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Deliverable D2.5

SESAME Final Architecture and PoC Assessment KPIs

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Abstract

Deliverable D2.5 is the fifth deliverable report of WP2, with the aim of presenting updates and/or small modifications that have been required since the submission of the previous documents describing the overall SESAME architecture, namely: D2.2: *"Overall System Architecture and Interfaces*"; D2.3: "*Specification of the CESC components*", and; D2.4: *"Specification of the Infrastructure Virtualization, Orchestration and Management*". Thus, D2.5 presents the current outcomes of iterating Tasks 2.2, 2.3 and 2.4 with regard to the design and specification of the SESAME system architecture and the related components and/or modules.

The aim has been to produce an architectural proposal which fulfils most "key" Small Cell- and NFV-*related* requirements. This implements all use cases defined in D2.1 ("*System Use Cases and Requirements*") and, *at the same time*, it allows implementation in a relatively short timeframe with reasonable technical complexity. Taking into account the use cases and requirements laid out in D2.1, D2.2, as well as SESAME project's outcomes so far also including standardisation trends, a high-level overall architecture is so proposed, which encompasses all the component entities of the SESAME system. The architecture is structured by "merging" the two main SESAME worlds, namely the Small Cells featuring the LTE network and the NFV environment.

The main concepts of SESAME dedicated to the implementation of Cloud-Enabled Small Cells (CESCs) are presented, so as to deliver edge cloud computing in a multi-service ecosystem. The SESAME roadmap to prototype is also analysed and presented here in a detailed way, at the component/sub-system and system level. A plan to deploy multi-operator enabled small cells, enhanced with a virtualised execution platform is presented, while at the system level we provide the envisaged architecture to manage and control the cloud-enabled small cell infrastructure. A thorough analysis of the identified KPIs concludes the deliverable.

5G-PPP Disclaimer:

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Contributors

First Name	Last Name	Partner	Email
Ioannis	Giannoulakis	NCRSD	giannoul@iit.demokritos.gr
Anastasios	Kourtis	NCSRD	kourtis@iit.demokritos.gr
Emmanouil	Kafetzakis	ORION	mkafetz@orioninnovations.gr
Pouria	Sayyad Khodashenas	i2CAT	pouria.khodashenas@i2cat.net
August	Betzler	i2CAT	august.betzler@i2cat.net
Jordi	Ferrer Riera	i2CAT	jordi.ferrer@i2cat.net
Eduard	Escalona	i2CAT	eduard.escalona@i2cat.net
Ioannis	Chochliouros	OTE	ichochliouros@oteresearh.gr
Evangelos	Sfakianakis	OTE	esfak@oteresearch.gr
Maria	Belesioti	OTE	mbelesioti@oteresearch.gr
Nikolas	Bompetsis	OTE	nbompetsis@oteresearch.gr
Jordi	Perez-Romero	UPC	jorperez@tsc.upc.edu
Oriol	Sallent	UPC	sallent@tsc.upc.edu
Javier	García	ATOS	javier.garcial@atos.net
Jose Oscar	Fajardo	EHU	joseoscar.fajardo@ehu.es
Alan	Whitehead	IPA	Alan.Whitehead@ipaccess.com
Leonardo	Goratti	CNET	leonardo.goratti@create-net.org
Pavel	Bliznakov	VOSYS	p.bliznakov@virtualopensystems.com
Daniele	Munaretto	ATN	Daniele.munaretto@athonet.com
Antonino	Albanese	ITL	antonino.albanese@italtel.com
Paolo Secondo	Crosta	ITL	paolosecondo.crosta@italtel.com
Athanassios	Dardamanis	SMNET	adardamanis@smartnet.gr
Ioannis	Neokosmidis	INC	i.neokosmidis@incites.eu

Glossary

Acronym	Explanation
3GPP	3rd Generation Partnership Project
4G	4th Generation (of mobile communications)
5G	5th Generation (of mobile communications)
5G-PPP	5th Generation-Public Private Partnership
AC	Admission Control
ANR	Automated Neighbour Relationship
AP	Application Protocol
API	Application Programming Interface
ARM	Advanced RISC Machine
BAU	Business as Usual Scenario
BF	Broadband Forum
BR	Bit Rate
BSMIS	Billet Structure Management Information System
CAR	Context Aware Routing
CCO	Coverage and Capacity Optimization
CESC	Cloud Enabled Small Cell
CESCM	CESC Manager
CM	Cognitive Management
CN	Core Network
CPE	Customer Premises Equipment
CPU	Central Processing Unit
cSON	centralized Self-Organizing Network
DC	Data Centre
DPI	Deep Packet Inspection
DSCP	Differentiated Devices Code Point
dSON	decentralized Self-Organizing Network
DSP	Digital Signal Processor
E2E	End-to-End
EC	European Commission
EM	Element Manager
EMS	Element Management System
eNB	Evolved Node B
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FCAPS	Fault, Configuration, Accounting, Performance and Service
FG	Forwarding Graph
FP	Framework Programme
FP7	The 7th Framework Programme
GA	Grant Agreement
GBE, Gbe	Gigabit Ethernet
GBR	Guaranteed Bit Rate
GPRS	General Packet Radio Service
GPU	Graphics Processing Unit
GS	Group Specification
GTP	GPRS Tunnelling Protocol

GWCN	Gateway Core Network
H2020	Horizon 2020
HeNB	Home eNB
HTTP	HyperText Transfer Protocol
HW	Hardware
IA	Innovation Action
ICIC	Inter-Cell Interference Coordination
ICT	Information and Communication Technology
ID, id	Identifier
IEEE	Institute of Electrical and Electronic Engineers
IEG	Industry Enabling Working Group
IFIP	International Federation for Information Processing
IP	Internet Protocol
IT	Information Technology
ITU	International Telecommunication Union
KPI	Key Performance Indicator
KVM	Kernel-*based* Virtual Machine
Light DC	Light Data Centre
LIPA	Local IP Access
LTE	Long Term Evolution
µS	micro server
M2M	Machine-to-Machine
MAC	Medium Access Control
MANO	Management and Orchestration
MEC	Mobile Edge Computing
MIB	Management Information Base
MIS	Management Information Systems
MLB	Mobility Load Balancing
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MRO	Mobility Robustness Optimisation
MVNO	Mobile Virtual Network Operator
NF	Network Function
NFV	Network Function Virtualization
NFVFG	Network Function Virtualization Forwarding Graph
NFVI	NFV Infrastructure
NFVO	NFV Orchestrator
NGMN	Next Generation Mobile Networks
NM	Network Management
NM	Network Manager
NMS	Network Management System
NOS	Network Operating System
NS	Network Service
OAM	Operation Administration and Management
QCI	QoS Class Identifier
Qemu, QEMU	Quick Emulator
QoS	Quality of Service
ODL	Open DayLight
OF	Open Flow
OVS	OpenVSwitch

PCI	Peripheral Component Interconnect
PCIe	Peripheral Component Interconnect Express
PDCP	Packet Data Convergence Protocol
PHY	Physical layer
PLMN	Public Land Mobile Network
PNF	Physical Network Function
PoC	Proof of Concept
PoP	Point of Presence
PPP	Public Private Partnership
R&I	Research and Innovation
RAM	Random Access Memory
RAN	Radio Access Network
RB	Resource Block
REA	Research Executive Agency
RLC	Radio Link Control
RRC	Radio Resource Control
RRM	Radio Resource Management
S1AP	S1 Application Protocol
SC	Small Cell
SCF	Small Cell Forum
SCNO	Small Cell Network Operator
SCTP	Stream Control Transmission Protocol
SDN	Software Defined Network
SFC	Service Function Chaining
SGW	Serving Gateway
SIPTO	Selected IP Traffic Offload
SLA	Service Level Agreement
SoC	System on Chip
SON	Self-Organizing Network
SOTA, SOA	State-of-the-Art
SW	Software
TCO	Total Cost of Ownership
TEID	Tunnel Endpoint Identifier
TO	Traffic Offload
TP	Transmission Protocol
TR	Technical Report
TS	Technical Specification
TTI	Transmission Time Interval
TU	Transcoding Unit
UC	Use Case
UE	User Equipment
UML	Unified Modeling Language
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network
VA	Video Analytics
vCashing	virtualised caching
vCAR	virtualised Context Aware Routing
vDPI	virtualised Deep Packet Inspection
vGTP	virtualised GTP
VIM	Virtualised Infrastructure Management

VM	Virtual Machine
vMOCN	virtualised MOCN
VNF	Virtual Network Function
VNFM	VNF Manager
VSCNO	Virtual Small Cell Network Operator
vTU	virtualised Transcoding Unit
vVA	virtualised VA
vWM	virtualised Water Mark
WAN	Wide Area Network
WG	Working Group
Wi-Fi, WiFi	Wireless Fidelity
WM	Water Mark
WP	Work Package

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1. Introduction

1.1. Motivation and scope

In order to "address" the needs and requirements of robust and agile network management (NM), and building upon the pillars of network functions virtualisation[1] (NFV), mobile-edge computing[2] (MEC) and cognitive management[3], SESAME's goal *-under Grant Agreement (GA) No.671596 with the European Commission (EC)-* is the development and demonstration of an innovative architecture, capable of providing Small Cell[4] (SC) coverage to multiple operators "*as-a-Service*". To that end, SESAME envisages "to virtualise and to partition" Small Cell capacity while, *at the same time*, it aims to support enhanced edge cloud services by enriching Small Cells with micro-servers (µs).

From the perspective of service provisioning, the proposed approach can be used to provide edge cloud capabilities and enable accelerated services, content and application due to the increased network responsiveness. Operators may provide the network's edge (i.e., the Light DC) to third party partners, allowing the rapid deployment of cutting-edge services to users and enterprises, translating to added value and creating opportunities for vendors, service providers and operators by enabling them complementary and advantageous positions[5],[6].

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[1] The White Paper of the ETSI Industry Specification Group NFV provides an excellent description of the problem area which network function virtualisation is going to provide a solution for.
More details can be found at: http://portal.etsi.org/NFV/NFV_White_Paper.pdf
Also see, *inter-alia,* the contents included in: ETSI GS NFV-MAN 001 V1.1.1 (2014): "*Network functions virtualisation (NFV); Management and Orchestration*". Available at: http://www.etsi.org/deliver/etsi_gs/NFV-MAN/001_099/001/01.01.01_60/gs_nfv-man001v010101p.pdf
An interesting broader NFV-*based* and SDN-*based* approach is also proposed in the study: Verizon (2016, *February*): *"SDN-NFV Reference Architecture – Version 1.0*".
Available at: http://innovation.verizon.com/content/dam/vic/PDF/Verizon_SDN-NFV_Reference_Architecture.pdf

[2] Mobile-Edge Computing (MEC) offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the mobile network. This environment is characterized by ultra-low latency and high bandwidth as well as real-time access to radio network information that can be leveraged by applications. For more details see, *inter-alia*: http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing

[3] In the context of modern management, Cognitive Management (CM) is considered as one of the innovative trends. Management activities in cognitive management are carried out through tools affecting human cognitive capabilities. The subject field of cognitive management is the process of managing organizational knowledge, which is possible in the information society and is most effective in a social environment. Cognitive networks can "dynamically adapt" their operational parameters in response to user needs or changing environmental conditions. They can learn from these adaptations and exploit knowledge to make future decisions. Essential information about cognitive management can be found, for example, in: *J. Mitola (2000): "*Cognitive Radio – An Integrated Agent Architecture for Software Defined Radio*", (Ph.D. Dissertation).* Kista, Sweden: Royal Institute of Technology. Available at:
https://web.archive.org/web/20120917062752/http://web.it.kth.se/~maguire/jmitola/Mitola_Dissertation8_Integrated.pdf
Also see: Q. Mahmoud (2007): *Cognitive Networks: Towards Self-Aware Networks*. John Wiley and Sons.
Interesting discussion for the issue is also provided in: C. Fortuna, and M. Mohorcic (2009): "Trends in the development of communication networks: Cognitive networks", *Computer Networks, 53*(9), pp.1354-1376.

