A Modern Architectural View Based upon Enhancements of the SESAME Innovative Approach

Ioannis P. Chochliouros[1], Ioannis Giannoulakis[3],
Evangelos Sfakianakis[1], Alexandros Kostopoulos[1],
Anastasios Kourtis[3], Dimitrios Arvanitozisis[2],
Anastasia S. Spiliopoulou[2], Maria Belesioti[1]
[1]OTE, Research Programs Section-Fixed
[1,2]Hellenic Telecommunications Organization S.A. (OTE)
Maroussi-Athens, Greece
[1]*{ichochliouros, esfak, alexkosto, mbelesioti}@oteresearch.gr*
[2]*{darvanito, aspiliopoul}@ote.gr*
[3]NCRS “Demokritos”, Greece
{giannoul, kourtis}@iit.demokritos.gr

Pouria-Sayyad Khodashenas[4], Jose Oscar Fajardo[5],
Athanassios Dardamanis[6], Javier Garcia Llloreda[7],
Emmanouil Kafetzakis[8], Jordi-Perez Romero[9]
[4]i2CAT, Spain *pouria.khodashenas@i2cat.net*
[5]UPV/EHU, Spain *joseoscar.fajardo@ehu.es*
[6]SmartNet S.A., Greece *ADardamanis@smartnet.gr*
[7]ATOS Spain, *javier.garcial@atos.net*
[9]ORION Innovation Private Company, Greece
mkafetz@orioninnovations.gr
[10]UPC, Spain *jorperez@tsc.upc.edu*

***Abstract*—The SESAME 5G-PPP project targets innovations in three fundamental 5G areas such as the “placement” of network intelligence and applications in the network edge through NFV and cloud computing, the substantial evolution of the Small Cell concept and the consolidation of multitenancy in modern communications infrastructure. A dedicated architecture has been proposed for that purpose. In the present work and taking onto account recent challenges, we discuss latest innovations and/or potential updates of the corresponding architecture, in specific areas covering the SC-Common VNF as fun-in/fun-out module, the progress in SESAME Small Cell functional splits, the placement of “Self-x” features and wireless backhauling. Moreover, we proceed further and analyse the functional description of the related architectural components, in order to promote future improvements.**

Keywords—5G; Cloud-enabled Small Cell (CESC); Network Functions Virtualization (NFV); Multitenacy; “Self-x” properties; Small Cell (SC); VNF (Virtual Network Function).

I. INTRODUCTION

The transition towards the realization of the much promising “5G era” implicates for a multiplicity of challenges and opportunities for the electronic communications market sector. In this context, the actual EU-*funded* SESAME project (GA No.671596) promotes the concept of the Small Cells (SCs) virtualization and their utilisation and partitioning into logically isolated “slices”, offered to multiple operators-tenants. The main aspect of this innovative feature which is referred to as “*multitenancy*” is about the capability to “accommodate” multiple operators under the same infrastructure, by satisfying the profile and requirements of each operator separately, thus creating opportunities for further market growth [1]. Moreover, NFV (Network Functions Virtualization) permits virtualization of software-*based* network functions, which implicates for a multiplicity of network-related benefits: in fact, instead of installing and managing dedicated hardware devices for networking and servicing functions, these are realized as “software components” and deployed on commodity or special hardware infrastructures. Network elements are thus expected to become “computing equivalent” equipment that gathers programmable resources, interfaces and functions, based on virtualisation technologies. Thus, NFV improves elasticity in provisioning network services while, *simultaneously*, enhancing scalability and reducing time to market [2]. To further enhance the virtualisation capabilities of the Small Cell deployment, so that to include not only network capacity resources but also edge processing capabilities, a micro-scale virtualised execution infrastructure is proposed by SESAME, in the form of a “Light Data Centre” (Light DC). The Light DC concept will be considered to build a clustered infrastructure with high manageability and will be optimised to reduce power consumption, cabling, space and cost [19].

A. The SESAME-based Approach

The architecture provided so far by the SESAME project (see Fig.1, and [19]), acts as a “*solid reference point*” for 5G multi-tenant small cell infrastructures with mobile edge computing (MEC) capabilities.

