networks.