[4] "Small Cell" is an umbrella term for low-powered radio access nodes that operate in licensed spectrum and unlicensed carrier-grade Wi-Fi, with a range of 10 meters up to several hundred meters. These contrast with a typical mobile macrocell that might have a range of up to several tens of kilometers. The term covers femtocells, picocells, microcells and metro cells.

[5] See, *for example,* the wider context and the framework proposed in: ETSI GS MEC-IEG 004 V1.1.1 (2015-11): "Mobile-Edge Computing (MEC); Service Scenarios". Available at: http://www.etsi.org/deliver/etsi_gs/MEC-IEG/001_099/004/01.01.01_60/gs_MEC-IEG004v010101p.pdf

Besides, the Light DC will enable the rapid on-demand deployment of cutting-edge network services in the form of Virtual Network Functions (VNFs) – such as data processors, security appliances, proxies, media transcoders, Machine-to-Machine (M2M) gateways etc., close to the mobile nodes. Locating virtual service processing nodes closer to users reduces latency, improves throughput, and reduces traffic in the core network (CN)[7],[8].

This document presents the final approach to the high-level overall architecture of the SESAME system, the entities and the main reference points.
All SESAME partners contributed to this endeavour, achieving consensus among the consortium members on the finalized architectural vision.

The deliverable presents the main concepts of the SESAME architecture with the aim of delivering edge cloud computing[9] in a multi-service ecosystem as elaborated during the first phase of the project.
Furthermore, the SESAME roadmap to prototype is also analysed and presented here in a detailed way, at the component/sub-system and system level. A plan to deploy multi-operator enabled small cells[10], enhanced with a virtualised execution platform is presented while, *at the system level*, we provide the envisaged architecture to "manage and control" the cloud-*enabled* small cell infrastructure.
A thorough analysis of the identified KPIs concludes the deliverable.

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6 Also see the framework in: IBM Corporation (2013): "*Smarter wireless networks – Add intelligence to the mobile network edge*". Available at: *http://www-935.ibm.com/services/multimedia/Smarter_wireless_networks.pdf*

7 I. Neokosmidis and E. Kafetzakis (2016): *Second Thoughts on Common Home Objects: Lamps and Home Gateways*. Presentation given in the *Joint Expert Group and 5G Vision Working Group Workshop*, Bologna, Italy, *March 16, 2016*. Available at: *https://networld2020.eu/wp-content/uploads/2016/03/S04P03_VLC_vCPE_Bologna_Neokosmidis_Kafetzakis.pdf*

8 See the context proposed in: ETSI GS NFV 001 V1.1.1 (2013-10): "*Network Functions virtualization (NFV); Use Cases*". Available at: *http://www.etsi.org/deliver/etsi_gs/nfv/001_099/001/01.01.01_60/gs_nfv001v010101p.pdf*

9 For a broader consideration see: P. Rost, C.J. Bernados, A. De Domenico, M. Di Girolamo, M. Lalam, A. Maeder, D. Sabella, D. Wübben (2014, May): "Cloud technologies for flexible 5G radio access networks", *IEEE Communications Magazine*, vol. 52(5), pp.68-76.

10 A wider informative framework is also provided in: S. Wilson (2015): *Small Cells-as-as-Service: An assessment of the Business Case- Research Strategy Report,* Analysys Mason Limited, London.

1.2. SESAME overall architecture

The architecture provided so far by the SESAME project (see Figure 1) and [1], act as a "*solid reference point*" for 5G multi-tenant small cell infrastructures with mobile edge computing capabilities[11]. It combines the current 3GPP framework for network management in RAN sharing scenarios[12],[13] and the ETSI NFV framework for managing virtualised network functions[14]. The 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[15],[16].

The execution platform is used to support VNFs that implement the different features of the Small Cells, as well as to support the mobile edge applications of the end-users.

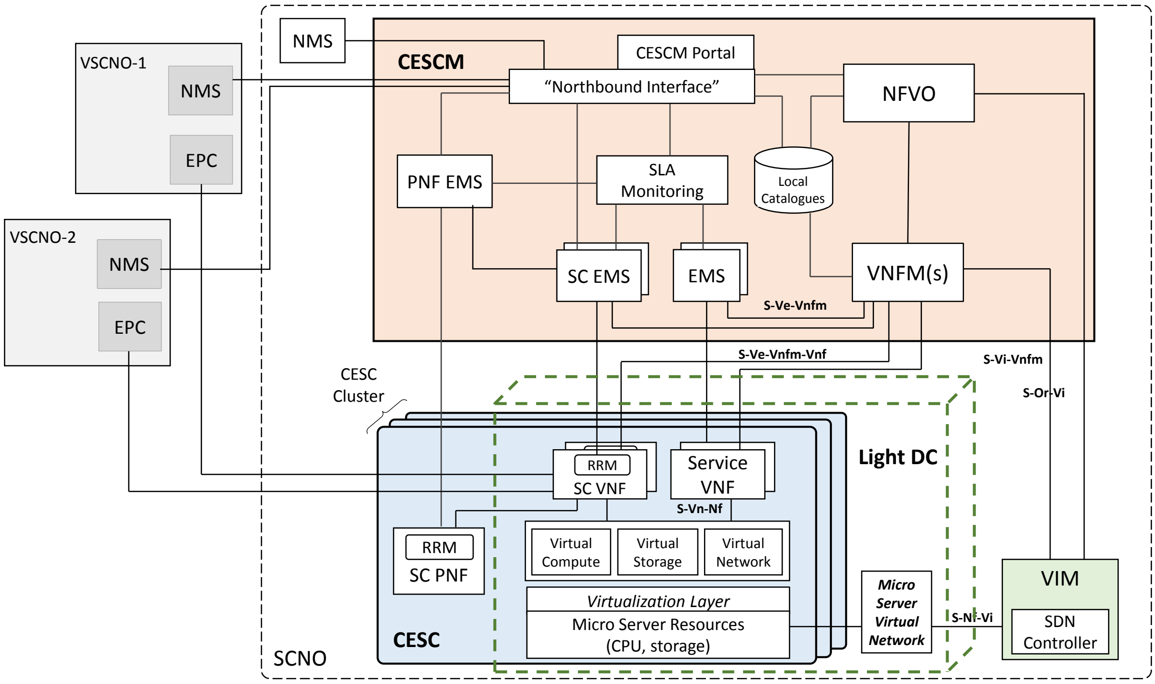

Figure 1: SESAME architecture and components' interactions

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11 Also see: I. Giannoulakis, P.S. Khodashenas, A. Albanese, et *al.* (2016). "*Enabling Technologies and Benefits of Multi-Tenant Multi-Service 5G Small Cells*". In *Proceedings of the EuCNC-2016 Conference*, Athens, Greece, *June 27-30, 2016.*

12 For more information see, *for example*: http://www.3gpp.org/news-events/3gpp-news/1592-qush

13 Also see: 3GPP TR 22.852 (2015): "*Study on Radio Access Network (RAN) sharing enhancements – Release 12*". Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=668

14 See, *for example,* the wider context and the framework proposed in*:* ETSI GS NFV 002 V1.1.1 (2013-10): "*Network Functions Virtualization (NFV); Architectural Framework*". Available at: http://www.etsi.org/deliver/etsi_gs/nfv/001_099/002/01.01.01_60/gs_nfv002v010101p.pdf

15 Krebs, R., Momm, Ch., and Kounev, S. (2012): Architectural Concerns in Multi-tenant SaaS Applications. In *Proceedings of the 2nd International Conference on Cloud Computing and Services Science (CLOSER 2012). Conference on Cloud Computing and Services Science.* SciTePress. Available at: https://se2.informatik.uni-wuerzburg.de/pa/uploads/papers/paper-371.pdf

16 Also see: Bezemer, C.-P., and Zaidman, A. (2010): Multi-tenant SaaS applications: maintenance dream or nightmare? In Proceedings of the *Joint ERCIM Workshop on Software Evolution (EVOL) and International Workshop on Principles of Software Evolution (IWPSE), IWPSE-EVOL '10*, pp.88-92, New York, NY, USA. ACM.

1.3. Document structure

This document is structured as follows:

Firstly, Section 2 focuses on the main updates on the architecture, i.e., on: (i) Small Cell - 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.

After, an overall description of the objective in Section 3, this section is devoted to the roadmap for the final SESAME prototype and the proof of concept evaluation strategy.

Finally, Section 4 contains the conclusions gathered from the contents of this document.

2. SESAME Architecture and updates

2.1. Overall SESAME architecture

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)[17] enabling framework coupled with an edge-*based*, virtualised execution environment[18],[19].

SESAME falls in the scope of these two principles and promotes the adoption of Small Cell multi-tenancy[20], i.e., 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 Small Cells (SCs) with some virtualized functions, with each Small Cell containing also a micro-server through appropriate fronthaul technology[21].
A micro-server is based on a non-x.86[22] architecture using 64-bit ARMv8[23] technology. Together with the SC, they "form" the Cloud-*Enabled* Small Cell (CESC) and a number of CESCs form the "CESC cluster" capable to provide access to a geographical area with one or more operators[24].

The overall SESAME system architecture is shown in Figure 1. The SESAME architecture foresees the split of the small cell physical and virtual network functions[25], respectively Physical Network Function (PNF) and VNF, based on the Multi-Operator Core Network (MOCN) requirements[26] and associated Radio Resource Manager (RRM) and Operations and Management (OAM) features, which need to be supported. Also in the related architecture's scope is to identify, model and analyse security issues[27] from the early

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[17] See: A. Khan, W. Kellerer, K. Kozu, and M. Yabusaki (2011): "Network sharing in the next mobile network: TCO reduction, management flexibility, and operational independence", *IEEE Communications Magazine, 49*(10), pp.134–142.