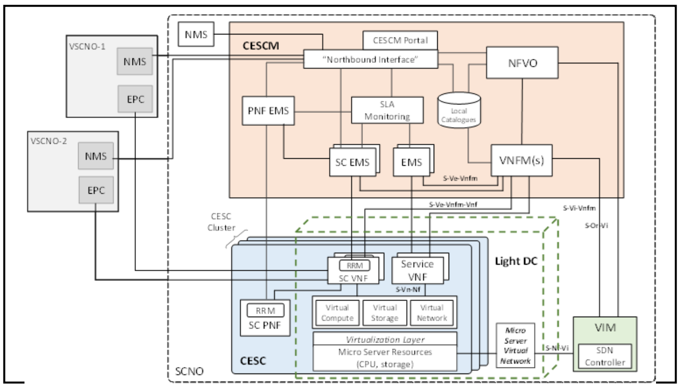

Fig. 1. SESAME essential architecture and component’s interactions

It combines the current 3GPP ("The Third Generation Partnership Project") framework for network management in RAN (Radio Access Networks) sharing scenarios and the ETSI NFV framework [2] for managing virtualised network functions. The Cloud-Enabled Small Cell (CESC) offers virtualised computing, storage and radio resources and the CESC cluster is considered as a cloud from the upper layers. This cloud can also be "sliced" to enable multi-tenancy. The execution platform is used to support VNFs (Virtual Network Functions) that implement the different features of the Small Cells, as well as to support the mobile edge applications of the end-users.The SESAME project develops the concept of Small Cell as-a-Service (SCaaS), which leverages on the separation between traditional market roles, with the aim of maximising the opportunities offered by opening SCs to multi-tenancy. This latter concept in opposition to typical mobile operators who deploy their own network infrastructure in competition with others, encourages both traditional and new market entrants to "share the infrastructure". In this case, operators can differentiate based on their service offers rather than on network connectivity. This flexible and dynamic system allows operators to reduce CAPEX and OPEX as required in the next generation of mobile networks [4].

II. RECENT INNOVATIONS AND UPDATES IN THE SESAME ARCHITECTURE

A. Conceptual Approach

The most important innovations proposed in the SESAME architecture focus upon the novel concepts of virtualising Small Cell networks by leveraging the paradigms of a multi-operator (multi-tenancy) [5] enabling framework coupled with an edge-*based*, virtualised execution environment ([6], [7]). SESAME falls in the scope of these two principles and promotes the adoption of Small Cell multi-tenancy [8]; that is, multiple network operators will be able to use the SESAME platform, each one using his own network "slice". Moreover, the main idea is to endorse the deployment of SCs with some virtualized functions, with each SC containing also a micro-server through appropriate fronthaul technology [9]. A micro-server is based on a non-x.86 architecture using 64-bit ARMv8 technology. Together with the SC, they "form" the Cloud-Enabled Small Cell and a number of CESCs form the "CESC cluster" capable to provide access to a geographical area with one or more operators [10].

The overall SESAME system architecture is as shown in Fig.1 and foresees the split of the SC physical and virtual network functions [11], respectively Physical Network Function (PNF) and VNF (Virtual Network Function), based on the Multi-Operator Core Network (MOCN) requirements and associated Radio Resource Manager (RRM) and Operations and Management (OAM) features, which need to be supported. Also within the related architecture's scope is to identify, model and analyse security issues [12] from the early stages of system design and software development, as well as to model and analyse threats and vulnerabilities [13] in existing software and protocols [14] that will be used in the SESAME system. Moreover, the SESAME project proposes a micro-scale virtualized execution infrastructure in the form of a Light DC [15] to enhance the virtualization capabilities of the Small Cell deployment, providing high processing power at the network edge. The Light DC concept [16] which encompasses the micro-servers of the different CESCs in a cluster, provides a high manageable architecture optimized to reduce power consumption, cabling, space and cost. To achieve these requirements, it relies on an infrastructure that aggregates and enables sharing of computing, networking and storage resources available in each micro-server belonging to the CESC cluster. The Light DC infrastructure also provides the backhaul [17] and fronthaul [18] resources for guaranteeing the requirements for connectivity in case of multi-tenancy scenarios. The hypervisor computing virtualization extensions enable access of virtual machines to the hardware accelerators for providing an execution platform that can support the deployment of VNFs. Different types of VNFs can be deployed through the Virtual Infrastructure Manager (VIM), for carrying out the virtualization of the Small Cell, for running the cognitive/"Self-x" management operations ([19], [20]) and for supporting computing needs for the mobile edge applications of the end-users. The combination of the proposed architecture allows achieving an adequate level of flexibility and scalability in the edge cloud infrastructure [21]. Finally, the CESC Manager (CESCM) is a component with an overall knowledge of the virtual and physical resources, responsible for the deployment, monitoring, configuration and orchestration of the Light DC cloud environment and radio access functionalities, over a single/multiple CESC cluster(s) with a minimum cluster size of one CESC. The main challenge to address is to design a uniform platform where the radio access management task (e.g. transmission power control, packet scheduling, handover and cell reselection thresholds, etc.) and NFV management responsibilities (e.g. VNF/service instantiation, lifecycle management, policy management, etc.) can be handled in an orchestrated way [22].