[18] I.P. Chochliouros, I. Giannoulakis, A. Kourtis, M. Belesioti, E. Sfakianakis, A.S. Spiliopoulou, et *al.* (2016): "A Model for an Innovative 5G-*Oriented* Architecture, Based on Small Cells Coordination for Multi-tenancy and Edge Services". In Iliadis and I. Maglogiannis (Eds.), *Proceedings of AIAI 2016, IFIP AICT 475*, pp.666-675. Springer International Publishing Switzerland.

[19] J.O. Fajardo, F. Liberal, I. Giannoulakis, E. Kafetzakis, V. Pii, et *al.* (2016): "Introducing Mobile Edge Computing Capabilities through Distributed 5G Cloud Enabled Small Cells", *Mobile Networks and Applications, 21*(4), pp.564-574.

[20] For more information also see: J. Oueis, E. Calvanese Strinati, E. Sardellitti, and S. Barbarossa (2015): "Small Cell Clustering for Efficient Distributed Fog Computing: A Multi-User Case". In *Proceedings of the IEEE 82nd Vehicular Technology Conference (VTC Fall)*, pp.1-5. Boston, US, *September 06-09, 2015*.

[21] For a more generalized informative framework also see: M. Peng, C. Wang V. Lau, and H.V. Poor (2015, April): "Fronthaul-Constrained Cloud Radio Access Networks: Insights and Challenges", *IEEE Wireless Communications, 22*(2), pp.152-160.

[22] For more information about x.86 see, *among others:* *https://en.wikipedia.org/wiki/X86*

[23] The ARMv8 architecture introduces 64-bit support to the ARM architecture with a focus on power-efficient implementation, while maintaining compatibility with existing 32-bit software. More related information can be found at: *https://www.arm.com/products/processors/armv8-architecture.php*

[24] L. Goratti, C.E. Costa, J. Perez-Romero, O. Sallent, et *al.* (2016): "Network Architecture and Essential Features for 5G: The SESAME Project Approach". In Iliadis and I. Maglogiannis (Eds.), *Proceedings of AIAI 2016, IFIP AICT 475*, pp.676-685. Springer International Publishing Switzerland.

[25] For a wider informative overview also see, *inter-alia*: M. Hoffmann and M. Staufer (2011): "Network virtualization for future mobile networks: General architecture and applications", in *Proceedings of the 2011 IEEE International Conference on Communications Workshops (ICC-2011)*, pp.1-5. Kyoto, Japan, *June 05-09, 2011.*

[26] Also see: JDSU (2014, January): "*Application Note: Multi-Operator Core Network (MOCN) Revenue Assurance and Troubleshooting*".
Available at: *http://www.viavisolutions.com/sites/default/files/technical-library-files/MOCN_an_nsd_nse_ae.pdf*

[27] V. Vassilakis, I.P. Chochliouros, A.S. Spiliopoulou, E. Sfakianakis, et *al.* (2016): "Security Analysis of Mobile Edge Computing in Virtualized Small Cell Networks". In Iliadis and I. Maglogiannis (Eds.), *Proceedings of AIAI 2016, IFIP AICT 475*, pp.653-665. Springer International Publishing Switzerland.

stages of system design and software development, as well as to model and analyse threats and vulnerabilities[28] in existing software and protocols[29] 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 Data Centre[30] (Light DC) to enhance the virtualization capabilities of the Small Cell deployment providing high processing power at the network edge.
The Light DC concept[31], 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 provides also the backhaul[32] and fronthaul[33] resources for guaranteeing the requirements for connectivity in case of multi-operator (multi-tenancy) scenarios. The hypervisor computing virtualization extensions enable access of virtual machines to the HW 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[34]/"Self-x"[35][36] management operations 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[37].

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

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[28] H. Mouratidis, S. Islam, C. Kalloniatis, and S. Gritzalis (2013): A framework to support selection of cloud providers based on security and privacy requirements. *J. Syst. Softw. 86*(9), pp.2276-2293.

[29] For consideration of the wider relevant context see, *for example*: H. Mouratidis, and P. Giorgini (2007): "Secure tropos: a security-oriented extension of the tropos methodology", *Int. J. Softw. Eng. Knowl. Eng. 17*(2), pp.285-309.

[30] An interesting and extensive survey on the management of server and network resources over virtualised Cloud DC infrastructures, highlighting key concepts and results, and critically discussing their limitations and implications for future research is proposed in: F.P. Tso, S. Jouet and D.P. Pezaros (2016): "Network and server resource management strategies for data centre infrastructures: A survey", *Computer Networks, 106*, pp.209-225. Available at: *http://www.sciencedirect.com/science/article/pii/S1389128616302298*

[31] For informative purposes and in order to further extend and comprehend the role of Data Centres to support network virtualization purposes see, *for example*: F. Bari, R. Boutaba, R.P. Esteves, et *al.* (2013): "Data Center Network Virtualization: A Survey", *IEEE Communications Surveys & Tutorials, 15*(2), pp.909-928.

[32] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan (2011): "The Evolution of Cellular Backhaul Technologies: Current Issues and Future Trends", *Communications Surveys & Tutorials, IEEE*, *13*(1), pp. 97-113.

[33] D. Mavrakis (2015): *Why Fronthaul Matters – A Key Foundation for Centralized and cloud RANs. White Paper.* Ovum. Available at:
http://e-blink.com/wp-content/uploads/Why_Fronthaul_Matters_EBLINK_Ovum_whitepaper.pdf

[34] B. Blanco, J.O. Fajardo and F. Liberal (2016): "Design of Cognitive Cycles in 5G Networks". In Iliadis and I. Maglogiannis (Eds.), *Proceedings of AIAI 2016, IFIP AICT 475*, pp.697-708. Springer International Publishing Switzerland.

[35] Self-Organizing Network (SON) functionalities, also referred to as "Self-x" functionalities, corresponds to a set of features and capabilities for automating the operation of a network so that operating costs can be reduced and human errors minimised. With the introduction of "Self-x" features, classical manual planning, deployment, optimization and maintenance activities of the network can be replaced and/or supported by more autonomous and automated processes, making network operations simpler and faster. "Self-x" functions can automatically tune global operational settings of the small cells (e.g., maximum transmit power, channel bandwidth, electrical antenna tilt) as well as specific parameters corresponding to Radio Resource Management (RRM) functions (e.g., admission control threshold, handover offsets, packet scheduling weights, etc.).

[36] Also see: J. Ramiro, K. Hamied (2012): *Self-Organizing Networks. Self-planning, self-optimization and self-healing for GSM, UMTS and LTE.* John Wiley & Sons.

[37] I. Son, D. Lee, J.-N. Lee and Y.B. Chang (2014): "Market Perception on Cloud Computing Initiatives in Organizations: An Extended Resource-based View", *Information & Management, 51*(6), pp.653-669.

access management task (e.g. transmission power control, packet scheduling, handover and cell reselection thresholds, etc.) and Network Function Virtualization (NFV) management responsibilities (e.g. VNF/service instantiation, lifecycle management, policy management, etc.) can be handled in an orchestrated way[38].

2.2. Updates from the version included in D2.2

From the perspective of the high level architecture, the main SESAME evolutions are related to the detailed functionality of the CESCs.

Evolution 1 – SC-Common VNF as fun-in / fun-out module

SESAME Deliverable D2.2 specified the functional split of the Small Cell 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 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 Small Cell. Depending on different parameters (e.g., fronthaul capacity[39], 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 SESAME CESC design provides a good basis for prototype-*oriented* and research-*oriented* activities in SESAME.

Evolution 2 – Progress in SESAME Small Cell functional splits

SESAME has progressed in the definition of the Small Cell functional split[40],[41]. 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, SC-C-VNF and SC VNF components.

Two alternative functional splits are addressed: S1-level functional split and RLC-MAC functional split[42],[43]. Each functional split implicates a series of capabilities and requirements (related to underlying resources needed).

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38 In order to assess the broader relevant context, see, *for example*: R. Riggio, A. Bradai, T. Rasheed, et *al.* (2015): "Virtual Network Functions Orchestration in Wireless Networks". In *Proceedings of the 11th International Conference on Network and Service Management (CNSM),* pp.1-6. Barcelona, IFIP/IEEE, *November 09-13, 2015*.

39 For informative purposes also see: A. Checko (2015): "*Cloud RAN fronthaul - Options, benefits and challenges*". Presentation given in the iJOIN Winter School "5G Cloud Technologies and Challenges", Bremen, Germany, *February 23, 2015*. Available at: *http://www.ict-ijoin.eu/wp-content/uploads/2015/03/3b_Checko_C-RAN-FH.pdf*

40 Also see: D. Harutyunyan and R. Riggio (2016): "Functional Decomposition in 5G". In R. Badonnel et *al.* (Eds.), *Proceedings of AIMS 2016, LNCS 9701*, pp.62-67. Springer-Verlag New York.

41 A more generalized context of informative validity is also proposed in: A. Maeder, M. Lalam, A. De Domenico, E. Pateromichelakis, D. Wübben, et al. (2014): "Towards a flexible functional split for cloud-RAN networks". In: Proceedings of EuCNC-2014, pp.1-5, Bologna, Italy, *June 26-29, 2014.*

42 Also see: 5G-PPP Architecture Working Group (2016): *View on 5G Architecture – White Paper.* Available at: *https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-5G-Architecture-WP-For-public-consultation.pdf*

43 INFSO-ICT-317941 iJOIN project: Deliverable 3.1 *"Final report on MAC/RRM state-of-the-art, Requirements, scenarios and interfaces in the iJOIN architecture*", November 2013.

The former is considered for the SESAME proof-of-concept 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[44],[45].
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 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 scope of SESAME Deliverable D2.2, 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[46] to the vEPCs.

In order to cope with the SESAME requirements, the wireless fronthauling/backhauling system is designed to support multi-tenancy and is driven by SDN operations[47], allowing the implementation of SDN rules[48] based on different metrics such as wireless link quality, processing capacity, etc.[49]

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.

Available at: http://www.ict-ijoin.eu/wpcontent/uploads/2014/01/D3.1.pdf

[44] J. Perez-Romero, O. Sallent, C. Ruiz, A. Betzler, et *al.* (2016): “Self-X in SESAME”, In *Proceedings of the EuCNC-2016*, Athens, Greece, *June 27-30, 2016.*

[45] Also see: O.G. Aliu, A. Imran, M.A. Imran, and B. Evans (2015): “A Survey of Self Organisation in Future Cellular Networks”, *IEEE Communications Surveys & Tutorials, 15*(1), pp.336-361.

[46] Also see the specific context discussed in the study: Next Generation Mobile Networks Alliance (2008, August): “*NGMN Optimised Backhaul Requirements*”. Available at: http://www.ngmn.org/uploads/media/NGMN_Optimised_Backhaul_Requirements.pdf

[47] For a boarder consideration see the discussion provided in: B.N. Astuto, M. Mendonça, X.N. Nguyen, K. Obraczka, and T. Turletti (2014): “A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks”, *IEEE Communications Surveys and Tutorials, 16*(3), pp.1617-1634.

[48] See, *for example,* the scope proposed in: S. Sun, L. Gong, B. Rong, and K. Lu (2015): “An intelligent SDN framework for 5G heterogeneous networks,” *IEEE Communications Magazine, 53*(11), pp.142–147.

[49] Also see: W.H.W. Tuttlebee (2003): *Software Defined Radio: Enabling Technologies*. Wiley, New York, NY, USA.

2.3. Functional description of recent components

2.3.1. SC-C-VNF as fun-in / fun-out module

The SC-Common VNF as a helper function was introduced in [1] and expanded in [4]. The top-level functionality described in [3] is largely unchanged, consisting of the following:

1) S1 Multiplexer:
   - Accepts a single S1 connection request from the PNF;
   - Creates up to six S1 connections to each SC-VNF;
   - Routes S1 messages from the PNF to the appropriate SC-VNF (and *vice-versa*);
   - Performs a small amount of identity translation.

2) Cell-wide Admission Control in the Virtualised domain

As described in [3] and also here, the SC-Common VNF also performs cell-wide admission control[50] with regard to the number of UEs and bearers permitted.

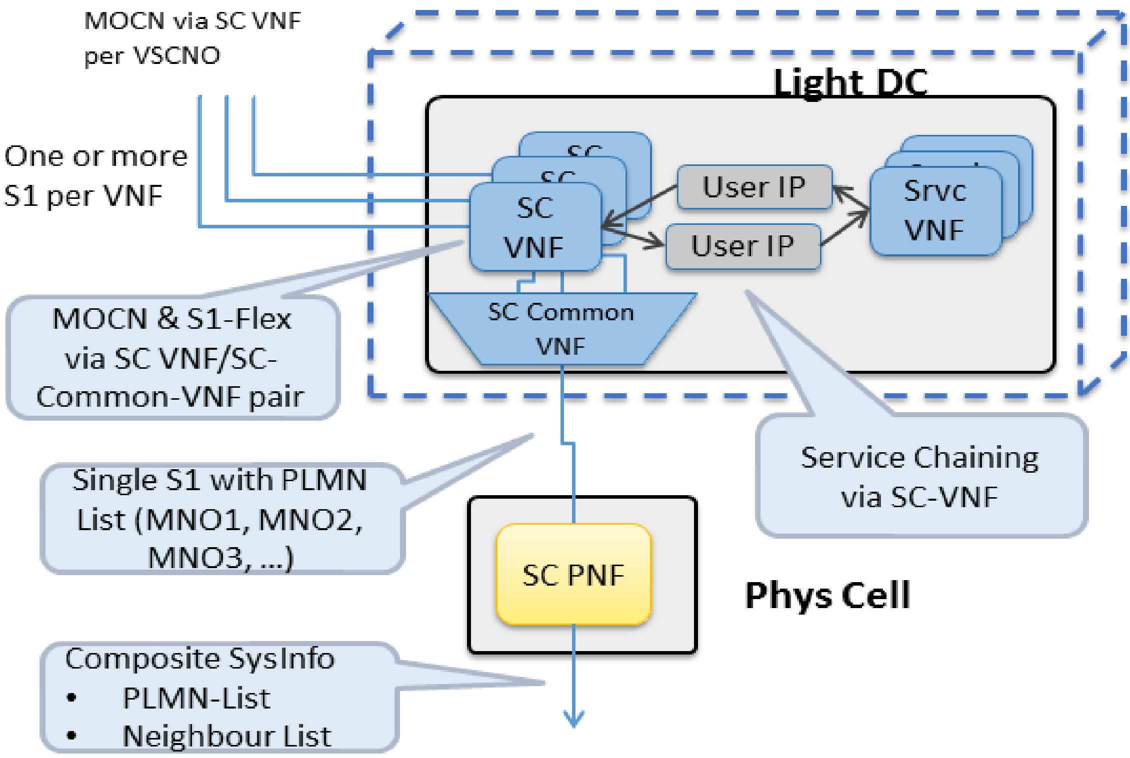

Figure 2: SC-Common VNF placement within the Light DC

[50] Admission Control is a validation process in communication systems where a check is performed before a connection is established to see if current resources are sufficient for the proposed connection. For more details also see: *https://en.wikipedia.org/wiki/Admission_control*

A change from the architecture described in [2] 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 TR-069[51], it was considered too complicated for the configuration and fault management of the SC-Common VNF and a more lightweight option was explored. For the PoC demo, IPA proprietary "BSMIS" protocol has been selected. The reasons for this are as follows:

- The protocol is already supported by the EMS;
- It has a rich set of capabilities based on the ITU X.730 series of recommendations[52];
- It has a comprehensive set of supporting tools allowing MIBs and documentation to be auto-generated from a UML model[53].

The SC-VNF was introduced in [2] and expanded upon in [4]. The top-level functionality described in [2] is largely unchanged, consisting of the following features and/or "components":

- Traffic shaping;
- Tenant-specific Admission Control (AC) based on limits applied to the specific tenant;
- GTP TEID Management[54] within the CESC;
- Congestion control via blind handover (not supported by the PoC demo);
- DSCP[55] marking per QCI[56] (not supported by the PoC demo);
- S1AP[57] routing to and from the Core Network.

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:

- A new Guaranteed Bit Rate (GBR) bearer is not admitted if, by so doing, *Max Uplink Bandwidth* or *Max Downlink bandwidth* would be exceeded.
- 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:

- 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,
- 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.
As for the SC-Common VNF, the SC-VNF uses the IPA BSMIS management protocol for configuration and fault management.

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51 Broadband Forum (2011, July): *TR-069: CPE WAN Management Protocol*. Available at: https://www.broadband-forum.org/technical/download/TR-069_Amendment-4.pdf

52 International Telecommunication Union (ITU) (1992, February): *ITU Recommendation X.730: Information Technology - Open Systems Interconnection - Systems Management: Object management function.* Available at: https://www.itu.int/rec/T-REC-X.730-199201-I/en

53 See: https://en.wikipedia.org/wiki/Unified_Modeling_Language

54 For more information see, *inter-alia:* https://en.wikipedia.org/wiki/GPRS_Tunnelling_Protocol

55 For more information see, *inter-alia:* https://en.wikipedia.org/wiki/Differentiated_services

56 For more information see, *inter-alia:* https://en.wikipedia.org/wiki/QoS_Class_Identifier

57 For more details see: http://lteworld.org/specification/s1-application-protocol-s1ap

2.3.2.Functional Split

The work included in [1], [2], [4] 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[58]. In this regard, also 3GPP[59] has recently made studies and proposals regarding functional split options and requirements have been submitted [6]-[17].
For the next generation of virtualized small cells, the studies made by 3GPP have begun in *Release 13*[60] and fall within the activities towards completion of *Release 14*[61], and are part of the wider work[62] on virtualisation of the Radio Access Network (RAN).

For the sake of completeness, the possible functional splits are: above the Packet Data Convergence Protocol[63] (PDCP), between the PDCP and the Radio Link Control[64] (RLC) and between the RLC and the Medium Access Control[65] (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[66], 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 small cell VNF and the small cell PNF is called *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 [2], [4]. 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[67] (TTI), or in other words every 1 ms, therefore carrying computational intensive tasks depending also upon the number of connected User Equipments (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, the CESC, is the junction of a small cell and a micro-server computing node through the logical S1 interface[68] (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.

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58 For more details about the activities of the Small Cell Forum (SFC), see: http://www.smallcellforum.org/
59 For more details about the activities of 3GPP, see: http://www.3gpp.org/about-3gpp
60 3GPP Release 13 comprises of around 170 high-level features and studies. In addition to enhancements to existing services and features, this release saw the completion of the first set of specifications covering mission-critical services, in particular mission-critical Push-To-Talk, the essential functionality for LTE to be used by "blue light" services for private mobile radio voice communication. For more details see: http://www.3gpp.org/release-13
61 See: http://www.3gpp.org/release-14
62 For informative purposes also consider: http://www.3gpp.org/news-events/3gpp-news/1614-sa_5g
63 PDCP is a protocol is specified by 3GPP in TS 25.323 for UMTS and TS 36.323 for LTE. The PDCP is located in the Radio Protocol Stack in the UMTS and LTE Air Interface on top of the RLC layer.
For more details, also see: https://en.wikipedia.org/wiki/PDCP
64 Radio Link Control (RLC) is a layer 2 protocol used in UMTS and LTE on the Air interface. This protocol is specified by 3GPP in TS 25.322 for UMTS and in TS 36.322 for LTE. RLC is located on top of the 3GPP MAC-layer and below the PDCP-layer. For more details, also see: https://en.wikipedia.org/wiki/Radio_Link_Control
65 For more information about MAC see, *for example*: https://en.wikipedia.org/wiki/Media_access_control
66 For more details see, *for example:* https://en.wikipedia.org/wiki/Physical_layer
67 For more information see, *for example*: https://en.wikipedia.org/wiki/Transmission_Time_Interval
68 For more information see: http://lteguide.blogspot.gr/2011/11/s1-interface.html

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 [5], 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 [5] 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[69]-*based*. Specifically, for the ARM-*based* technology the NXP platform LS2085A Reference Board[70] and the STM platform[71] (ST Barcelona Reference Board) will be included as computing nodes.
Hereinafter, the two types of functional split researched within SESAME and candidate to implementation and demonstration are discussed.

S1 Functional Split (S1 virtualisation). This is the functional split that was anticipated in [2], [4] that involves the virtualisation of the S1 Application Protocol for both control and user plane traffics. In the context of SESAME, the S1 virtualisation goes together with the possibility of deploying the 3GPP feature of Multi-Operator Core Network (MOCN)[72].
In the SESAME architecture, the micro-servers are connected to the virtualised EPC (vEPC) of different operators for handling end-to-end (E2E) connectivity and managing user's mobility and data traffic. The main advantage of the S1 split is to relax latency and throughput constraints over the fronthaul link connecting the micro-server hosting the VNF with the PNF. In this way, it is possible to avoid using optical fibre for implementing the S1 taking a 1 Gbit/s constraint over the fronthaul [5]. The S1 virtualisation has other specific advantages since it is relatively easy to implement, it implies low complexity and it does not need the definition of non-3GPP compliant interfaces, just to name a few.