B. Evolutionary Steps of the Main Architecture

From the perspective of the high level architecture, the main SESAME evolutions are related to the detailed functionality of the CESCs and described as follows, *per case*.

Evolution 1 – SC-Common VNF as fun-in/fun-out module: SESAME has previously specified [23] the functional split of the SC in physical functions (SC PNF) and virtualised functions (SC VNF). Further design decisions have led to the introduction of a new functional entity, named SC-Common VNF (SC-C-VNF). The SC-C-VNF can be seen as "*one of the virtualised SC VNF functions*", but for clarity reasons it has been decided to define it as "*a new element in the SESAME architecture that resides between the SC PNF and the different SC VNFs*". With this design decision, there is a unique SC-C-VNF per CESC, which performs control-plane multiplexing and coordination functions from the SC-PNF to the virtualised world. Each SC-VNF supports a single VSC Network Operator (VSCNO) and maintains its own control and user plane connections to the VSCNO's core network. This design enables a flexible functional split for the SC. Depending on different parameters (e.g., fronthaul capacity [24], processing power, business decisions, etc.), one SC could implement a higher level functional split while others could go for a lower level functional split. The essential SESAME CESC design provides a good basis for prototype-*oriented* and research-*oriented* activities in the framework of the entire project effort.

Evolution 2 – Progress in SESAME Small Cell functional splits: SESAME has progressed in the definition of the SC functional split ([25], [26]). Although this has not a direct impact on the high level architecture components, it has an impact on the definition of the interfaces between the SC PNF, the SC-C-VNF and the SC VNF components. Two alternative functional splits are addressed as follows: (i) S1-level functional split, *and*; (ii) RLC (Radio Link Control) – MAC (Medium Access Control) functional split [27]. Each one implicates a series of capabilities and requirements (related to the underlying resources needed). The former functional split is considered for the SESAME intended proof-of-concept (PoC) and the latter for research and prototyping activities.

Evolution 3 – Placement of "Self-x" features: The analysis of different "Self-x" functionalities has leaded to the specific identification of the most convenient components to support these functionalities ([28], [29]). The design decisions do not implicate a modification of the high-level architecture, since the different alternatives are supported at different functional elements. Centralised "Self-x" features are supported at CESCM level though the SC VNF EMS (Element Management System) and SC PNF EMS modules. Distributed "Self-x" features are supported at CESC level though the SC VNF and SC PNF modules.

Evolution 4 – Wireless backhauling: In the original approach of the SESAME Architecture [23], the CESC Cluster has been established by means of wired connections between the different CESCs. As an evolution to support a wider range of deployments and enhanced resiliency models, it has been introduced the possibility of connecting the different CESCs through wireless links. In this way, the different CESCs in the cluster can be connected in an *ad-hoc* way, and enabling one or several of them to serve as providers for the backhaul connection [30] to the vEPCs (virtualised Evolved Packet Cores). In order to cope with the SESAME requirements, the wireless fronthauling/backhauling system is designed to support multi-tenancy and is driven by SDN (Software-Defined Radio) operations [31], allowing the implementation of SDN rules [32] based on different metrics such as wireless link quality, processing capacity, etc. [33]. From a high level architecture standpoint, the wireless fronthauling/backhauling system resides at the same level than the wired system, while the SDN Controller resides at the VIM level since the VIM is the component in charge of managing the consolidated set of resources in a CESC Cluster.

III. FUNCTIONAL DESCRIPTION OF UPDATED SESAME ARCHITECTURAL COMPONENTS

In the following paragraphs we discuss, one-by-one of the previously identified evolutionary steps of the main SESAME-*based* architecture and we focus upon the functional description of their corresponding architectural components.