In SESAME, S1 virtualisation relies on the development of two small cell-specific VNFs: Small Cell (SC) VNF and SC-Common-VNF (SC-C-VNF). The first manages user plane traffic and in particular it operates on the GTP tunnelling connection. The second instead operates on control plane traffic and it routes signalling traffic to/from one operator's core network in the MOCN configuration.
The SC-C-VNF in upstream takes the aggregated traffic of all UEs of all tenants hosted by a CESC and it de-multiplex them based on PLMN ID, separating different S1 flows for each tenant. For downstream traffic, the different S1 streams are multiplexed into a single Stream Control Transmission Protocol[73] (SCTP) connection before sending to the PNF. The SC-VNF is instead operating on the data plane traffic de-encapsulating and re-encapsulating the S1-U logical connection[74] that carries the GTP traffic. In SESAME,

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[69] x.86 is a family of backward compatible instruction set architectures based on the Intel 8086 CPU and its Intel 8088 variant. More relevant information can be found, *inter-alia*, at: https://en.wikipedia.org/wiki/X86

[70] See: http://www.nxp.com/products/microcontrollers-and-processors/arm-processors/qoriq-arm-processors/qoriq-ls2085a-rdb-reference-design-board:LS2085A-RDB

[71] See: http://www.st.com/en/evaluation-tools.html

[72] Also see the discussion provided in: G. Songqiao (2012, September): "Network sharing: A case study", *Huawei Communicate, 67,* pp.50-53. Available at: http://www1.huawei.com/en/static/HW-193401.pdf

[73] For more details see, *for example*: https://en.wikipedia.org/wiki/Stream_Control_Transmission_Protocol

[74] For more details see: ETSI TS 136 410 V9.1.1 (2011-05): *"LTE; Evolved Universal Terrestrial Radio Access Network (E-UTRAN); S1 general aspects and principles (3GPP TS 36.410 version 9.1.1 Release 9)".* Available at: http://www.etsi.org/deliver/etsi_ts/136400_136499/136410/09.01.01_60/ts_136410v090101p.pdf

there will be a separate SC-VNF for each tenant, being this the point of connection to/from the tenant's core network.

Functional split between RLC and MAC. This is the second functional split targeted by SESAME. In this case the MAC and PHY layers still reside in the PNF, whereas layers including the RLC and above reside in the virtualised micro-server environment. Similar to S1 virtualisation, the virtualised layers reside in each CESC. As shown in [18], this type of functional split requires specific latency and throughput constraints. In [18], the ideal latency is set as low as 250 µs with 187.5 Mbit/s of downlink constraint on the fronthaul and 62.5 Mbit/s in uplink. The requirements come from the tight interaction between the MAC and RLC layers. This split provides several benefits, including an alternative way of sharing the small cell by different tenants, and the possibility for tenants to share functionalities though isolation between them and security has to be ensured.

Furthermore, this type of functional split carries the same inherent benefit of more flexibly adding/removing services from the CESCs. This split provides also additional benefits in terms of manageability of processor resources, which consists of shifting processor resources to heavily loaded services and tenants, together with potentially higher scalability in using accelerators.
Finally, the MAC-RLC functional split can favour the adoption of a centralised "Self-x" for better management of the interference environment.
As a drawback introduced by this functional split, it must be mentioned a higher implementation complexity if compared to S1 virtualisation, and additional communication overhead to enable communication between the two separate MAC and RLC layers.

Furthermore, non-3GPP standardised interface is likely to be developed to achieve seamless interaction between the separate MAC and RLC layers that reside in the PNF and VNF, respectively.

For completeness, the two functional splits just described will be developed over different test-beds, still in full compliance with the general SESAME system architecture. Detailed description of both testbeds is provided in [19].

2.3.3. Self-X functionalities

The "Self-x" or Self-Organizing Network (SON) functionalities[75],[76] in the context of SESAME were categorized and explained in [1] and further elaborated in [4].
However, the initial SESAME architecture of [1] did not "depict" them explicitly. In this respect, Figure 3 of this deliverable presents an update of the SESAME architecture that includes these functionalities.

As shown in Figure 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[77].

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.

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[75] For more information also see: http://www.3gpp.org/technologies/keywords-acronyms/105-son
[76] Also see: 3GPP TS 32.500 (2015, January): *"Telecommunication management; Self-Organizing Networks (SON); Concepts and requirements – Release 8"*. Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2031
[77] For informative purposes also see: https://en.wikipedia.org/wiki/Self-organizing_network

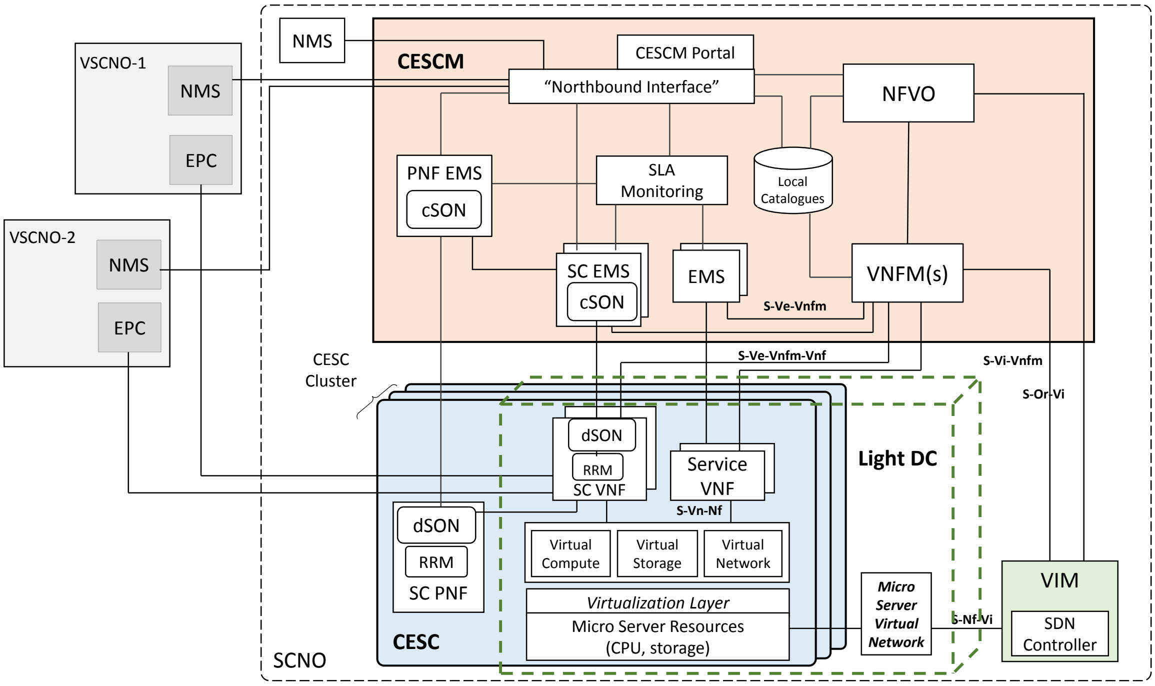

Figure 3: Update of SESAME overall architecture in relation to self-x functionalities

In addition, Table 1 presents a likely mapping of the specific Radio Resource Management (RRM) functions and "Self-x" functions of [1], in the different components of the architecture of Figure 3.
As shown in this table, this mapping depends in general on the selected functional split between the physical and virtualized functions.

Moreover, as shown in Table 1, 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[78], 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[79], and to SON coordination functions[80]. Regarding the self-optimisation functions[81], different cases are identified in Table 1.
For example, some functions like Coverage and Capacity Optimization (CCO) functions[82] or energy saving, will likely be executed at the EMS level following a centralized SON approach, because they require a view encompassing multiple cells.

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78 Also see, *inter alia*: K. Marcisz (2009): *"Towards Self-organizing Networks – White Paper"*, Comarch. Available at: http://www.comarch.com/files_en/file_983/Whitepaper-TowardsSelf-OrganizingNetworks_955.pdf

79 For the SON function see, *for example*: https://en.wikipedia.org/wiki/Self-organizing_network.
For the specific case of self-healing also see, *inter alia*: O. Scheit (2014): "Self-Healing in Self-Organizing Networks", Seminar Innovative Internettechnologien und Mobilkommunikation SS2014, pp.1-7. Munich, Germany. Available at:
https://pdfs.semanticscholar.org/7b7a/b53a4754243363ba3f1bbeef55edbcefca8f.pdf

80 For informative purposes about the broader scope of SON coordination functions, also consider the discussion proposed in: http://www.fp7-socrates.eu/files/Workshop2/SOCRATES_final%20workshop_Neil%20Scully.pdf

81 See: M. Peng, D. Liang, Y. Wei, and H.H. Chen. (2013, May): "Self-Configuration and Self-Optimization in LTE-Advanced Heterogeneous Networks," *IEEE Communications Magazine, 51*(5), pp.36-45.
Also see the context proposed in: H. Hu, J. Zhang, X. Zheng, Y. Yang, and P. Wu (2010, February): "Self-configuration and self-optimization for LTE networks", *IEEE Communications Magazine, 48*(2), pp.94-100.

Instead, other functions like the Automated Neighbour Relationship[83] (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[84] 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[85] (MRO), Mobility Load Balancing[86] (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.

Table 1: Mapping of RRM and self-x functions in the SESAME architecture

		Functional split at S1				Functional splits at RRC-PDCP, PDCP-RLC or RLC-MAC				Functional splits at MAC or PHY			
		SC PNF	SC VNF	PNF EMS	SC EMS	SC PNF	SC VNF	PNF EMS	SC EMS	SC PNF	SC VNF	PNF EMS	SC EMS
RRM functions	Packet Scheduling	X				X					X		
	Admission Control		X				X				X		
	Congestion Control		X				X				X		
	Handover		X				X				X		
	Power Control	X				X					X		
Self-x functions	Self-planning functions (planning a new cell, RF planning of a new cell, spectrum planning)			X	X			X	X			X	X
	Coverage and Capacity Optimization (CCO)			X	X			X	X			X	X

[82] See, *for example*: S. Xu, M. Hou, K. Niu, Z.-Q. He, and W.-L. Wu (2012, August): "Coverage and capacity optimization in LTE network based on non-cooperative games", *The Journal of China Universities of Posts and Telecommunications, 19* (4), pp.14-21.

[83] For more details see: http://lteworld.org/wiki/automatic-neighbour-relation-anr

[84] The Radio Resource Control (RRC) protocol is used in UMTS and LTE on the Air interface. It handles the control plane signalling of Layer 3 between the User Equipment (UE) and the Radio Access Network (UTRAN or E-UTRAN as well as for the radio interface between a Relay Node and the E-UTRAN. This protocol is specified by 3GPP in TS 25.331 for UMTS and in TS 36.331 for LTE. RRC messages are transported via the PDCP-Protocol. For more details, also see: https://en.wikipedia.org/wiki/Radio_Resource_Control

[85] See, *for example*, the discussion in: W. Zheng, H, Zhang, X. Chu, and X, Wen (2013, February): "Mobility robustness optimization in self-organizing LTE femtocell networks", *EURASIP Journal on Wireless Communications and Networking.* Available at: http://link.springer.com/article/10.1186/1687-1499-2013-27

[86] See, for example: S. Hahn, D.M. Rose, T. Kürner, (2014, May): "*Mobility Load Balancing – A Case Study: Simplified vs. Realistic Scenarios",* Technische Universität Braunschweig (TUBS), Germany. Available at: http://fp7-semafour.eu/media/cms_page_media/9/SEMAFOUR_2014_COSTIC1004_TD(14)10030.pdf

	Automatic Neighbour Relationship (ANR)	X		X(*)			X		X (*)		X		X(*)
	Mobility Robustness Optimisation (MRO)		X		X(*)		X		X (*)		X		X(*)
	Mobility Load Balancing (MLB)		X		X(*)		X		X (*)		X		X(*)
	Optimization of admission control		X		X(*)		X		X (*)		X		X(*)
	Optimization of packet scheduling	X		X(*)		X		X(*)			X		X(*)
	ICIC	X		X(*)			X		X (*)		X		X(*)
	Energy saving			X	X			X	X			X	X
	Self-healing functions (Cell outage detection / Cell outage compensation)			X	X			X	X			X	X
	SON coordination			X	X			X	X			X	X

(*) In case of hybrid SON solution

2.3.4. Wireless Backhaul

The wireless backhaul[87] is a flexible and cost efficient alternative to wired backhauls[88] 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[89] designed in SESAME avoids these technical issues.

In this subsection, we detail the main design choices made for the SESAME wireless backhauling architecture. Further details can be found in the WP3 deliverables.

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) [21]. This framework was

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87 Also see: S. Chia, M. Gasparroni and P. Brick (2009, August): "The next challenge for cellular networks: Backhaul", *IEEE Microwave Magazine, 10*(5), pp.54-66.

88 Next Generation Mobile Networks (NGMN) Alliance (2015, June): "Small Cell Backhaul Requirements", White Paper. Available at: https://www.ngmn.org/uploads/media/NGMN_Whitepaper_Small_Cell_Backhaul_Requirements.pdf

89 Also see: A. Basta, W. Kellerer, M. Hoffmann, K. Hoffmann, K., and E.-D. Schmidt (2013): A Virtual SDN-Enabled LTE EPC Architecture: A Case Study for S-/P-Gateways Functions. In: *Proceedings of the 2013 IEEE SDN Conference for Future Networks and Services (SDN4FNS),* pp.1-7. Trento, Italy, *November 11-13, 2013.*

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* [22] communications between the agent nodes of the network and the SDN controller. OpenVSwitch (OVS) [20] 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 [23]) for high precision bandwidth calculations.

Further, the ODL controller will provide an API from/to other SESAME components that is used to:
1) Configure the shares each tenant has of the wireless backhaul;
2) 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;
3) Notify SCs when a tenant may be reaching the limits of the available backhaul capacity.

2.4. Scientific and technological choices

Final decisions for software versions and dependencies between them are explained in this section (e.g., VIM Kilo version[90], Keystone v.2[91] (for NXP), Orchestrator and SFC in x.86, ARM, etc.).

SESAME VIM

The software to be used as VIM in SESAME has been chosen to be OpenStack[92]. The reasons for this decision have been the following:

- OpenStack has become the *de facto* standard for Virtual Infrastructure Management[93]. Despite existing a number of VIM software products available, the wide community and the contributions from big actors in the IT world have made it one of the most popular options nowadays.

- It is released as an Open Source project. The complete code of the main projects in OpenStack as well as any parallel project is publicly hosted. To guarantee the quality of the releases, the code contributions follow very strict rules of style and code quality and go through several review processes before approval.

- Flexibility to do modifications of the code. Because of the Open Source nature of the code and the documentation available, modifications of part of the code either to adapt or even extend a specific functionality for SESAME needs becomes perfectly feasible.

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[90] For more details see: *https://www.openstack.org/software/kilo/*
[91] See, *for example*: *http://www.pldatraining.com/courses/nxp/nxp-arm*
[92] For more details see: *https://www.openstack.org/*
[93] See, *for example*: OpenStack Foundation Report (2016): *"Accelerating NFV Delivery with OpenStack"*. Available at: *https://www.openstack.org/assets/telecoms-and-nfv/OpenStack-Foundation-NFV-Report.pdf*

- Prior knowledge from partners involved in SESAME. This project counts with several partners, such as i2CAT, VOSYS, ITALTEL, OTE, ZHAW and Atos, that are or have been involved in projects working with OpenStack, which makes the development and integration work within SESAME easier.

More specifically, the version upon which SESAME VIM is being built is based on the *Kilo Release* from *April 2015*, the 11th OpenStack release. Because of the 6-month cycle of OpenStack releases, Kilo version is currently in the End-Of-Life support stage, with official updates and patches being discontinued in favour of more recent releases.
However, there exist numerous software releases that still require Kilo version to work properly, as migration to newer versions is not always trivial. The main reason for SESAME to choose the Kilo release has been the out-of-the-box support for this version from the NXP development board used in the Light DC deployment. This allows minimizing the time needed to have a working implementation of OpenStack for testing and focusing on more complex tasks for the final prototype such as the SFC or service scaling functionalities. Furthermore, the SESAME NFVO, based on TeNOR[94], was reported to work correctly with OpenStack Kilo release.

Considering the distributed nature of SESAME CESCs deployment, extensions to the components related to the overall control (i.e. Nova[95]) and networking (i.e. Neutron[96]) are being evaluated.
Current functionality in OpenStack is focused on a more traditional view of cloud infrastructure where the exact deployment of virtual appliances is not critical, however this may be a big issue in the environment proposed in SESAME, where low-powered devices are spread over an area and decisions about power saving or traffic throughput optimizations depending on radio coverage can be taken.

Also, one development network component of SESAME architecture Netfloc[97], which is a SDN-*based* SDK for data-center network programming and offers a set of tools and libraries packed as Java bundles that interoperate with the OpenDaylight controller, was observed to behave more efficiently with Kilo release.
Including the above SESAME software (TeNOR and Netfloc) and keeping in mind that VNFs should be OpenStack release agnostic, the last part that must be OpenStack compatible is QEMU[98]/KVM ARM[99] platform virtualization libraries.
ARM platform virtualization task is leaded by VOSYS and decided to adapt the libraries to the NOVA computing agent in OpenStack Kilo release. Considering the release version, one more significant technological choice is raised.

SESAME should also choose Keystone version. In more detail, Keystone[100] is an OpenStack service that provides API for clients' authentication, services, and distributed multi-tenant authorization by implementing OpenStack's Identity API.

The Identity service provides a catalogue of services and their locations. Each service that you add to your OpenStack environment requires a service entity and several API endpoints in the catalogue.
Keystone implements two major HTTP API versions, along with several API extensions that build on top of each core API. These two APIs are specified as Identity API v2.0[101] and Identity API v3[102].
Kilo release offers as default Identity the API v2.0 but in subsequent OpenStack releases Identity API v3 is used. API v3 is a superset of all the functionality available in v2.0 and several of its extensions, and provides a much more consistent developer experience to boot.

94 For more details see: *https://github.com/T-NOVA/TeNOR*
95 See: *https://wiki.openstack.org/wiki/Nova*
96 See: *https://wiki.openstack.org/wiki/Neutron*
97 For more details see: *http://icclab.github.io/netfloc/*
98 For more details see: *http://wiki.qemu.org/Main_Page*
99 For more informative details see: *https://systems.cs.columbia.edu/projects/kvm-arm/*
100 For more informative details see: *http://docs.openstack.org/developer/keystone/*
101 See: *http://developer.openstack.org/api-ref/identity/v2/*
102 See: *http://developer.openstack.org/api-ref/identity/v3/index.html*

SESAME consortium agreed to use API v2.0 and build on it all communication between OpenStack services and development SESAME modules.
With the commitment on API v2.0, SESAME project ensures that there are no incompatibilities on the CESC components.

SESAME NFVO

Generally speaking, NFVO is responsible to bind together different functionalities (VNFs) into end-to-end, resource-coordinated Network Services (NSs). That is, based on the user request (VSCNO in our case), it determines which VNFs are involved in a NS and dictates how data should flow from one to another. This role is important, if we think of NSs crossing over various geographical points, or within a single geographical location but over multiple resources (like SESAME Light DC).
Actually, NFVO's does not directly intervene with the NFVI; instead, it emits triggers (in the form of template files, e.g. Heat template[103]) with an appropriate level of details and delegates the actual interaction with the NFVI to the VIM (OpenStack in our case).

The main benefit of NFVO in this context is the automation of the lifecycle management, especially in terms of wide deployments and continuous monitoring.

As stated in the framework of the Deliverable D6.1 [24], SESAME has adopted TeNOR [25] as the "basis" for the SESAME NFVO.

The reasons for doing so are as follows:

1. It is an open source ETSI compliant solution developed by FP7 T-NOVA project [26] with many common partners in SESAME (e.g. i2CAT, ZHAW, Atos, ORION, ITALTEL, and NCSRD). That is, SESAME starts the NFVO developments from a suitable jumping-off place.

2. TeNOR has been implemented using the modular programming paradigm. Such that each module contains everything necessary to execute only one specific aspect of the desired overall functionality. Besides many other benefits that this software development paradigm provides [27], it gives a great flexibility to TeNOR. For example, for a specific use case, it is possible to branch a copy out of the TeNOR master version containing a subset of overall available modules. Then customize one/some modules (modifying codes).

3. TeNOR has been proof tested over the OpenStack (SESAME selected VIM). It is able to send appropriate orders to OpenStack to automatically handle all NS lifecycle management duties (as defined by ETSI MANO [28]). That includes, NS instantiation, termination etc., as well as dictation of forwarding rules to the SESAME selected Service Function Chaining (SFC) solution, Netfloc – a tailored and customized version of OpenDayLight (ODL) [30] controller to enhance the Neutron functionality [31].

4. Besides the state of the art review presented on [24], a recent study compared the TeNOR capabilities with the other solutions available in the market [32]. In summary, despite some implementation choices, there is no difference in terms of carried out NFVO responsibilities.

SESAME Light DC

Initially, the SESAME Light DC was intended as a homogeneous ARMv8-*based* hardware platform. However, in order to "reflect" real NFVI deployments the Light DC conception evolved to a heterogeneous cluster, including both ARMv8-*based* nodes such as ST Barcelona and NXP LS2085, and x.86 nodes, especially the low-power Intel Atom series[104].

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[103] See: *https://wiki.openstack.org/wiki/Heat*
[104] See: *https://en.wikipedia.org/wiki/Intel_Atom*

One of the main goals when designing the Light DC is to bring computational power close to the end-user at low price, in a limited space, with minimal need of auxiliary infrastructure.
Those considerations were taken into account during the board development in T4.1 [5]. The outcome of this task, that is the ST Barcelona board, represents those advantages, which make it suitable for coupled deployment with the SESAME SC-PNF.

However, some scenarios might need running more complex VNFs and SFCs, therefore requiring more computational power. For this reason, the SESAME consortium considered a second ARMv8 platform, which has a bigger form factor and greater power consumption, but offers very good core density and disposes of hardware accelerators inside the SoC, namely NXP LS2085A[105]. It provides also two PCIe[106] slots that can be used to host additional HW accelerators, realized on commercial off-the-shelf add-in cards, to optimize specific tasks like security, DPI, video/audio transcoding.
In such high load scenarios, the LS2085A can be deployed either as remote, auxiliary compute node at places where power and deployment space for small cells are limited and therefore the STM Barcelona is "more suitable" for CESC implementation, or as micro-server part of the CESC, whenever space and power are available.