The SC-C-VNF as fun-in/fun-out module: The SC-Common VNF as a helper function was introduced in [23] and expanded in [34]. The top-level functionality described in [35] is largely unchanged, consisting of the following: 1) S1 Multiplexer: (i) Accepts a single S1 connection request from the PNF; (ii) creates up to six S1 connections to each SC-VNF; (iii) routes S1 messages from the PNF to the appropriate SC-VNF (and vice-versa*), and; (*iv) performs a small amount of identity translation, *and; 2)* Cell-wide Admission Control in the Virtualised domain. As described in [31], the SC-Common VNF likewise performs cell-wide admission control with regard to the number of User Equipments (UEs) permitted.

A change from the architecture previously described in [36] is that the SC-Common VNF no longer performs management of the front-haul bandwidth across each of the connected SC-VNFs. This function has been moved into each individual SC-VNF, which is now self-policing. This change has simplified the implementation by removing the need for a separate interface between the SC-Common VNF and each SC-VNF. As described in [37], it was considered too complicated for the configuration and fault management of the SC-Common VNF and a more lightweight option was explored.

The SC-VNF was introduced in [36] and expanded upon in [34]. The top-level functionality described in [36] is largely unchanged, consisting of the following features and/or "components": (i) Traffic shaping; (ii) Tenant-specific AC (Admission Control) based on limits applied to the specific tenant; (iii) GTP (GPRS Tunnelling Protocol) TEID (Tunnel Endpoint Identifier) Management within the CESC; (iv) Congestion control via blind handover (not supported by the PoC demo); (v) DSCP (Differentiated Services Code Point) marking per QCI (QoS Class Identifier) – (not supported by the PoC demo), *and*; (vi) S1AP (Application Protocol) routing to and from the Core Network (CN). As described above, the SC-VNF now polices its own fronthaul bandwidth utilisation. This is based upon two configurable parameters: *Max Uplink Bandwidth* and *Max Downlink Bandwidth*. Fronthaul bandwidth utilisation is controlled in two ways: (i) A new Guaranteed Bit Rate (GBR) bearer is not admitted if, by so doing, *Max Uplink Bandwidth* or *Max Downlink bandwidth* would be exceeded, *and*; (ii) The SC-VNF continuously monitors the current bandwidth in use by the virtual cell across all bearers and, *if necessary*, discards packets for non-GBR bearers in order to bring the total throughput within the configured limit. In addition, the SC-VNF is configured with a per-tenant limit, *Max UEs*, which defines the maximum number of concurrently active UEs that it supports. Thus, for UE admission, control is exerted at two levels: (i) If the total configured capacity of the cell as a whole has been reached, the SC-Common VNF rejects a new user admission regardless of whether or not the VSCNO's individual limit has been reached, and; (ii) If admitted by the SC-Common VNF the SC-VNF will reject a new user if the maximum capacity allocated to the associated VSCNO has been reached. Similar behaviour applies to bearer admission where the SC-Common VNF monitors the cell as a whole and the SC-VNF polices a VSCNO's individual share.

Functional Split: The work included in [23], [34] and [36] have already surveyed the possible type of functional splits which have been advocated in different fora, with specific attention to the Small Cell Forum (SCF) activities. In this regard, also 3GPP has recently realised studies and promoted proposals regarding functional split options and so, requirements have been submitted (such as, *inter-alia*, those in [38], [39]). For the next generation of virtualized small cells, the studies made by 3GPP have begun in *Release 1* (which comprises of around 170 high-level features and studies) and fall within the activities towards completion of *Release 1*, and are part of the wider work on virtualisation of the Radio Access Network (RAN). For the sake of completeness, the possible functional splits are: above the Packet Data Convergence Protocol (PDCP), between the PDCP and the RLC and between the RLC and the MAC. This latter split is further differentiated between the separation between high-MAC and low-MAC. The last functional split is focused on the Physical (PHY) layer, distinguishing also in this case between high-PHY and low-PHY. It is known that each of the functional splits carries *pros and cons*, with more or less stringent requirements in terms of aggregate data rate and latency. It is worth reminding that due to the functional split, the protocol stack is divided in central and remote small cell functions. The central function is the part of the protocol stack subject to virtualization, which is hence implemented as VNF (or a chain of VNFs), whereas the remote function is referred to as PNF. One central VNF can be connected to multiple remote PNFs provided that the required timing and throughput constraints are fulfilled for a given functional split. The link between a SC VNF and the SC PNF is called the *fronthaul*, whereas the link between the central VNF and the vEPC is called the *backhaul*.