Studies have been carried also on the integration of more power consuming platforms, targeting the datacenter, for example the Cavium ThunderX CN8800-1S-CDK[107], which provides a 48 cores ARMv8 SoC.
Although such platforms require to be installed in dedicated premises, close to the network edge, they would make possible the evolution of the entire SESAME infrastructure in cases there is constant or occasional higher demand for computational power.
In fact, compute nodes can be dynamically added and removed from the Light DC infrastructure, thus making the deployment flexible in terms of costs and scalability.

The investigation of different hardware accelerator solutions in the scope of Task 4.2 [34] shown that the considered ARM-*based* platforms are not well supported by a number of PCI-card mounted hardware accelerators on the market.
The effort was focused on the integration of NVIDIA QUADRO M4000 GPU[108]. One main issue is that the power, provided by the PCIe slot of both ARM-*based* solutions is not enough for this GPU, which is the main stopper for this integration.

Additionally, the manufacturer decided to remove ARM support from the latest versions of their CUDA[109] toolkit [35].
This leads to the conclusion that in order to ensure versatility and adaptability in terms of hardware accelerators, the SESAME Light DC should also include x.86-*based* micro-servers.

Finally, the Light DC architecture was transformed from homogeneous network, powered by identical devices to a heterogeneous cluster of different platforms (Figure 4), which can be combined in various ways to provide optimal deployments according to every specific use case.

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[105] *http://www.nxp.com/products/microcontrollers-and-processors/arm-processors/qoriq-arm-processors/qoriq-ls2085a-rdb-reference-design-board:LS2085A-RDB*
[106] See, *for example*: *https://en.wikipedia.org/wiki/PCI_Express*
[107] See: *http://www.cavium.com/pdfFiles/Short_Form_Catalog_Spring_2015.pdf?x=9*
[108] See: *http://www.pny.com/nvidia-quadro-m4000*
[109] Also see: *https://developer.nvidia.com/cuda-toolkit*

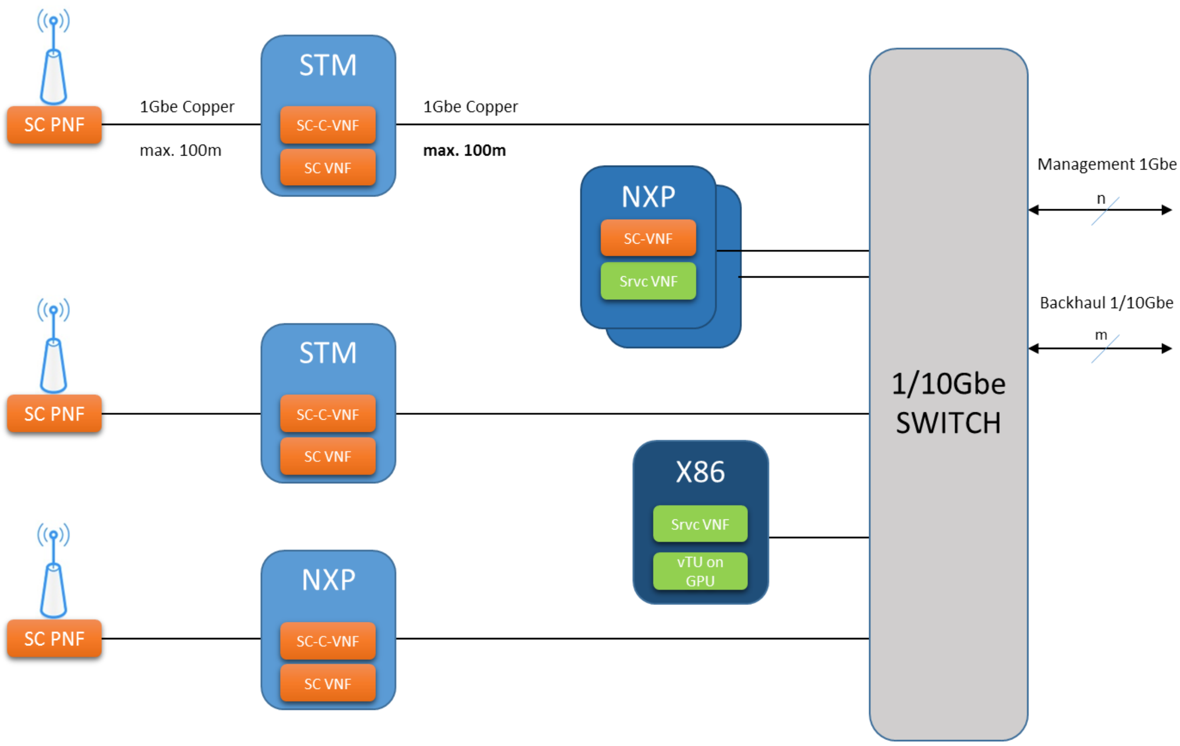

Figure 4: Heterogeneous Light DC architecture

3. Roadmap to Prototype

3.1. SESAME Proof of Concept evaluation strategy

The second version of the prototype will be seen as a complete outcome, integrating all features of the platform. The final prototype will be subject to test and measurement against the architecture and selected KPIs.

As it is shown on the overall SESAME architecture, NFVO is an important internal module inside the CESCM which is responsible for the management and coordination of lifecycle events.
Based on the inputs on section 2.4, a TeNOR based solution is the SESAME choice for NFVO. As a matter of fact, on SESAME year one (Y1) demo presented in the First Project Review Meeting (that took place at the Commission's premises in Brussels, Belgium, on *September 20, 2016*), the SESAME project has already showed "how TeNOR can be integrated with OpenStack (selected SESAME VIM) and other CESCM components (e.g. CESCM portal)". Just to recap the scenario, SESAME first year demo was a single tenant case where on the downlink (from vEPC to UE) a video was transmitted to an end-user. With the help of TeNOR, VSCNO was able to "instantiate" a watermarking VNF (vWatermarking) and "chain" it with a software responsible for S1 bearer encapsulation/decapsulation.

As a result, at any arbitrary time instant, VSCNO was able to add/drop SESAME logo watermark to the video received by the user using the instantiated edge service.

As the next step, SESAME on its future demo has targeted two main improvements. First, to show multi-tenancy by adding more VSCNOs to the scenario, e.g. 3 VSCNOs (with corresponding 3 vEPCs), each having its own set of edge services running on the Light DC. Second, to show automation of lifecycle management via establishing the full cycle of monitoring, decision making and reaction.
For example, upon the occurrence of a SLA violation, system breakdown, etc. CESCM will be able to detect the case and, based on a logical procedure, decide and react upon it.

3.2. KPIs for assessment

The use of KPIs (Key Performance Indicators) has become a recognized common practice to measure and analyse system performance. This section highlights the different types of KPIs selected by SESAME to evaluate, measure and assess the performance of the SESAME systems, as well as pillar components.
The KPIs selected and presented hereinafter rely on the work initially started in [33] and are tightly related to the SESAME use cases.

3.2.1. KPI selection

The SESAME KPIs are partly built upon the KPIs defined by 5G-PPP, which have been reviewed in [33] together with a qualitative assessment of relevance (High/Medium/Low) to the project, and the initial planning of SESAME contributions toward their achievement.
Following this approach, the targeted KPIs, the high-level relevance with respect to the SESAME goals and the way SESAME has planned to contribute are described below:

- (**P1: Relevance Low**) – *Providing 1000X wireless area capacity and more varied service capabilities, as compared to those of 2010*:

    SESAME KPIs:

    a) related to the capability of deploying high-density multi-service small cells;

b) related to the achievable data rates through small cell deployments.

- (**P2: Relevance High**) – *Reducing the average service creation time cycle from 90 hours to 90 minutes (as compared to the equivalent time cycle in 2010)*:

  SESAME KPIs:
  a) related to the deployment of a virtualized cloud environment at the network's edge;
  b) related to the support of multiple virtualized services deployed over a fast time scale.

- (**P4: Relevance Medium**) – *Creating a secure, reliable and dependable Internet with a "zero perceived" downtime for services provision*:

  SESAME KPIs:
  - related to the integration of multiple virtual operators (multi-tenancy) sharing the CESC provider's infrastructure, allowing isolated and secure provision of vertical services for massive amount of connected UEs;
  - related to the capability of adaptive resource provisioning (i.e. rebalancing or repurposing) of network resources through "Self-x" features, and orchestration capabilities;
  - related to lower latency by bringing and managing services closer to the end-users.
- (**S3: Relevance Low**) – *European availability of a competitive industrial offer for 5G systems and technologies*:

  SESAME KPIs:
  a) management of the multi-tenant infrastructure leveraging on an edge-computing architecture and deployment of "Self-x" and optimization procedures.

3.2.2.KPI Assessment

This section explains the process of assessing the KPIs described in the respective SESAME Deliverable D2.1 [33].

The aim of selection of the KPIs is to:

- Select among the KPIs determined from the literature the ones relevant for the 5G context of SESAME;
- Develop target and evaluation mechanisms;
- Have compatibility and consistency along SESAME cases, and;
- Group KPIs under different categories.

The technical KPIs (cloud computing, 5G and networking) have been obtained through consultation with SESAME partners and the use case-specific KPIs through consultation with the relevant stakeholders for each use case and with the feedback from partners.

Moreover, our first target is to select final SESAME KPIs and to "refine" the old ones from SESAME KPIs repository; a list of these has been provided to the technical partners. For more information, as the SESAME consortium, we have chosen several KPIs from different categories, which are relevant to our project (such as system utilization, integrity, accessibility, mobility and cloud virtualization).

All partners have explicitly contributed to this task, under the guidance of OTE and Atos (for the SLA of CESC components); in addition, all partners have been asked to provide respective feedback, that is whether SESAME project was missing or had irrelevant KPIs, performance objectives, etc.

The above categories of KPIs have been described during the First Year (Y1) Review of SESAME and were at a high level of abstraction. Our current goal is to provide "concrete definitions and methodology" to choose among them. Hence, this high level input was taken as a "general guidance" for the starting point of the KPI detailed definitions. The actual input for the KPI definitions was based upon partners' views, external sources (i.e. existing literature) and working knowledge coming from other research projects, in order to maintain the links and build upon the previously published works.

The overall approach to evaluate and select the KPIs of our MEC-5G solution is based on the comparison between two scenarios:

1. Technical benefits:
   - The Research and Innovation Scenario (R&I) corresponding to a solution under test;
   - The Business as Usual Scenario (BAU) corresponding to a situation when the solution is not operative, as if it had never been installed.

For both scenarios, the benefit of the solution regarding a technical aspect is calculated.
The KPI is calculated as the difference between the benefit calculated in these two situations. It represents virtualization - mobile edge computing (MEC) solution.