The initial choices taken from the point of view of the SESAME project have been partially addressed in [34] and [36]. The overall SESAME architecture can "suit well" different type of functional splits, bearing in mind that a functional split at the MAC layer (high or low), as well as at the PHY layer (high or low) are the most demanding in terms of latency and aggregated throughput requirements between VNF and PNF. Indeed, scheduling of Resource Blocks (RBs) occurs every Transmission Time Interval (TTI) or, in other words, every 1 ms therefore carrying computational intensive tasks depending also upon the number of connected UEs. On the other hand, baseband processing usually involves complex operations that can drain a significant amount of computing power. In the context of SESAME, the "atomic" network component, (that is, "the CESC"), is the junction of a small cell and a micro-server computing node through the logical S1 interface (VNF-PNF connection). The collection of several CESCs constitutes the edge cloud environment developed by SESAME, referred to as "the CESC cluster" with the cloud of interconnected micro-servers that identify the local exemplification of the Light DC. Since one of the most important objectives of SESAME is to deliver a cost-effective solution, the MAC/PHY functional split might add a high load to the micro-server environment. Indeed, a micro-server connected to a small cell is a one-to-one relation between them. In this regard, small cell VNFs should be executed over a single micro-server with the addition of service VNFs that can better exploit the edge-cloud environment.

Referring to [40], service VNFs include virtualised video transcoding unit (vTU), virtualised Deep Packet Inspection (vDPI), virtualised context aware routing (vCAR) and virtualised caching (vCaching). On the other hand, small cell VNFs depend on the particular type of functional split adopted. It is anyway important to mention that small cell VNFs are most likely to be deployed within the same micro-server for each CESC. Independently of the specific functional split, the virtualised small cell has to be able to manage the multi-tenant environment and the S1 incoming/outgoing traffic on a per tenant basis (i.e., VSCNO). Besides the micro-server constraints, the medium used to implement the S1 interface is the first real bottleneck. In this regard, the work in [40] has addressed already the core requirements for each VNF and the achievable performance depending on the implementation solution for the S1 interface (e.g. optical fibre or copper). From an implementation standpoint, two functional splits are under research in SESAME considering that a hybrid Light DC environment will be composed of the interconnection of different micro-server technologies: ARM-*based* and x.86-*based*. Specifically, for the ARM-*based* technology the NXP platform LS2085A Reference Board [41] and the STM platform (ST Barcelona Reference Board) [42] will be included as computing nodes. Hereinafter, the two types of functional split researched within SESAME and candidate to implementation and demonstration are discussed.

"Self-x" Functionalities: The "Self-x" or Self-Organizing Network (SON) functionalities in the context of SESAME were categorized and explained in [23] and further elaborated in [34]. However, the initial SESAME architecture of [23] did not "depict" them explicitly. In this respect, Fig.2 presents an update of the SESAME architecture that includes these functionalities. As shown in Fig.3, the PNF EMS and SC EMS include the centralised "Self-x" functions (cSON) and the centralised components of the hybrid SON functions. In turn, the dSON functions - or the decentralised components of the hybrid functions - reside at the CESCs. Concerning the dSON functions, they can be implemented as a PNF or, if proper open control interfaces with the element (e.g. the RRM function) controlled by the "Self-x" function are established, they can also be implemented as a VNFs running at the Light DC.

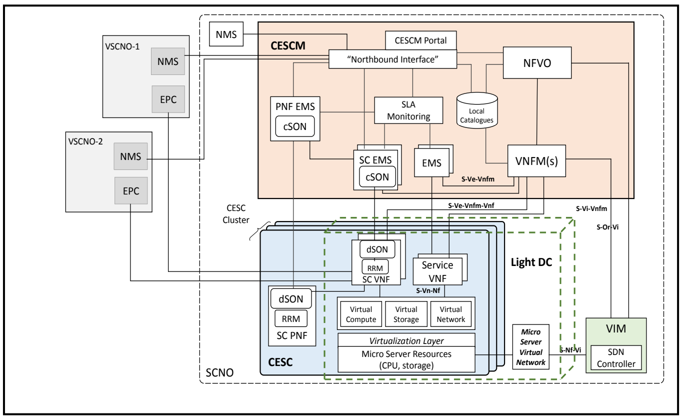

Fig. 2. Update of the SESAME architecture in relation to "Self-X" functionalities