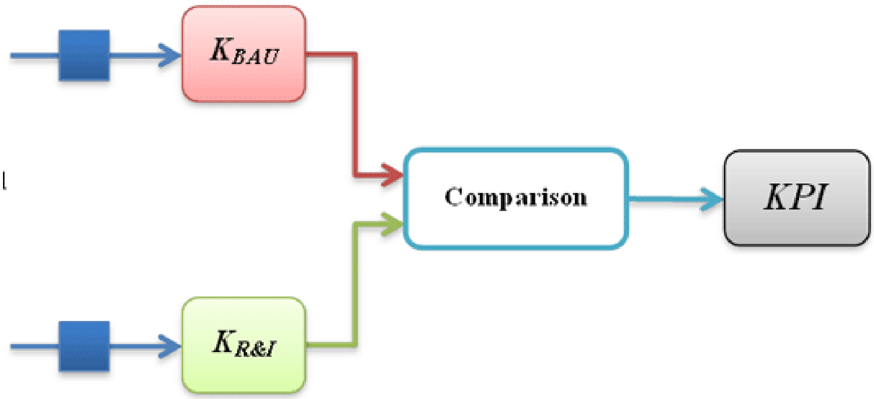

Figure 5: Technical benefits of SESAME KPIs

2. Economic benefits:

   As the technical, the economic benefits are evaluated using a Cost Benefits Analysis. This analysis takes into account:
   - The variance between prototyping and large scale development of the solutions.
   - Application of the cloud computing solution on large part of the distribution network.
   - The increasing evolution of the loads and the expected integration of the SESAME project.

3.2.3.Targeted 5G-PPP Societal KPIs

Besides 5G-PPP KPIs, high-level KPIs have been identified to address the different SESAME use cases in [33]. The high-level KPIs were selected to adequately capture the requirements of the SESAME platform, in order to:

1) Measure the fulfilment of the 5G-PPP KPIs and the SESAME use case KPIs;

2) Evaluate the improvements introduced by SESAME technologies (as perceived by the end-users) in the delivery of the services envisioned by the use cases and to understand the different deployment options (e.g. by minimizing costs, maximizing benefits or flexibility);

3) Assess the benefits of different SESAME deployment options, thus providing insights from a technology viewpoint of suitable functional split selection, *among others*;

4) Define a minimum set of requirements/functionalities to be implemented in the PoC/experimental set up, *and*;

5) Measure the compliance of the PoC with the SESAME architecture.

The process of selecting SESAME KPIs was driven by the following characteristics:

- *Relevance* – towards achieving the 5G-PPP KPIs and the SESAME use cases requirements, and in general towards the previously defined objectives.

- *Measurability* – not every KPI is easily quantifiable, and precise definition may be needed in the cases of ambiguity.

- *Assessment/evaluation methodology* – Testbed measure/Simulation/Analytical (as described in Section 3.2.2 for KPI assessment).

- *Requirements* (i.e. value/s to be met, desired and/or performance range that have to be achieved) and KPI values may vary across use cases and test cases since a single KPI cannot not usually catch all the SESAME use cases.

More in-depth explanation of SESAME KPIs is presented in following section together with an explanation of each KPI and "how SESAME intends to tackle it".
Given the multidisciplinary research topics addressed SESAME KPIs are further distinguished by the different technological choices.

3.2.4.Small Cell and mobile communications

Multi-tenancy: Multi-tenancy is a key requirement for SESAME. The whole architecture must support the operation of different tenants (e.g. VSCNOs with corresponding vEPCs) sharing the same infrastructure.

KPI: Number of supported tenants in both CESCs and CESCM.

"Self-x" features: "Self-x" features developed within SESAME allow autonomic network self-planning, self-optimisation and self-healing, with the aim to optimise the resource assignment among tenants.

KPI: CESC set-up time and CESC cluster configuration.

3.2.5.Cloud and virtualization environment

Components interoperability: SESAME system components have to expose management interfaces to offer accessibility and configurability for: the CESCM has to provide external interfaces to enable tenants to request network services (i.e. dashboard in the portal) and new resource instances; the CESC to allow the management of the micro-server environment (e.g. VNF management) and small cell; the VIM as the intermediary element between the CESCM and the CESC in charge of managing the NFVI (e.g. NFV Forwarding Graph, or NFVFG).
KPI: Accessibility of information from the SESAME system through management interfaces (i.e. CESCM, VIM, CESC, EMS) and number programmable services/functions.

Resource monitoring: Monitoring both physical (e.g. CESC, network links) and virtual (e.g. VNFs) resources is required for efficient (re)configuration of the system. By gathering operative and performance measurements of the architecture components, resource optimization algorithms (e.g. through "Self-x") can be applied to achieve improved network performance. In this regard the Element Management

System or EMS has an important role to perform FCAPS (Fault, Configuration, Accounting, Performance and Security) operations[110]. Monitoring of tenant metrics are also needed to determine the compliance with agreed SLAs.
KPI: Amount of network traffic, number of connected UEs, small cell related performance indicators within a single CESC and/or CESC cluster on a per tenant VSCNO basis.

Dynamic configuration of virtual resources: SESAME virtualization environment has to support the dynamic configuration and scaling of virtualised services. CESCM components such as the NFVO, VNFM, VIM and the SDN controllers need to modify the VNFs and network services (i.e. NFVFG) by adjusting configuration parameters and update virtual network configuration dynamically.
KPI: Time to configure or reconfigure, boot and deploy individual VNFs or network services, memory and RAM requirements.

Hardware and network acceleration: State-of-the-art (SOTA) mechanisms to improve the VNF performance by means of both hardware and network accelerators. These include the use of a heterogeneous hardware architecture based on ARM SoC, and in particular on multi-core A53 ARMv8 64-bit processor, GPUs, DSPs and FPGAs.
KPI: VNF performance in terms of processing speed and resource consumption.

VNFs and service functions chaining at the networks edge: The Light DC made of the interconnection of micro-servers in each CESC inside a cluster is the environment for deploying VNFs and network services. This is a key feature of SESAME that unveils a platform capable of moving VNFs from the network core to the edge of the network.
KPI: Number of available VNFs in the SESAME's catalogue, number of VNFs within a service chain that can be supported without impacting negatively the performance (e.g. network delay), number of available services.

Security and privacy: Secure access to all SESAME components has to be provided, as well as guaranteed data protection on a per tenant and per slice basis.
KPI: Type of security features developed or adopted for the SESAME system.

3.2.6.SESAME KPIs for *Demo*nstrations

This section aims to briefly present the SESAME KPIs that will be demonstrated through demonstrations, which is a subset of the wider set of SESAME performance indicators discussed above.

1. Number of different VNFs implemented.
2. Different types of VNFs deployed: e.g. vWatermarking, vGTP, etc.
3. Number of tenants (i.e. VSCNO) supported by the SESAME system deployed for demonstration purposes.
4. Number of VNFs or network services deployed in the CESC and CESC cluster.
5. Number of compute nodes connected in the Light DC (i.e. Processing power).
6. Use of HW acceleration in the deployment of services.
7. Technology used for the micro-server (ARM and x.86).

3.2.7.KPI assessment

In order to "evaluate and quantify" the impact of adopted technical solutions on the SESAME system performance, the KPIs (and associated evaluation metrics) are assessed by relying on different methods.

110 For more informative details also see: *https://en.wikipedia.org/wiki/FCAPS*

KPI assessment is done through different evaluation methods. These methods are complementary and do not substitute each other: if the results of all them support each other, the final output is much stronger and considered much more trustworthy.

The SESAME project will follow one or more of these methodologies whenever possible and adequate to the scope of the project.

Inspection methods – This type of evaluation is assessment-*based* and can be applied to all KPIs that depend on the system design and implementation. KPIs are evaluated by looking into general system design information, and require a simple “yes”/”no” answer for assessment.

Analytical procedure – This is applied to KPIs that can be assessed using analytical calculations (based on analytical models) and technical information available about the technology components used. This can be an algorithm, a module or a protocol. Analytical methods are applied to KPIs that can be assessed by using calculation methods. Although some input parameters for such KPIs (e.g. network load) can be specified using simple simulations, in general their value is repetitive or static during regular network operations.

Simulations – These include both system level and link level simulations (although it is expected that the majority of solutions will be “assessed” by using system level evaluation). Simulation methods are applied to 5G KPIs that are heavily dependent on instantaneous network conditions, such as availability of infrastructures and related radio resources, number of users, radio conditions, etc.

Testbed measurements – This is used to evaluate (SESAME architecture, Proof-of-Concept. etc.) concrete test scenarios based on the use cases defined in the Deliverable D2.1, and that will be implemented in a test-bed environment. Each test scenario typically covers challenges/requirements/constraints from one or more use cases.

3.2.8. Demonstration of SESAME use cases

The test scenarios serve as the basis for evaluating and refining SESAME technical solutions. Each test scenario is identified by a description, set of requirements, and a set of KPIs from the end-user perspective. For brevity, only the main challenges and description of each test scenario is provided in this document.

1. Sporadic Crowd Event. It will demonstrate the automatic deployment of a few selected VNFs for two MVNOs. It is presupposed that the CESC infrastructure supporting multi-tenancy exists in an area, like a stadium. Two MVNOs wish to exploit this infrastructure in order to provide their services to end-users. A few selected VNFs for MVNO1 and some others for MVNO2 will be automatically deployed. The HW infrastructure for micro-servers will be heterogeneous and will include x.86, NXP and STM platforms. The VNFs to be demonstrated will be selected among vTU, vWM (vWaterMark-NCSRD), vVA (vVideo Analytics-FLE), vDPI, vMOCN and vGTP.

2. Managing inter-tenant traffic classification & Multimedia services at the edge. This UC will demonstrate a dynamic environment. Initially, the total bandwidth of the CESC is divided between the two MVNOs as 30% for MVNO1 and 70% for MVNO2. This is accomplished through NOS of IPA.

3. Service Function Chaining (SFC) in Multi-tenant environment and demonstration of an SFC (vDPI-vTC-vTU) in an x.86 micro-server platform.

4. Mechanisms enabling Optimized Radio Network Capacity Planning and Operation of the Small Cell Network Operator. Monitoring data from the NOS of IPA will be collected during a period of time. These data will be processed in order to extract relevant knowledge that can feed the management decisions made by “Self-x” algorithms.

Underlying assumptions and more detailed requirement descriptions will be presented in WP7 deliverables (e.g. the respective Deliverable D7.1). Although the test scenarios described in this document are rather specific, the solutions derived from them are expected to “address” a much wider class of problems relevant for the same fundamental challenges that the test cases are based on.

Depending on the test scenarios implementation choice, it will be possible to “map” the end-user KPIs into solution-specific KPIs.

The concrete test scenarios KPIs provide a direction for research and a measure of SESAME success.

4. Conclusions

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.

SESAME promotes the creation of a better ecosystem from the standpoint of SC coordination developing “Self-x” (self-planning, self-healing and self-optimizing) techniques, which are inherent features of the CESCs, and better management of the workload across the CESC cluster.

Using the overall architecture as reference, the project can proceed to the next tasks, which are the integration and the validation of the SESAME platform, taking into account the detailed definition and implementation of the SESAME layers and subsystems (to be contained in the Deliverables D7.1 worked in parallel) as well as to the initiation of the implementation phase.

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