In addition, a mapping of the specific Radio Resource Management (RRM) functions and "Self-x" functions of [23], in the different components of the architecture of Fig.3 has taken place, as also discussed in [46]. This kind of mapping depends in general on the selected functional split between the physical and virtualized functions. In this scope, RRM functionalities such as the packet scheduling or the power control, which involve the lower layers of the protocol stack, can only be included in the SC VNF when functional split at MAC or PHY levels is considered. Regarding self-planning functions, which involve decisions for deploying new cells or for changing the spectrum assigned to each cell, they are likely to follow a centralized implementation at the EMS given that they operate in the long term and they need to consider the vision of the whole network. The same applies to self-healing, and to SON coordination functions. Regarding the self-optimisation functions, different cases can be identified; for example, some functions like Coverage and Capacity Optimization (CCO) functions or energy saving, will likely be executed at the EMS level following a centralized SON approach, because they require a view encompassing multiple cells. Instead, other functions like the Automated Neighbour Relationship (ANR) will follow a decentralized approach, possibly supported by a centralized component in case of hybrid SON. In the case of ANR, the decentralized component, which acts over the neighbour lists used at RRC level, will be placed at the SC PNF or the SC VNF depending on the position of this layer in the functional split, as shown in the table. In turn, other functions like Mobility Robustness Optimisation (MRO), Mobility Load Balancing (MLB) or Optimisation of Admission control, which act over the handover and admission RRM functions running at the SC VNF, will likely be executed at the SC VNF as well, possibly supported by a centralized component at the SC EMS in case of a hybrid SON approach.

Wireless Backhaul

The wireless backhaul [47] is a flexible and cost efficient alternative to wired backhauls to interconnect the SCs of a SESAME deployment with each other and with the core network. Providing every SC with a wired, high bandwidth connection (e.g., fibre) to the core networks is very costly and very limited when choosing locations where SC has access to the required backhauling infrastructure. Further, the deployment requires a careful planning or even new infrastructure, making solutions very rigid. The wireless, SDN-based backhauling architecture designed in SESAME avoids these technical issues. In this part we detail the main design choices made for the SESAME wireless backhauling architecture. The main task of the backhaul is to provide connectivity for the S1 tunnels that are established between the SC-VNF of each tenant and its corresponding S-GW. Additionally, in SESAME the wireless backhauling infrastructure needs to be virtualized, so that a per tenant-*based* slicing of the physical radio resources can be applied. The SDN controller, that monitors the state of the network, offers interfaces to other SESAME modules, takes routing decisions and is based on OpenDayLight (ODL). This was chosen because of it is open source, the good support from the community, and the availability of software bundles that served as a basis for the OpenFlow (OF)-*based* communications between the agent nodes of the network and the SDN controller. OpenVSwitch (OVS) is used in the agent nodes to virtualize the wireless radio interfaces. The different components of the SDN architecture (ODL, OF, OVS) have been designed to work with wireless interfaces (originally OVS is intended for wired interfaces). On each backhaul node (corresponding to a CESC), virtual interfaces are created on top of the physical interfaces for every tenant that is operating on the CESC. Virtual switches belonging to a tenant then are interconnected to form a wireless mesh. As a result, every tenant “owns” a virtualized backhaul network that is composed of its virtual switches plus the virtual links between the switches. The slicing of the virtualized physical radio links across the backhaul network is handled by a scheduling software module developed for Linux. This module can be dynamically loaded during runtime and it will be configurable via an API that tells the module which part of the link share each of the virtual interfaces gets. (i.e., on a *per-tenant* basis). The software module requires minimal interaction with the underlying MAC (for Wi-Fi this is IEEE 802.11) for high precision bandwidth calculations. Further, the ODL controller will provide an API from/to other SESAME components that is used to: (i) Configure the shares each tenant has of the wireless backhaul; (ii) Set up new end-to-end data flows between SCs and a gateway node that connects the wireless backhaul to a tenant’s vEPC, *and*; (iii) Notify SCs when a tenant may be reaching the limits of the available backhaul capacity.

IV. CONCLUSIONS AND OVERVIEW

The SESAME platform targets to take advantage from the existing NFV infrastructure - that provides a virtualization platform to network functions enhancing it with new computing/storage resources and creating a virtualization environment for a wide range of applications running at the mobile network edge. In this paper, based upon the initial SESAME architecture we have discussed, *in detail*, recent innovations and evolutionary steps covering: (i) SC-Common VNF as fun-in/fun-out module; (ii) progress in SESAME Small Cell functional splits; (iii) placement of “Self-x” features, *and*; (iv) wireless backhauling. We have further realised a functional description of the corresponding updated architectural components, as identified above, with the aim of providing a “more reliable and concrete” architecture able, to ensure the proper realization of the original SESAME’s aims and specific targets.

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